Preliminary Guidelines for the Rotorcraft Certification by Simulation Process[1] Update No 1, March 2023

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This document presents preliminary Guidance for the application of (rotorcraft) flight modelling and simulation in support of certification for compliance with standards CS-27 and CS-29, PART B (Flight) and other Flight-related aspects (e.g. CS-29, Appendix B, Airworthiness Criteria for Helicopter Instrument Flight).

The Guidance is presented in the form of a structured process, starting from the relevant paragraphs in the Certification Specifications, through a comprehensive description of the assembly of flight simulation requirements, informed by judgements on Influence, Predictability and Credibility, and on into the detailed building of the three major elements of the process:

- the flight simulation model (FSM),
- the flight simulator (FS), and,
- the flight test measurement system (FTMS).

The FTMS feeds both the flight model and simulator development with real-world test data to support validation and fidelity assessment. A structured and systematic approach to data/configuration management and documentation is recommended, aided by the creation of the Rotorcraft Certification by Simulation (RCbS) project management plan.

This is the first update of the RCbS Guidelines and includes modifications based on the first round of feedback received before and after the European Rotors RoCS workshop held in Cologne on November 9th 2022. The Guidelines will continue to be updated, as appropriate, with the next major revision to include exercising the process in case studies based on applicable certification requirements from EASA CS-27 and CS-29 (to appear in Section 10). In the current update, the RoCS team have also addressed the issue of resourcing the RCbS process (within Section 9) and suggested potential next steps for aspiring applicants (new Section 11).

The RoCS Team

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EXECUTIVE SUMMARY

This document is a principal output of the RoCS project. It presents Guidance for the application of (rotorcraft) flight modelling and simulation in support of certification for compliance with standards CS-27 and CS-29, PART B (Flight) and other Flight-related aspects (e.g. CS-27/9, Appendix B, Airworthiness Criteria for Helicopter Instrument Flight). The Guidance is presented in the form of a structured 'Rotorcraft Certification by Simulation' (RCbS [2]) process, starting from the relevant paragraphs in the Certification Specifications, through a comprehensive description of the assembly of flight simulation requirements, informed by judgements on Influence, Predictability and Credibility, and on into the detailed building of the three major elements of the process; the Flight Simulation Model (FSM), the Flight Simulator (FS), and the associated Flight Test Measurement System (FTMS). The latter feeds both the flight model and simulator development with real-world test data to support validation and fidelity assessment. A structured and systematic approach to data and configuration management and documentation is recommended, aided by the creation of the RCbS Project Management Plan (PMP), in Phase 0 of the process.

A requirements-based approach is advocated and outlined, acknowledging the profound importance of assembling preliminary requirements, as complete as possible (Phase 1), before embarking on simulation development processes (Phase 2). 'Assembling' refers to deriving requirements from the certification basis and engineering design requirements, considering the intended utility of the flight simulation. A detailed, and flexible, approach to requirements-capturing highlights the value in having multiple iteration/feedback routes from the build processes back to the requirements, ultimately to maximise the coherence between credibility and certification, and the requirements themselves. This dynamic is reflected in the content of this Guidance where some details of the requirements are uncovered and described in the development Phases 2a (FSM), 2b (FS) and 2c (FTMS).

In the current context, the power of modelling and simulation (M&S) is contained within their ability to describe and predict flight behaviour. Used here, *describe* has the broad meaning that physical understandings can be gained for relationships between causes and effects. Such understandings are often blurred by the complexities of rotorcraft aeromechanics, and revealed only in limited ways by test data. The *predictive* capability of modelling is clearly critical in aircraft design and development and is expected to be key to extrapolation and credibility assessment in the RCbS process. Predictive fidelity is presented in this Guidance in terms of the three flight characteristics - trim, stability and response - that together provide a complete description of flight behaviour, including performance, controllability and manoeuvrability. A pilot's ability to engage with these characteristics determines the aircraft's handling qualities and connects with a companion requirement for flight simulators – perceptual fidelity. Good predictive and perceptual fidelity maximise the utilisation of RCbS. The Guidance herein presents examples of metrics for quantifying the fidelity that is 'sufficient' for application to relevant Applicable Certification Requirements (ACRs). The concept of 'adaptive fidelity' is introduced in this Guidance to emphasise that what might be sufficient is task-specific.

A deep appreciation of the overlapping and interacting nature of predictive and perceptual fidelity is considered fundamental to the development of Guidance for RCbS. Consequently, the importance of applicant experience and specialist technical skills in the effective use of the power of (rotorcraft) M&S is stressed; a message that should ring loud and clear throughout this Guidance material.

Although there has been considerable progress over the previous decades, this Guidance acknowledges that the status of rotorcraft M&S is far from perfect. Much remains to be done to enable full certification credit solely based on flight simulation across all ACRs. In this Guidance, we refer to the following four options of 1) de-risking,

[2] RoCS and RCbS are both used for 'Rotorcraft Certification by Simulation' but differentiated so that RoCS is the 'Project' name and RCbS refers to the 'Process'.

2) critical-point analysis, 3) partial credit and 4) full credit, when considering the Influence Levels for RCbS. Within each Influence Level, Predictability Levels are then defined by the extent of interpolation and extrapolation between and beyond conditions (planned to be) validated by test data. A third dimension is added to the framework by consideration of the Confidence Level required for the application. This 3-dimensional framework is reinforced by the manifold of domains within which RCbS is undertaken – the domain of physical reality (DoR), the domain of prediction (DoP), the domain of validation (DoV) and the domain of extrapolation (DoE). The latter refers to the extent of the domain of prediction that is outside the domain of validation. It is within this sub-domain particularly that uncertainties and confidence levels in the modelling and simulation adopted need to be analysed and quantified. The confidence-ratio concept is introduced to reflect confidence when a performance margin is being predicted. Such quantifications and judgements will inform the crucial 'Credibility Assessment' in Phase 3, that establishes whether the selected Influence levels have been achieved for the ACRs.

This Guidance is intended to provide support (initially) to early adopters of RCbS, including those who have considerable experience and expertise in the use of M&S in support of design and development. It is acknowledged that there exists much good practice in the rotorcraft Industry in this regard. However, while building on this, what is presented herein is considered a significant step forward in the development of this practice, particularly in terms of the importance of a structured, requirements-based, process utilising adaptive-fidelity descriptive and predictive simulation tools and associated pre-certification flight testing, focussed on validation.

As with all such endeavours in engineering, the process should commence with the production of an RCbS PMP, in what is described as Phase 0 of the process. The PMP provides a framework for the whole RCbS process and is discussed further in Section 9, along with project documentation, data and configuration management and resource requirements. The first issue of the PMP is strictly 'preliminary', noting that until the Requirements Specification for the selected ACRs is developed in preliminary form in Phase 1 and consolidated in Phase 2, what is achievable and the required resources can only be best estimates.

The importance of following the structured process is thus emphasised, so that steps are not missed and lessons learned from early adopters can be used in the continuous improvement of this Guidance.

In extended summary form, the Phases are as follows:

a) Phase 0; RCbS Project Management Plan, addressing,
   i. resources and timescales,
   ii. dependencies and constraints,
   iii. risks and mitigations,
   iv. process control, documentation, configuration and data management,
   v. structure for documenting the RCbS certification case,
   vi. **Output – the RCbS PMP used to provide governance for all activities in Phases 1–3 (Section 9).**

b) Phase 1; assembly of the (preliminary) RCbS Requirements Specification including,
   i. ACR(s) from the Certification Specifications are identified for RCbS,
   ii. the four domains within which the RCbS will be carried out are defined (DoV, DoP, DoE, DoR),
   iii. the Influence and Predictability Level matrices are defined for the selected ACRs,
   iv. the relevant aircraft design data are collected together with related uncertainties,
   v. preliminary description of expected complexity content for the FSM, FS and FTMS needed to achieve 'sufficient fidelity' for each of the selected ACRs,
   vi. analysis and metrics for DoV fidelity assessment, together with tolerances for sufficiency, are defined, in preparation for meetings with certification authorities,

    vii. definition of test data requirements to characterise the domain of validation including programme for pre-certification flight trials and ground tests,
    viii. analysis and metrics for uncertainty characterisation and credibility assessment are defined,
    ix. Output; the (preliminary) RCbS Requirements Specification assembled based on the above, using a comprehensive descriptive framework (see Section 3).

c) Phase 2; development of the FSM, FS and FTMS based on the (preliminary) Requirements Specification
    i. FSM build, verification and validation and fidelity assessment, including updating/tuning,
    ii. prototype FSM supplied to the FS and FTMS developers to support parallel activities,
    iii. FS build, verification and validation and fidelity assessment, noting that legacy facilities could be used which may, or may not, require modification,
    iv. FTMS build, verification and validation and fidelity assessment, noting that legacy facilities and approaches could be used which may, or may not, require modification,
    v. conduct pre-certification ground and flight test programme to support validation of FSM and FS,
    vi. multiple iterative pathways managed and exercised as required throughout Phase 2,
    vii. updates to Requirements Specification based on Phase 2 activities,
    viii. Outputs; FSM and FS verified and validated for intended purpose, included in fidelity assessment reports (Sections 5, 6, 7).

d) Phase 3; credibility assessment and certification
    i. RCbS certification tests performed for relevant ACRs
    ii. uncertainty characterisation undertaken throughout the domain of prediction,
    iii. credibility assessments undertaken based on the results from fidelity and uncertainty analyses,
    iv. results assembled and presented to certification authorities to make the ‘means of compliance’ case in the certification,
    v. based on the feedback from Phases 2 and 3, the Requirements Specification is updated to constitute a formal element of the case for RCbS for the selected ACRs.
    vi. Outputs; updated RCbS Requirements Specification and Type/Supplemental-Type Certificate documentation (Section 8).

In this second, public-domain, version of the Guidance, feedback on the first version, received from a variety of sources, has been embodied in the document. The next major update will include results from Case Studies drawn from selected ACRs and presented in Section 10. These will aim to demonstrate the efficacy of aspects of the process and include example metrics and tolerances for fidelity sufficiency and credibility analysis.

The guidelines presented in this document are intended to support applicants gain an appreciation of a route to achieving RCbS. Furthermore, the guidelines provide a framework for community-wide debate and critical reviews ahead of any potential formal acceptance of such processes, and the publication of related standards, by the certification authorities.

The RoCS team recognise that establishing a comprehensive RCbS capability will require both short and long-term investments. Benefits in certification time, cost, safety and performance are likely to be accrued gradually, with initial applications rich in learning and capability-development experiences. The Guidance addresses possible routes towards developing such a RCbS capability, in terms of both technical breadth and depth, and drawing on existing certification cases to exercise the process. Section 11 discusses the ‘next steps’ along such routes, within the context of a long-term industrial strategy, addressing ACR options for early successes and capability development.

Finally, this Guidance makes use, in places, of the grammar modals should, shall, can, may, etc. Unlike in formal requirements specifications or rules, there is no intention to be prescriptive here or to differentiate between levels of modal importance. However, the RoCS team envisage this Guidance as a starting point in achieving a grander objective of defining a formal Acceptable Means of Compliance with certification specifications using modelling and simulation.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this document is to provide guidance on the multiple aspects to be considered when using flight simulation to support, either directly or indirectly (e.g. full-credit or de-risking), the showing of compliance with the flight-related requirements within Certification Specifications CS-27/29 [1] [2]. The Guidance is intended to facilitate the development and define the constraints for the effective use of flight simulation, to support, augment or replace flight testing in the demonstration of such compliance, without sacrificing the level of safety. The simulation may take the form of e.g. off-line, desktop simulations using a stand-alone Flight Simulation Model (FSM), or of real-time piloted simulations in a suitable Flight Simulator (FS).

The scope of the document is broad, encompassing a requirements-based approach to the development, verification and validation, and usage of flight simulation models and associated flight simulators. Through modelling and simulation, rotorcraft flight mechanics is described and quantified, and linked with the certification specifications, within the behavioural elements of trim, stability and response and associated flight handling qualities. Fidelity assessment through simulation validation are major aspects of the approach described in the Guidance, hence attention is also given to the requirements for test data and the development of the Flight Test Measurement System (FTMS).

Following common practice in design and manufacturing, the Guidance is assembled in the form of a structured process, proposed to be followed by applicants to ensure maximum benefit from the adoption of flight simulation as an alternative means, or to otherwise support the showing of compliance with the applicable standards.

The content has taken into consideration the outputs from various related activities including the European Union Aviation Safety Agency (EASA) Proposed Certification Memoranda CM-S-014 Issue 01 on Modelling & Simulation (M&S) for CS-25 Structural Certification Specifications [3] and the parallel evolution of the Proposed Means of Compliance (MOC) with the Special Condition VTOL (MOC SC-VTOL) [4].

1.2 BACKGROUND

To quote from the standards, proof of compliance with CS-27/29 Subpart B must be obtained by *"tests upon a rotorcraft of the type for which certification is requested, or by calculations based on, and equal in accuracy to, the results of testing."* As in the Federal Aviation Administration (FAA) Advisory Circular AC-29.21(a) [5], the term "*calculation*" includes flight simulation. The term "*equal in accuracy*" is subject to interpretation and will be addressed in this Guidance in the material on fidelity and credibility assessment, and measured in terms of fidelity metrics defined by the applicant and agreed by the certification authority.

Flight testing is costly, time consuming and may carry with it significant risk. It is anticipated that certification compliance demonstration through flight simulation, under the right conditions, may yield benefits in all three aspects. However, to deliver these benefits, a concerted effort is required on the part of the applicant to develop, validate and maintain a simulation environment that is of sufficient fidelity for the application and is exercised within the limits of its validity. Outside the limits of proven validity, extrapolation might be used to enable flight simulation to reach areas of the domain of prediction (DoP) that, for various reasons, are not populated with test data, e.g. ACRs associated with high-risk failure conditions, or areas of the envelope that require relocation to high-altitude test sites. The Guidance expands on the important concept of 'sufficiency', and the various 'domains' in which M&S are used, in Sections 3, 5 and 6.

The FAA's AC 25-7D §3.1.2.6 defines the general principles under which flight simulation may be proposed as an acceptable alternative to flight testing for large aeroplanes [6]. In the case of [6], the simulation is taken as one of the elements, or possibly in some cases as the only element, to inform decision-making on airworthiness. Paramount to the acceptance of this approach for certification purposes, is that it must be shown that the simulation leads to credible predictions of flight behaviour. Conventionally, the prediction error is determined by comparisons between (ground and/or flight) test data and analytical/numerical results, performing a set of analyses that fall under the term 'Validation'. Beyond validation, for the usage of simulation to support airworthiness decision-making, it is necessary to show that the models are also 'Credible', in that the uncertainty of the predicted outcome, beyond and within the validation domain, is known and acceptable. Validation is addressed within the relevant Sections (3, 4, 5, 6) while credibility is introduced in Section 3 and addressed in more detail in Section 8.

The idea of using simulation for certification is not peculiar of the aerospace sector, and other technological sectors are pursuing a similar path. In particular, it is worth noting the specification for the type approval of the automated driving system of fully automated vehicles adopted by the European Parliament, where in part 4 the principle of credibility assessment of models for certification are laid down [7].

While the Guidance herein is intended to be equally applicable to Original Equipment Manufacturer (OEM) Type Certificate (TC) and Supplemental Type Certificate (STC) applicants, it is recognised that a lack of access to OEM engineering design data and development flight test data, such as might be the case for STC applicants, may skew the cost-benefit trade analysis in favour of flight testing. Equally, it is understood that applicants may elect to exploit an existing FS and/or FTMS, provided the minimum requirements specified and agreed in Phase 1 are satisfied.

As the state-of-the-art in flight modelling and simulation is continuously evolving, it is expected that their utility and application for certification purposes will increase over time. This Guidance attempts to provide a route for such increased, more extensive, application. Furthermore, ground testing and/or pre-certification, developmental flight testing, for the (sole or partial) purpose of validation, are expected to remain an integral part of ensuring simulation credibility. As such, the requirements for pre-certification testing become part of the process described in this Guidance.

1.3 Document Structure

The material in this Guidance falls under two main categories. The first category (Sections 2–9) contains the description of the overall Rotorcraft Certification-by-Simulation (RCbS) process, commencing with an overview of the process (Section 2). Section 3 describes the flight simulation requirements capture and build process. Then, Section 4 introduces the types of flight simulation that might be used, followed by Sections 5 and 6 addressing model/simulator-building and validation and fidelity assessment, and Section 7 for the flight test measurement system development. Credibility assessment and certification are presented in Section 8, while Section 9 addresses RCbS project management aspects, such as resource requirements, risks and constraints, and data/configuration management. Within this first category (Sections 2–9), the following phases and sub-processes are featured; verification and validation (V&V) of the FSM, calibration of the FTMS, FS fidelity assessment, model-updating and credibility assessment etc.

Figure 1-1 summarises of the contents of the Guidance, section by section.

Figure 1-1: RCbS Guidance in brief, section by section

The second category is contained in Sections 10 and 11. Section 10 features guidance for specific sections of the Certification Specifications, drawn from the results of assessments with state-of-the art FSMs and FSs. The opportunity is taken to illustrate particular aspects of the RCbS process that were exercised in these 'case studies'. The initial content will be populated with examples from the Cleansky2 RoCS project [8] in the second update to this Guidance, but it is anticipated that the content of Section 10 will continue to evolve with further material drawn from different RCbS applications. Section 11 suggests possible next steps along the routes forward for the early adopters of the RCbS process outlined in this Guidance.

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1.5 ABBREVIATIONS

ac	aerodynamic centre
cg	centre of gravity
tc	torsion centre
AC	Advisory Circular (FAA)
A/C	aircraft
ACR	Applicable Certification Requirement
ADS-33	Aeronautical Design Standard-33
AFCS	Automatic flight control system
AlU	Aleatory uncertainty

AMC	Acceptable Means of Compliance
AR	Augmented Reality
ATC	Air Traffic Control
CFD	Computation Fluid Dynamics
CPA	Critical Point Analysis
CR	Confidence Ratio
CS	Certification Specification (EASA)
CSRFA	Certification by Simulation for Rotorcraft Flight Aspects
DoE	Domain of Extrapolation
DoFs	Degrees of Freedom
DoP	Domain of Prediction
DoR	Domain of Physical Reality
DoV	Domain of Validation
DS	Dynamic Stability
EASA	European Union Aviation Safety Agency
EP	Evaluation Pilot
ES	Environment System
EpU	Epistemic uncertainty
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCS	Flight Control System
FoR	Field of Regard
FoV	Field of View
FS	Flight Simulator
FSM	Flight Simulation Model
FT	Flight Test
FTG	Flight Test Guide
FTMS	Flight Test Measurement System
HITL	Hardware-in-the-Loop
HQs	Handling Qualities
HT	Horizontal Tail

IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
I-P	Influence-Predictability
LDO	Lateral-directional-oscillation
M&S	Modelling and Simulation
MBDS	Multi-Body Dynamic System
MDA	Motion Drive Algorithm
ML	Machine Learning
MOC	Means of Compliance
MR	Mixed Reality
MUAD	Maximum Unnoticeable Added Dynamics
NPA	Notice of Proposed Amendment
OEM	Original Equipment Manufacturer
OMCT	Objective Motion Cueing Test
OS	Operator Station
OTW	Out-The-Window
p-model	Phenomenological model
PAO	Pilot Assisted Oscillations
PMP	Project Management Plan
QTG	Qualification Test Guide
RoCS	Rotorcraft Certification by Simulation (project name)
RCbS	Rotorcraft Certification by Simulation (process name)
RPCs	Rotorcraft-Pilot Couplings
SAS	Stability Augmentation System
SCAS	Stability and Control Augmentation System
SME	Subject Matter Expert
STC	Supplementary Type Certificate
TC	Type Certificate
UAQ	Uncertainty Analysis and Quantification
UQ	Uncertainty Quantification
V&V	Verification and Validation

VeMCS	Vestibular Motion Cueing System
VzMCS	Visual Motion Cueing System
VR	Virtual Reality

1.6 DEFINITIONS

Accuracy	The closeness of a parameter or a variable with the assumed true reference. It usually requires a metric to be quantified.
Aleatory uncertainty	The inherent variation associated with the physical system or the environment under consideration, e.g. the variation of geometric and or material properties due to manufacturing process It is stochastic and irreducible below a certain threshold.
Applicable Certification Requirement	A requirement, normally specified by a paragraph in a Certification Specification, that is considered a candidate (applicable) for compliance demonstration using modelling and simulation.
Average pilot	A pilot able to apply a normal level of skills required in the context of civil rotorcraft operations. An average pilot would not require exceptional skills in the course of their flying duties.
Comparison Error	The difference between the result of an experiment, or any other referent, and the corresponding simulation result. It is indicated with the symbol δ_c.
Compliance demonstration	The process of demonstrating that a system is compliant with defined requirements or standards.
Conceptual Model	The collection of assumptions and abstractions applied to develop a physical model of the system of interest.
Credibility	The quality of a simulation for being convincing or believable in its representation of flight behaviour.
Damping ratio	A characteristic measure describing how an oscillation in a system decays after a disturbance; for low damping, it is approximately proportional to how much the oscillation decays/grows in a cycle, as described in the logarithmic decrement method
Data Pedigree	A record of traceability of the data used to build the FSM. It should cover all aspects of data source, transmission, storage and processing to its final form used to build or validate the FSM.
Degrees of Freedom	The set of independent variables that completely define the state of the flight simulation model.
Domain of Extrapolation	The domain within which extrapolation of predictions are made to achieve certification at defined Influence Levels for an ACR.

Domain of Physical Reality	The domain within which the laws of physics being used are adequately represented in the flight model and flight simulator. Since all models and simulations used in the RCbS process will include approximations to physical reality, this domain is strictly the region where the approximations are valid, reflecting the description 'adequately represented'.
Domain of Prediction	The domain within which it is the intention to predict the behaviour of the aircraft or component and to use these predictions to achieve certification at the defined Influence Levels for an ACR.
Domain of Validation	The domain within which test data will be used to validate the flight model or simulator and their components/features. Validation means a positive outcome has been achieved for the relevant metrics in the fidelity assessment. Within the DoV, interpolation is used to predict behaviour between validation points.
Domain of Verification	The region of all conditions for which FSM/FS codes and implementations are deemed to be correct (i.e. function as intended) and solutions have been determined to possess the required accuracy.
Epistemic uncertainty	The potential inaccuracy in any phase or activity of the modelling process that is due to a lack of knowledge or to intentional approximations applied by the analyst. It is potentially reducible by model improvements or by a better measuring technique employed to assess model parameters.
Experimental Error	The difference between the experimental value, or the value of any other referent, and the true (unknown) value. It is indicated with the symbol δ_r. To this error, it is possible to associate a numeric uncertainty u_r.
Input Error	The error in a parameter used as input for the simulation model. It is indicated with the symbol δ_{inp}. To this error, it is possible to associate a numeric uncertainty u_{inp}.
Flight Simulation	Flight simulation refers to either offline desktop simulation, or real-time pilot-in-the-loop simulation in a suitable FS.
Flight Simulation Model	A computational model that can be created and analysed through the employment of software, to generate data useful to support the design, development and certification processes.
FSM fidelity	Fidelity of the FSM as reflected in the accuracy with which flight behaviour is modelled compared with the real aircraft or, more generally, the referent. It is assessed through the definition of one or more metrics to identify the model accuracy. The same model can have different fidelities, depending on the usage of the model and on the prediction domain chosen. So, the concept of fidelity must be always associated with the FS and the prediction domain.
FSM Uncertainty	Estimated variation in the results of simulation of the FSM due to factors inherent to the model and not to the referent used for validation.

Flight Simulator	A device for enabling a pilot to fly tasks associated with an ACR in a virtual environment.
FS fidelity	How well the outputs of the flight simulator agree with the corresponding values in the referent (parameters that quantify the fidelity). The FS fidelity is composed by two parts: the predictive fidelity and the perceptual fidelity.
Handling Qualities	As defined by Cooper-Harper in Ref [32], "*Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role*."
Influence level	The extent to which the use of RCbS influences the Certification process classified in four levels - full credit, partial credit, critical point analysis, de-risking
Mathematical Model	Mathematical formulation of the relationships between cause and effect
Metrics	Normally a mathematical function to measure a distance between two elements: two points or results, or two sets of points or results.
Model calibration	The process of adjusting physical modelling parameters in the model to improve agreement with a referent (commonly used in other fields of application).
Model component	The subsystems or individual elements that make up the Flight Simulation Model. A model component to be defined as such must be a system for whom it is possible to perform a specific validation. Typically, each FSM is composed by several components interconnected together.
Model Error	The error caused by the modelling assumptions. It is indicated with the symbol δ_{model}.
Model tuning	The process of adjusting model parameters to improve agreement with a referent. Can also be used in cases where the physics-based structure of the model is not considered critical.
Model updating	The process of updating model structure and content to improve agreement with a referent (term more commonly used than model calibration in flight mechanics applications).
Modelling & Simulation	Modelling and Simulation (M&S) is the use of a (conceptual, mathematical or numerical) model as a description or representation of a real system or phenomena for simulation by computational means. Modelling is the act of constructing a model; simulation is the execution of a model to obtain results.
Numerical Error	The error due to the numerical algorithms employed to solve the problem. It is indicated with the symbol δ_{num}. To this error, it is possible to associate a numeric uncertainty u_{num}.
Phenomenological model	A mathematical relationship between cause and effect that is created from measurements. This term is used in the RCbS process with reference to, e.g. linear models derived from system identification, usually with a

structure defined at the outset based on simpler, linear forms of the FSM. Other examples include models, such as wind tunnel aerodynamic data, or models obtained by using Artificial Intelligence or Machine Learning algorithms. The latter algorithms present specific risks and challenges, particularly with regards to extrapolation, which are not addressed within this Guidance [9].

Physics-based — A physics-based model is one where all relationships between cause and effect, inputs and outputs, are governed by the laws of physics. This is in contrast with phenomenological models, where relationships are generally constructed from measurements of cause and effect, inputs and outputs, often without regard for the underlying physical laws.

Physical laws — A scientific generalisation based on empirical observations of physical behaviour. Empirical observations are typically conclusions based on repeated scientific experiments over many years, and which have become accepted universally within the scientific community.

Perceptual fidelity — Perceptual fidelity refers to the fidelity of the cues that are transferred from the simulator hardware to the pilot to allow the pilot to put in place reactions that are as close as possible to those that will be implemented in flight. It is composed by many aspects and reflects the variety of sensorial inputs that can be acquired through the human body (visual, auditory, tactile and also movement perception).

Predictive fidelity — Predictive fidelity is the fidelity of the FSM, i.e. the fidelity of the numerical model associated with the vehicle and to the environment to be represented.

Referent — Data, information, knowledge, or experimental results against which a FSM or simulation can be compared. It can be real word data, or results obtained using analogous systems or, in some cases, higher fidelity models.

Requirements — The source description for how an entity (e.g. FSM, model component) should function, operate (including constraints) and interact with other entities through inputs and outputs. The associated requirements specification should be complete and traceable and testable within the V&V processes.

Risk — The risk is the combination of the predicted severity of consequences and the likelihood – i.e., probability – of an event. A risk can be reduced by addressing either of these two elements.

Sensitivity analysis — The study of how the variation of an output of the FSM can be appointed to different sources of variation in the model input and parameters.

States — Variables required to completely define the condition of a degrees of freedom. For example, a single degree of freedom mechanical system, whose dynamics is represented by a second order differential equation, requires two states to be modelled (often the position and the velocity of the degree of freedom).

Simulation Error	The difference between the simulation value and the true (unknown) value. It is indicated with the symbol δ_s.
Subject Matter Expert	An individual having education, training and/or experience in a particular discipline, system and process.
Validation	The part of the V&V process for determining the degree to which a model, or a simulation, is an accurate representation of the real world from the perspective of the intended uses of the model. It is conducted by comparing the model or simulation with a referent, extracted from the real word. The validation process aims to ensure that the model or simulation meets the associated fidelity requirements.
Validation Standard Uncertainty	An estimate of the standard deviation of the combination of the effects of input, numeric and experimental uncertainties. It can be estimated both in the domain of validation or in the domain of prediction. Indicated with the symbol u_{val}, or more generically with U.
Verification	The part of the V&V process for determining that a computational model accurately represents the underlying conceptual and mathematical models and their solutions. It is usually composed of two elements: code verification and solution verification. The verification process aims to ensure that the model meets the code structure and solution requirements, so functioning as intended.
Variables (Global)	Variables associated with the flight simulation model as a whole, at aircraft-level.
Variables (Local)	Variables associated with model components.
Virtual pilot	A computer-pilot operating through defined algorithms to fly manoeuvres and tasks.

1.7 LIST OF SYMBOLS

u_{inp}	Input uncertainty
u_{model}	Model structure or form uncertainty
u_{num}	Numerical uncertainty
u_p	Prediction uncertainty
u_r	Experimental (referent measurement) uncertainty
u_{val}	Validation uncertainty
u_{Xi}	uncertainty associated with input X_i
x_i	input in the context of input uncertainty analysis
M	Performance margin

N_r	yaw damping derivative (1/sec)
R	Referent data, from experimental data (in the DoV), used to compute validation error
S	result from Simulation prediction, used to compute validation error
U	Uncertainty (combined from variety of sources)
V	Aircraft velocity
V_{NE}	Never exceed velocity
V_Y	Best rate of climb velocity
α	Incidence
β	Sideslip
δ_c	Comparison error
δ_{inp}	FSM input parameter error
δ_{model}	FSM model (structure/form) error
δ_{num}	Numerical error in FSM solutions
δ_p	FSM prediction error
δ_r	Experimental error in producing the referent data
δ_{val}	validation error (S-R = δ_p - δ_r)
ω, ω_n	frequency and natural frequency of oscillation on the eigenchart
ζ, $\zeta\omega_n$	relative damping and damping of oscillation on the eigenchart

2 STRUCTURE OF THE ROTORCRAFT CERTIFICATION BY SIMULATION (RCbS) PROCESS

The comprehensive and structured RCbS process is illustrated in Figure 2-1, with activities in each 'box' having dedicated Sections or sub-Sections. Following on from the creation of a RCbS Project Management Plan in Phase 0, the RCbS process is organised in three main subsequent, but iterative, phases: 1) Requirements-capture and build, 2) FSM development (2a), FS development (2b) and FTMS development (2c), 3) Credibility assessment and Certification. It is emphasised that phases are to be managed to enable the multiple iterative cycles highlighted, to ensure that the results of any assessment (e.g. verification, fidelity, Credibility) can take the applicant back to a previous phase or sub-phase, as required. The Certification Requirements themselves are input to the 'Influence / Predictability / Credibility levels' activity, which act as input to assembling the Flight Simulation Requirements – the driver for the whole process. These requirements are also informed by inputs from the engineering requirements and data. The process diagram in Figure 2-1 uses solid lines to describe forward progress through the process. Recognising that activities in a phase or sub-phase might need to be updated as a consequence of results from a future phase, particularly fidelity and credibility assessment, dashed lines are used to highlight the return paths for iterative cycles. The Certification Requirements and Engineering Design Data/Requirements that feed Phase 1 are, of course, pre-defined inputs to the RCbS process. In this context, the Certification Requirements encompass the CS (or Federal Aviation Regulations, FAR, in the US) themselves, the associated Acceptable Means of Compliance AMC (AC in the US), as well as any Applicable Issue Paper, or Certification Review Item issued by the certification authority. It is particularly important in the RCbS process that the engineering 'data package' includes comprehensive references for the data sources and any uncertainties quantified. The latter will be important for the uncertainty analysis and qualification that supports validation and credibility assessment.

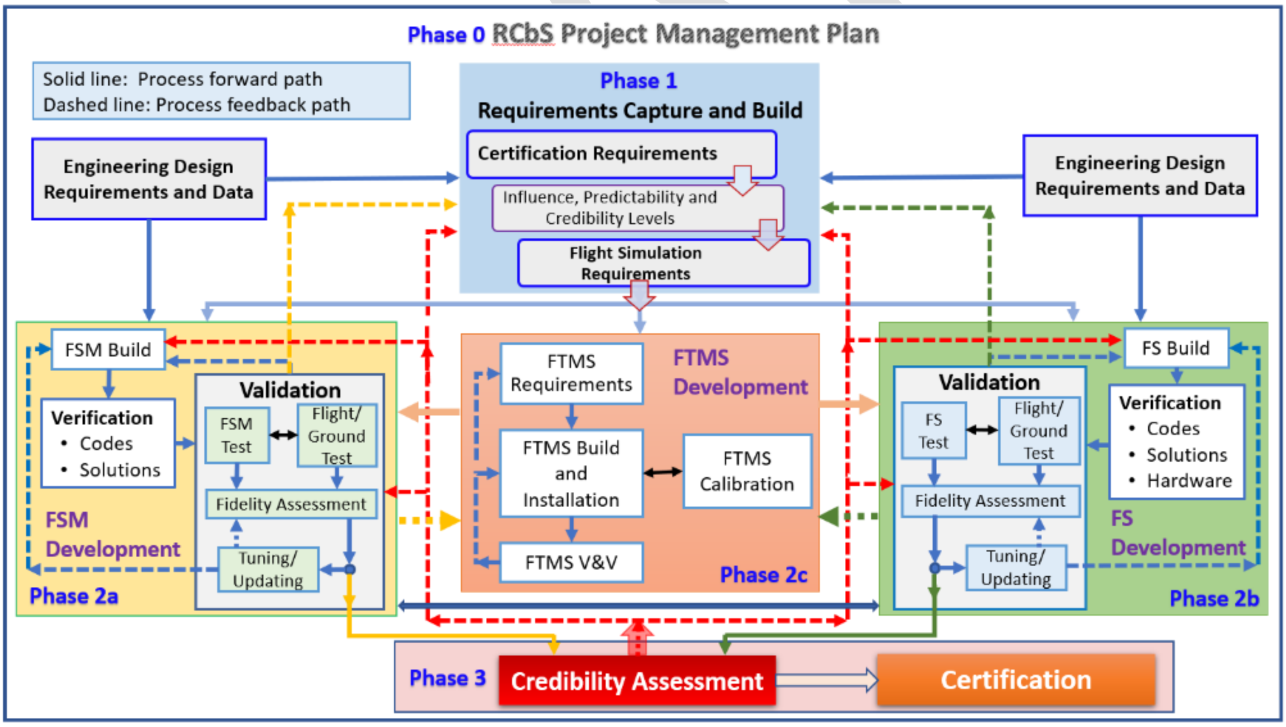

Figure 2-1: Overall structure of the Certification by Simulation Process

[FSM (Flight Simulation Model), FTMS (Flight Test Measurement System, FS (Flight Simulator)]

It is recommended that, in the early adoption of this RCbS process, progress from one phase of the process to the next could be managed by reaching consensus between the applicant and the authority. This is particularly important for the requirements capture phase and the planning of the simulation and flight test campaigns, but also for decision-making related to fidelity and credibility assessment.

To emphasise, the approach in this Guidance is driven by a requirements-based doctrine. It is well understood that the way requirements are expressed and quantified can evolve with application; they need testing to assess their veracity. We use the terms requirements ‘capture and build’ to emphasise the creative process involved here. Hence, iterative cycles are used extensively in this Guidance to allow all sub-processes to be improved based on the results of their application. Note that the requirements for the FSM, FS and FTMS may vary between ACRs, suggesting a tailored simulation development for a given application.

These process phases are described more fully in Sections 3 - 9 where sub-figures are used to highlight the primary inputs and outputs, as well as inputs from iterative cycles.

3 REQUIREMENTS-CAPTURE AND BUILD (PHASE 1)

3.1 INTRODUCTION

Before commencing the development of the RCbS process, it is necessary to understand the problem under consideration and determine the objectives of the analysis in terms of desired outcomes and required accuracy. These understandings and determinations have both a specific perspective, related to an ACR, and a general perspective, related to aircraft flight behaviour throughout the flight envelope. The understandings and determinations are captured within a set of requirements that the FSM, the FS and the FTMS, must satisfy. In other words, RCbS is a requirements-based process as illustrated in Figure 3-1, extracted from Figure 2-1. The descriptive verbs 'capture' and 'build' are used here to emphasise the constructive nature of assembling requirements. There is a parallel here with capturing requirements during the preliminary design of a rotorcraft, where the requirements firm-up as trade-off analyses are conducted on the design parameters. And, as with design trades, there are essential fidelity requirements, regarded as sufficient for application to certification. The requirements-capture phase is intended to ensure that the (complexity) content within the FSM, the FS and the FTMS is appropriate to achieve this sufficiency. The concept of sufficient fidelity has two dimensions; a predictive dimension, quantified by metrics and associated tolerances and a perceived dimension, where an evaluation pilot (EP) provides a fidelity assessment of the FS to be used in the RCbS process. The pilot's subjective fidelity assessment can also be supported through quantitative means such as by analysis of control activity (adaptation) and (comparable) task performance. As noted above, for the FSM, the acceptable differences between simulation and flight are quantified in terms of tolerances for the agreed metrics. Such tolerances will be ACR-specific and may evolve throughout Phases 1–3, e.g. when Phase 3 predictions are close to a performance or control margin limit, when the acceptable tolerances are likely to reduce.

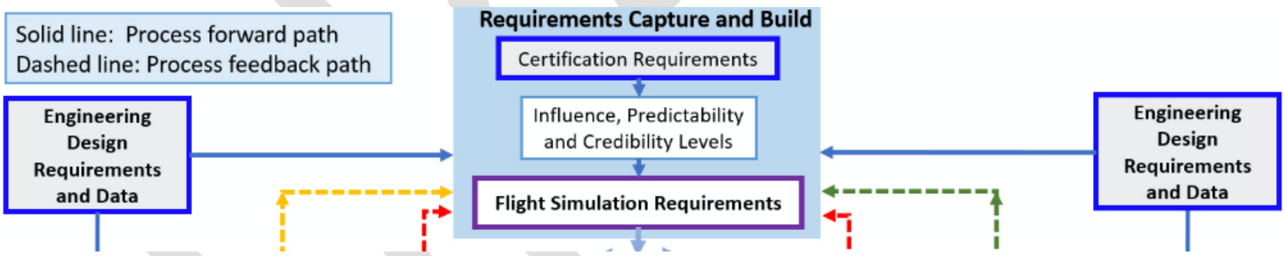

Figure 3-1: Requirement-capture and build phase of the RCbS process

The Requirements-capture and build phase starts with the identification of the ACRs, drawn from the CSs and associated material, for which simulation is foreseen to play a role in the compliance demonstration. For the traditional 'certification by flight test' process, the following elements would be defined for the test campaign related to a specific ACR:

a) Flight envelope, aircraft configurations, and environmental conditions to be tested,
b) Flight test points and associated piloting techniques,
c) Parameters and variables, and their associated accuracies, to be measured, and analysis to be performed
d) Required qualitative information, such as pilot or test engineer commentary,
e) Flight test monitoring parameters.

The RCbS process commences at the same 'starting point', but aims to address these elements through flight simulation. A crucial step in the simulation requirements development as proposed herein is the identification and description of the flight simulation Influence, Predictability and Credibility levels. These levels differentiate how modelling and simulation are to be used, how good the predictive capability needs to be and how credible the predictions are, particularly outside the domain of validation where judgements are made based on extrapolation.

3.2 Influence, Predictability and Credibility Levels

The ACRs, together with relevant rotorcraft engineering design requirements and data, form the basis for making decisions on the scope of the flight simulation to be developed for RCbS. The operational envelope, as part of engineering design inputs, defines the conditions under which the components and features of the flight simulation may be exercised, and so the complexity of the physics to be modelled. Using this information, it is possible to define the required prediction domain of the simulation or component, in terms of typical flight envelope parameters or component parameters. The prediction domain is one of four different domains relevant to the RCbS process, as described in the text box. The topic of FSM domains is revisited in Section 5.3.3.

The description of Influence, Predictability and Credibility levels are used to convey meaning to the underlying consequences of the application of RCbS, in terms of safety and efficiency in the certification campaign. These descriptions form a foundation for the requirements capture/build process. The degree of influence that the use of simulation will have on the certification decisions and the predictability level anticipated for the flight model and simulator, and associated flight test system, will then impact the level of effort required throughout the entire RCbS process, as expressed in [10].

This Guidance takes a somewhat different perspective on Influence than the description in [10], where the focus is on how rigorously the NASA standard should be followed, with influence descriptors - negligible, minor, moderate, significant and controlling. In the present Guidance, the levels of Influence on certification decisions similarly relate to the extent to which

The Four Domains in RCbS

Using M&S to describe and predict flight behaviour, four domains are considered (Figure 3-2). In the case of a whole aircraft, the domain concept is intended to encompass both the region of the flight envelope and the range of aircraft configurations relevant to the ACR. In the case of a component, or feature of the flight model or flight simulator, domain is intended to encompass the range of relevant describing variables and states. The four domains are defined as follows:

1. The domain of prediction (DoP); the domain within which it is the intention to predict the behaviour of the aircraft or component and to use these predictions to achieve certification at the defined Influence Levels for an ACR.
2. The domain of validation (DoV); the domain within which test data will be used to validate the flight model or simulator and their components/features. In Phase 2 of the RCbS process, validation implies a positive outcome has been achieved for the relevant metrics in the fidelity assessment. Within the DoV, interpolation is used to predict behaviour between validation points.
3. The domain of physical reality (DoR) is the domain within which the laws of physics being used are adequately represented in the flight model and flight simulator. Since all models and simulations used in the RCbS process will include approximations to physical reality, this domain is strictly the region where the approximations are valid, reflecting the description ‘adequately represented’. Of course, understanding the validity of approximations suggests a definitive knowledge of the DoR boundary. In practice this is hardly ever the case, so it is important to collect evidence that can show that the hypothesis underling the choices made to build the conceptual model are still valid. Sometimes this goal might be achievable by quantifying the error between the approximation and the results from a higher-order, more sophisticated, computational model.

To maximise the confidence in the results of modelling and simulation, the DoV should lie within the DoR and the DoP should lie within the DoV. In practice, the RCbS process will often imply a lack of validation test data within the full DoP. So, a 4th domain is introduced.

4. The domain of extrapolation (DoE); the domain, outside the DoV, but inside the DoR, within which extrapolation of predictions are made to achieve certification at defined Influence Levels for an ACR. Activity in the DoE may include, e.g., high (safety) risk failure cases and controllability or stability assessments at extreme atmospheric or aircraft loading conditions. Another example would be the case where (physics-based) flight-model updating, proved to be successful in the DoV, is used in the DoE as part of the Phase 2 fidelity assessment.

simulation is planned to be used in the certification associated with an ACR but are described by the four options in Table 3-1.

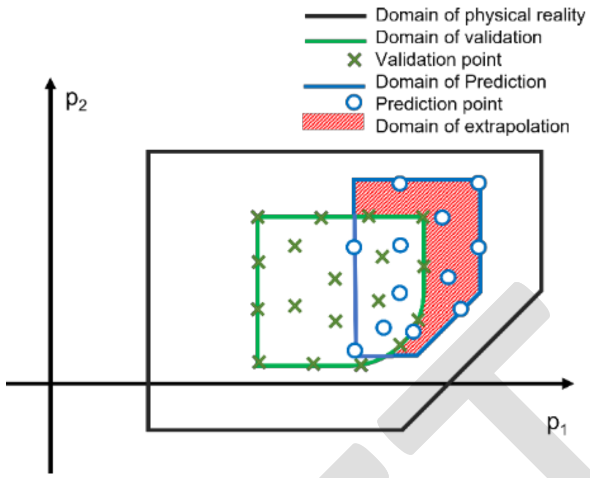

Figure 3-2: Illustrating the Domains concept in RCbS

Table 3-1: Influence Levels for use in Certification by Simulation

Influence Levels		Description
I	De-risking	The simulation is used to develop/familiarise with flight test procedures and to obtain an understanding of possible problems, hazards, or the need for additional data gathering etc.
II	Critical Point Analysis (CPA)	The simulation is used to explore the flight envelope to be tested for a specific ACR and to perform a down-selection of critical points to be tested in flight, yielding improvements in test efficiency and safety.
III	Partial Credit	The simulation is used to receive certification credit for a portion of the flight-envelope/aircraft-configuration matrix, or an aspect of an ACR. Supplementary flight tests will need to be performed to obtain full credit.
IV	Full credit	This category is for cases where certification flight tests for a specific ACR are replaced by simulation.

In theory, a higher influence level will translate into more activity required in the development of model(s) and simulator(s), and in the validation and credibility assessment phases, providing increased evidence that the models are a correct and properly implemented mathematical translation of physical phenomena and the simulation is a credible representation of real-word behaviour of the aircraft. However, there is potential for the Influence level to be revised during the certification process, upwards or downwards, following the credibility assessment in Phase 3 of the RCbS process. It is, therefore, recommended that the full RCbS process is undertaken, where possible and appropriate, regardless of the initially selected influence level.

The plurals 'models' and 'simulators' are used above, highlighting that several variants may be used in the RCbS process. Some will be specifically tailored for application to an ACR, others suitable for more exploratory or de-risking tasks; some able to run in real-time, others coupled with computational fluid/structural codes. An important aspect is then how these different 'versions' relate to one another; this question is addressed in Section 9, Controlled Development and Configuration Management. In the following, the plurals are omitted but implied.

Within the DoP, the outputs of RCbS are distributed throughout the domains of validation and extrapolation. This distribution is described in terms of the Levels of Predictability, as illustrated in Table 3-2 for an example ACR (elaborated further as example (b) in the following section). The Predictability levels are described in general terms as,

P1 Full interpolation: predictions performed within the DoV, the (interpolation) errors for the quantities of interest can be estimated with high confidence,

P2 Extensive interpolation in the DoV and limited extrapolation in the DoE: all cases of acceptable extrapolation as per the current CS-29 and CS-27 AMCs are of predictability level P2.

P3 Interpolation in the DoV and extensive extrapolation in the DoE: including extrapolation beyond CS-29 and CS-27 AMCs, as well as significant changes in design features.

P4 Full extrapolation: all points used in simulated tests are outside the DoV and so no direct comparisons of the complete FSM with flight test data are available.

The definition of a (STC) design change as either limited or extensive extrapolation depends on the extent to which the FSM predictions are affected by the proposed change as well as the means of compliance originally employed (i.e. test or analysis). In either case, the predictability level is assessed a posteriori and should be agreed with the authority.

Table 3-2: Typical layout for Influence-Predictability Level Matrix in the RCbS process

RCbS ACR	**Influence Levels**	**Predictability Levels**			
		Full Interpolation in DoV (P1)	Extensive interpolation in DoV Limited extrapolation in DoE (P2)	Interpolation in DoV Extensive extrapolation in DoE (P3)	Full extrapolation in DoE (P4)
ACR 29.143 (Controllability and Manoeuvrability) 1. Control margins for low-speed manoeuvring in winds	De-risking (I1)				
	Critical Point Analysis (I2)				X
	Partial credit (I3)				
	Full credit (I4)			X	

3.2.1 Credibility and the Assessment of Confidence

Credibility assessments then consider the consequences to human safety and operational performance from the reliance on simulation, considering the assigned Influence and Predictability Levels. Credibility is an assessment of confidence, and is particularly important for, but not exclusive to, test conditions in the DoE. So, for each ACR selected for RCbS, there needs to be such an assessment, to determine the extent of flight test data required and the technical content, the complexity, in terms of features and components, of both FMS and FS. An approach to credibility analysis is introduced later in this Section. Prior to this, the following examples are used to illustrate the integrated nature of influence and predictability assessment, and how this feeds through into the detailed FSM/FS requirements.

a) Appendix B of both CS-27 and CS-29 (Airworthiness Criteria for Helicopter Instrument Flight) quantifies the requirement for a helicopter's dynamic stability in terms of the damping as a function of oscillation period. The intention (Influence level) might be that partial credit is sought for this ACR by achieving credit for 50% of the speed-altitude envelope, for all weight and loading configurations. To achieve this RCbS level, it might be proposed that medium–high altitude tests are replaced by simulation, using the validation results and model-updating process successfully developed with data from low-medium altitude testing. A question that must be asked is what FSM characteristics are considered necessary to ensure sufficient Credibility in this 'extrapolation' process. Previous experience may have indicated that with the aerofoil sections used on the certification aircraft, dynamic stall is to be expected at high Mach numbers, with consequent impact on blade torsional response and the damping of the aircraft pitch-heave oscillations. Modelling correctly the loss of dynamic pressure at the vertical stabiliser, due to fuselage interference effects, might be considered critical to capturing the reduction in weathercock stability and the impact on the frequency of the lateral-directional-oscillation. The model-update process embodying this effect that was successful at low altitude could be replicated at the high-altitude conditions.

b) ACR 29.143 (Controllability and Manoeuvrability), requires that the *"wind velocities from zero to at least 31 km/h (17 knots), from all azimuths, must be established in which the rotorcraft can be operated without loss of control on or near the ground in any manoeuvre appropriate to the type."* To avoid the safety risk in flight test, a combination of off-line (CPA) and piloted simulation might be proposed to achieve partial or even full credit for defining the flight envelope within which loss of controllability in such low-speed manoeuvres might occur. The FSM characteristics considered to be important in this application involve the interaction of the main rotor wake with the ground, fuselage, empennage and particularly the tail rotor, when hovering in winds from different directions. It is recognised that, at least for conventional rotorcraft configurations, to achieve sufficient fidelity at critical azimuths, high fidelity CFD or vortex-wake solutions are likely to be necessary and converting the solutions into reduced-order models (e.g. data-maps) for real-time computations represents a significant, but not insurmountable, challenge. An FS characteristic considered important might be 'realistic' fine-textured ground surfaces that provide the pilot with the 'required' translational and attitude motion cues. It might also be proposed that the provision of vestibular motion cues is important, allowing the pilot to anticipate the visual motions. Likely characteristics required in the FTMS for the pre-certification flight testing to support validation are low airspeed pace-car trials with angles of incidence α and sideslip β sensing, and tail rotor flapping data.

c) ACR 29.53(a) relates to Category A take-off requiring that a rotorcraft, following an engine failure, can return to and land safely in the (confined) take-off area. De-risking might be sought by using a piloted simulation to evaluate the robustness of the defined rejected take-off procedures through simulated 'Abuse Case Testing', and to determine the maximum take-off weight from an energy management and controllability perspective for all foreseen helicopter configurations and within the applicable flight envelope. FSM characteristics considered important to the accurate prediction of power/torque limits, and transient one-engine-inoperative torque/rotorspeed response include the heave/yaw responses to collective control inputs, the importance of high-complexity rotor wake with strongly non-uniform radial inflow distribution, taking account of ground-effect, and the thermodynamic characteristics of the engines and the functions of the engine and rotorspeed control systems. In the FS, establishing sufficiency for the fidelity of the visual and vestibular cueing will need attention, particularly in the final phase of the manoeuvre prior to touch down.

d) A fourth example is drawn from the multiple requirements relating to stability augmentation systems (SAS). CS-29, Appendix B, VII(a) requires that *"for any failure condition of the SAS which is not shown to be extremely improbable, the helicopter is safely controllable when the failure or malfunction occurs at any speed or altitude within the approved IFR operating limitations."* Initially, the FSM might be used to conduct a CPA of in-flight SAS failures throughout the flight envelope to establish conditions to be tested using a flight simulator. The latter would then be used to achieve partial or even full credit, with a defined pilot reaction time, to demonstrate safe recovery and continued flight after the failure with representative cueing (aural, tactile, vestibular, etc.), and without "*exceptional piloting skill or force*". Important features here are likely to include the ability to model correctly the effect that the SAS failure has on aircraft response, the failure cueing (e.g. accelerations), control forces and flight characteristics at unusual attitude excursions that might arise during the recovery phase. Depending on the failure, Hardware-in-the-Loop (HITL) testing with the actuators and/or Flight Control Computer might also be considered appropriate.

As part of the Influence-Predictability (I-P) Level assessment, an applicant needs to define, for each ACR for which RCbS is sought, how the activity is distributed throughout the DoP described above. This can be achieved in terms of the extent of interpolation (activity within the DoV) and extrapolation (activity in the DoE). Returning to Table 3-2, example (b) above is used to illustrate how the I-P Levels might be defined, by identifying the planned elements of Influence and Predictability.

However, the selection of I-P Levels requires additional quantifiers to establish the level of credibility expected from the results of the RCbS process. Credibility also relates to the confidence an applicant has that the results from modelling and simulation reflect the behaviour of the real aircraft. Several factors will impact Credibility, for example;

a) The M&S capability of the applicant, documented in reports and papers, international recognition of subject-matter-experts, including fidelity assessment and experience with model-updating methods.
b) Extent of previous experience with the prediction of the specific behaviours related to an ACR, including on different types, and informed by understandings of the kind of physics required to match theory with test.
c) The extent of extrapolation, i.e., how far outside the DoV the prediction conditions are. It could be argued that the confidence relating to a small extrapolation is no worse than that from a large interpolation within the DoV.
d) Understanding of the way the flight-physics evolves from the outer boundary of the DoV to the boundary of the DoP. Such understandings can be derived from previous experience (see a) or from the results of modelling and simulation at various levels of complexity. Evolutions that feature strongly non-uniform or non-linear effects should attract detailed scrutiny to establish credibility.
e) Complementary with d), how the extrapolated referent data from within the DoV into the DoE evolves.
f) The confidence in the underpinning flight model updating methods used within the DoV and extended into the DoE.
g) A strong factor impacting relates to the expectations of the analyst, based on experience and understanding of how the physics is represented in the FSM. Bringing expectations into the quantification is important but also carries a risk. Prior experience may not be directly applicable to the new case and this needs to be reflected in the uncertainty analysis.

Confidence is an elusive concept, but for RCbS it must be reinforced by quantitative analysis of the uncertainties in predictions, and test data, in both the DoV and DoE. Figure 3-3 illustrates the Confidence Ratio (CR) concept used in this Guidance to quantify the credibility assessment relating to the prediction of a 'margin'. M is the margin, or the generalised 'distance', between the performance requirement (e.g. control limit, touch-down velocity or the damping of an oscillation) and the FSM prediction, i.e. the performance assessment. Credibility assessments are concerned with deriving, and ultimately ensuring, the sufficiency of, the variety of margins related to an ACR.

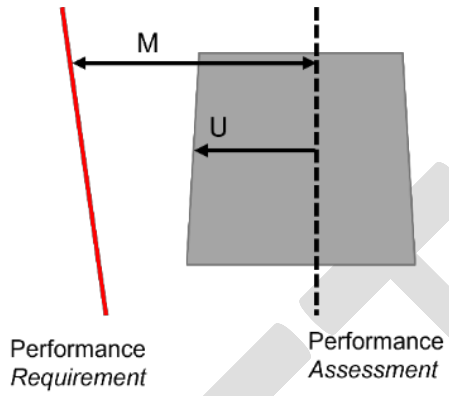

Figure 3-3: Conceptualisation of the confidence ratio relating to a performance margin (M) and uncertainty (U)

In Figure 3-3, U is the uncertainty in the prediction of the performance. A generalised CR can then be defined as,

$$CR = M/U \qquad (1)$$

An intuitive result of this simple expression is that the smaller the margin to the performance limit, then the lower should be the uncertainty. Credibility relates to the relative size of U and M, and from a safety perspective it seems appropriate to define a minimum acceptable CR for the credibility-safety trade-off. This topic will be returned to in Section 8 of the Guidance. In equation (1) both M and U must have the same units of course, relative or absolute e.g. % control margin or absolute kW of power margin. Later, in Section 8, the various components of U are discussed; those 'stemming from' uncertainties in, e.g. the design data input parameters (u_{inp}), the test/experimental data, the so-called referent, used in the validation and fidelity assessment (u_r), or the numerical/analytical solution processes (u_{num}). It is important to understand that it is the impact of such uncertainties on the uncertainty in the performance assessment/prediction that must be computed to form the combined U. Individual uncertainties will be designated with lower case u, and subscripts as indicated above. The way uncertainties at these sources are propagated through the model to impact the u's, and hence U, must be part of the credibility assessment.

In the above context, the CR concept only applies to situations where there is a defined performance requirement for a given parameter of interest. In case of ACRs for which such a performance requirement isn't readily specified, e.g. because it involves subjective pilot assessment, other criteria for assessing credibility will need to be agreed upon. In the case of subjective assessments, this might be related to opinion consensus between three test pilots.

The RCbS fidelity assessment process in Phase 2 will rely on metrics (defined in Phase 1) for a range of parameters to quantify the match between simulation and test data in the DoV, and deriving margins for the sufficiency of fidelity. Extending uncertainty analysis to the broader assessment of fidelity assessment requires a different perspective, as illustrated in Figure 3-4, showing a conceptual comparison of test results and FSM prediction. The figure shows the prediction extending beyond the test, i.e. into the DoE, where confidence in the predictions will be reinforced by the confidence achieved from analysis in the DoV. In the DoV, it will be important that the validation error, δ_{val},[3] i.e. the difference between test and simulation, lies within the combined prediction error

[3] In some references, the difference between the simulation and test is described as the 'comparison' error, δ_c. In the DoV, this is equivalent to the validation error, δ_{val}. Further discussion on this is deferred to Section 8.

uncertainty u_p and referent data uncertainty, u_r. Uncertainty in this context refers to the combination of the impact of input uncertainties, numerical uncertainties, test uncertainties, and model structure/form uncertainties (u_{model}), including both epistemic (due to a lack of knowledge or to intentional approximations applied by the analyst) and aleatory (due to inherent, probabilistic, variations associated with the physical system) characteristics [10]. So, it is expected that the fidelity deficiency would be contained within these, i.e. $u_p > \delta_p$, as suggested in Figure 3-4. Here, prediction error and prediction error uncertainty clearly have the same units; the source of the uncertainties being converted into units of the prediction. These error and uncertainty parameters will be discussed further in Section 5.3.5.

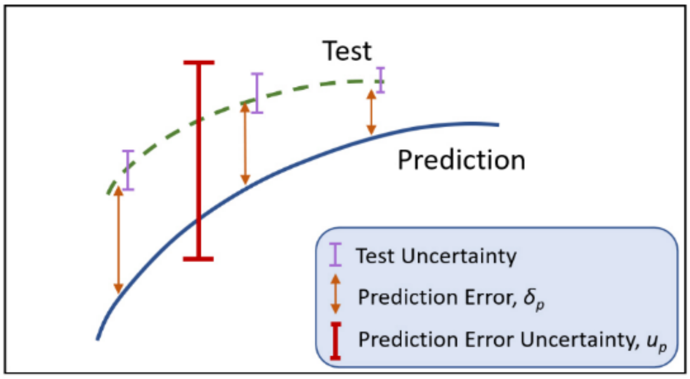

Figure 3-4: The concept of prediction uncertainty relating to prediction error

This broader assessment of uncertainty, in terms of fidelity requirements and predictions (acceptable errors between simulation and test), is only applicable in the DoV, where test data exist. In the DoE, with no test data, fidelity judgments will be based on, (1) the applicant's confidence in assessments in the DoV as discussed above, (2) confidence in their ability to predict any 'new' flight behaviours unique to the ACRs being investigated in the DoE, and (3) the quantified uncertainty, u_p, in predictions in the DoE.

The minimum requirement for the performance metric assessment is for positive confidence, i.e. *CR*>1. Note that *CR<1* implies uncertainty larger than the margin; a situation requiring further attention in Phase 3, should certification be sought for such cases.

For added assurance, values of *CR* in higher ranges could be used; e.g. as shown in Table 3-3. Here, the uncertainty is reflected in the level of confidence an applicant will have in the FSM prediction of the margin; the smaller the uncertainty reflecting a higher confidence level. However, at this stage in the Guidance development, it is emphasised that the limits of these levels are purely illustrative and are not based on a rigorous assessment or theory. Further discussion on how *M* and *U* might be quantified can be found in Section 8 of this Guidance.

Table 3-3: Suggested Confidence Ratio (CR) ranges

1.0<CR<1.1	Low confidence (L)
1.1<CR<1.25	Medium confidence (M)
1.25<CR<1.4	High confidence (H)
1.4>CR	Very High confidence (VH)

The uncertainty *U* incorporates (amongst other terms) the extrapolated prediction error uncertainties, as derived from the fidelity assessments in the DoV. The model-updating process carried out in the fidelity assessment will address the sources and extent of contributions to prediction errors and uncertainties. The trend in the evolution of errors within the DoV can be important for quantifying its extension into the DoE and hence the related uncertainties.

3.2.2 CR in the I-P Matrix

Bringing the *CR* metric into the I-P matrix allows for requirements to be set on the minimum levels of confidence in the predictive capability of the modelling and simulation. An example is shown in Table 3-4 which is colour-coded with the levels of confidence suggested in Table 3-3. Once again, the example is purely illustrative but conveys the idea that increased confidence is required in certain cases, e.g. for full credit in the DoE. In Phase 1, applicants should specify the expected/target *CR* for every I-P mix selected for an ACR. In future iterations of this document, Section 10 will contain guidance as to the required confidence levels for the ACRs for which the RCbS process has been further developed.

Table 3-4: Influence-Predictability Level Matrix with Confidence Ratios in the RCbS process

RCbS ACR	Influence Levels	Predictability Levels with Confidence Ratios			
		P1	**P2**	**P3**	**P4**
	I1	(L)	(L)	(L)	(L)
	I2	(L)	(L)	(M)	(M)
	I3	(L)	(M)	(H)	(H)
	I4	(M)	(M)	(H)	(VH)

For the time being, what is acceptable, in terms of the distribution of *CRs* within the table for an ACR, will likely be a topic of negotiation between the applicant and certification authority. Following the above process will ensure that applicants address credibility in Phase 1 of the RCbS process, setting the scene for the credibility analysis in Phase 3. It is no exaggeration to note that developments in uncertainty and credibility analysis are likely to feature large as RCbS is increasingly used. In this context, the community-wide sharing of good-practice by early adopters is strongly encouraged.

At this stage in the RCbS process, this matrix would be used to inform the detailed description of the flight simulation Requirements Specification – the primary output of Phase 1. Combining the levels of Influence and Predictability with *CRs*, along with the data requirements from the FTMS, it is possible to quantify the scale of effort and resources required to proceed with the RCbS process. This will also inform any revisions made at this stage to the RCbS Project Management Plan. It is considered important that applicants develop a good understanding of the technical requirements before firming up on the resource requirements; an obvious statement but one that needs to be stressed at this point in the guidelines.

The examples given in the paragraphs and Tables above relate to what we describe as <u>specific</u> requirements (i.e. related to an ACR). The <u>general</u> requirements, relating to flight behaviour throughout the flight envelope, also need to be captured, and how this might be achieved is outlined in the next section.

3.3 Flight Simulation Requirements

Using, as input, information from the set of certification requirements, the relevant engineering design requirements and data, and outputs from the I-P 'levelling' process, described in section 3.2, it will be possible to begin the flight simulation requirement-capture/build phase, to create the requirements specification. The objectives here are to establish:

1. The types of flight simulation to be employed, e.g. desktop 'off-line' simulation, pilot-in-the-loop simulation, or hardware-in-the-loop simulation.

2. The requirements in terms of characteristics that the FSM(s) and FS(s) must feature, and the associated predictive and perceptual fidelity they should satisfy.
3. The flight test data required to support validation, and consequent fidelity and credibility assessments.
4. Documentation detailing the proposed FS requirements as well as the associated rationale and/or justifications.

The requirements are composed of a detailed description of the characteristics and capabilities of the FSM(s) and the FS(s) and their components and features, and associated flight test measurements that are relevant to the RCbS process. It is recognised that applicant organisations are likely to have experience in developing requirements specifications for their products. This Guidance is intended to aid applicants build on this experience, and to propose an approach that forms a solid foundation for the FSM/FS/FTMS development processes. The following properties are suggested for the framework and content of the requirements specification:

a. Measurable - numerically quantifiable through a parameter or metrics
b. Unambiguous - clear, straightforward to interpret
c. Predictable - location in the prediction domain
d. Substantiated - drawn from known evidence
e. Traceable - with a specified, direct, association with ACR or more general flight behaviour
f. Appropriate - sufficiently robust to discern quality in the intended application
g. Complete - covering all functions and operations included in the ACRs

3.3.1 Components and features

Individual elements that can be distinguished by their function within the FSM are referred to as components in this Guidance. An FSM is then created as a collection of linked components. The FS also has components but in this Guidance the term ‘feature’ is used to characterise the systems that provide the pilot experience (e.g. visual system). The usage of this term is well known from ICAO Doc 9625 [11] and EASA’s Notice of Proposed Amendment (NPA) 2020-15 [12]. Components or features can be described in terms of the requirements they are serving, addressing functions, modes of operation, data structures, inputs and outputs, constraints and interfaces with other components. The prediction domain within which the component/feature should operate also needs to be specified, along with the DoV. A textual example is intended to be illustrative of functional and operational elements of an FSM component, but of course not prescriptive;

Each rotorblade is divided into N blade sections, spanning the radius, each with its own inertial, geometric and (optionally) elastic properties; each blade section is a component. The **function** of each blade section component is to generate a lift, drag and pitching moment in response to inputs from neighbouring rotorblade components and associated aerodynamic components, e.g. the atmospheric free-stream component, the finite-state inflow component and unsteady dynamic stall component. Typically, 2-dimensional aerodynamic data tables, derived from wind-tunnel or CFD experiments, provide the lift, drag and pitching moment, in coefficient form, as functions of incidence and Mach number. Three-dimensional effects could be included as a function of yawed flow angles. The DoP would be quantified by the functional variations, while the DoV would be defined by the variations of, e.g. incidence and Mach number, over which the aero tables have been drawn from test data. Through interfaces with neighbouring components, the blade section will typically **operate** at every time-step by transferring motions and forces to neighbouring components, through a solution process that is defined, verified and validated. Such interfaces also need to be defined (e.g. joints, rigid, elastic), together with constraints, such as attachments to the rotor hub with flap-stops and pitch links.

3.3.2 Domains of physical reality and validation

The degree of detail and level of complexity in the FSM aerodynamic modelling has proved important to achieving a level of fidelity appropriate for use in vehicle design, and this is expected to be even more true for RCbS. Of relevance to fidelity are the range and limits of approximations used in the FSM that need to be defined, with supporting evidence, as part of the validation process. Such ranges/limits define the domain of physical reality of the components; e.g. in terms of compressibility or dynamic stall conditions. Accordingly, each component, or collection of components, will have their own domain of validation, encompassing conditions that might fall outside of the domain of prediction at aircraft level.

3.3.3 Examples of tabulating FSM Requirements

Table 3-5 to Table 3-8 provide (non-exhaustive) examples for cataloguing the requirements in a form that captures the aforementioned properties. In the examples, the ‘fidelity metrics’ and ‘driving requirements’ are largely left blank, but are included for applicants to complete, if and when appropriate. References to component fidelity will feature in Section 10, as appropriate. This Guidance recommends that the documentation of such requirements be undertaken as a comprehensive process, providing a traceable foundation to support diagnostic analysis, and ultimately decision-making concerning validation and extrapolation domains of the components and the whole aircraft. This approach to component-level requirements and fidelity can be extended to the whole FSM and FS, i.e. aircraft-level, for simulating conditions throughout the flight envelope, for application to de-risking for example, as illustrated in Table 3-8. It is recognised that the results of component-level validation and fidelity assessment do not necessarily read across to the same at aircraft level; in some cases, the whole can be more deficient than the sum of the parts, e.g. as a result of integration and propagation effects. However, the ‘weakest link’ at component level, in terms of fidelity, might impact fidelity at aircraft-level to a disproportional amount and always deserves careful attention.

Table 3-5: Example FSM Requirements

FSM, FS or FTMS component/feature	
FSM - Horizontal Tail (HT, Left)	
Function	- Generate aerodynamic loads on the horizontal tail
Operation	- Active during all flight conditions - Updated every solution time-step
Data structures	- Location relative to aircraft reference - Tables of loads as function of local airflow magnitude and direction derived from wind tunnel and/or Computational Fluid Dynamics (CFD) tests - Incidence, sideslip ±180deg (interpolated from every 5deg)
Inputs	- Aircraft motion (velocities) - Local (main/tail) rotor wake (velocities) - Local fuselage interference - Atmospheric motion - Pitch control input (if moveable)
Outputs	- 3 forces/moments
Interfaces	- Fuselage - HT-right
Constraints	- Rigid attachment except for pitch (if moveable)
Domains of prediction and validation	- Ranges of velocities, incidence and sideslip angles from wind tunnel tests relevant to the ACR
Fidelity metrics	-
Driving requirement(s)	- Contributions to static and dynamic stability

Table 3-6: Example FS Requirements

FSM, FS or FTMS component/feature	
FS - Pilot's controls	
Function	- Pilot application and tactile feedback on cyclic, collective and pedal inputs
Operation	- Force-feel feedback system - Active during all flight conditions - Updated every solution time-step
Data structures	- Table look-up for forces as function of control displacement and rates and time
Inputs	- Pilot limb movements - Trim control switches - Autopilot parallel actuators
Outputs	- Control rod/linkage motions to actuators - Control movements to autopilot
Interfaces	- Main actuators - Autopilot system and actuators
Constraints	- Control stops - Actuation rate limits - Servo-transparency effects
Domains of prediction and validation	- Full range of control movements - Validation ground tests
Fidelity metrics	-
Driving requirement(s)	- FS perceptual fidelity

Table 3-7: Example FTMS Requirements

FSM, FS or FTMS component/feature	
FTMS - Air data sensor system	
Function	- Provide measurements of (total) aircraft velocity, incidence and sideslip (V, α and β), pressure altitude, vertical speed etc.
Operation	- Active during flight - Measured and recorded every (defined) measurement time-step - On-line computation of kinematic-consistent (with e.g. inertial system measurements) aircraft velocities
Data structures	- Location relative to aircraft reference - Calibration tables
Inputs	- Local air motion relative to sensors (typically pitot static tube measuring static and dynamic pressure, α and β vanes) - Computer algorithms processing raw measurements
Outputs	- Calibrated velocities, angles etc. at aircraft reference point
Interfaces	- Calibration algorithms
Constraints	- Physical limits of vanes
Domain of prediction and validation	- Range of calibrated V, α and β - Wind tunnel tests - Low airspeed measurements require independent validation
Fidelity metrics	- Derived from kinematic consistency analysis
Driving requirement(s)	- Minimise referent measurement errors and uncertainty

Table 3-8: Example FSM Requirements

FSM, FS or FTMS component/feature	
Flight Simulation Model	
Function	- To provide trim, stability and response analysis and characteristics across the range of flight envelope parameters used in certification, i.e. the domains of validation and prediction
Operation	- Off-line, desk-top (including trim, linearisation analysis and time/frequency analysis) - Real-time operation in piloted flight simulator - Coupled with virtual pilot for off-line studies
Data structures	- Configured as a data-driven (possibly multi-body) dynamic system of integrated components each described by parameters, time-varying states and controls
Inputs	- Pilot (real or virtual) control inputs - External (atmospheric) disturbances - Outside world surfaces
Outputs	- Trim, stability and response characteristics of the whole aircraft - Individual component state variations as functions of time or frequency
Interfaces	- Atmospheric model - Pilot, real or virtual - Cockpit systems (for FS) - Outside world surfaces
Constraints	- Outside world surface constraints defined by undercarriage characteristics and external shape - Defined by individual component constraints - When FSM is operating, the approach to any constraint should be flagged to the operator
Domain of prediction and validation	- Generally, all dynamic elements with natural frequencies up to, e.g. 30 rad/s and characteristic amplitudes within the component constraints - Range of trim, stability and response for which fidelity metrics are available from test data
Fidelity metrics	- Derived from aircraft-level dynamic response to control inputs
Driving requirement(s)	- Sufficient fidelity for the ACR

3.4 SUMMARY: PHASE 1

The activities contained within Phase 1 are summarised below.

a) Phase 1; assembly of the RCbS Requirements Specification
   i. ACRs from the Certification Specifications are identified for RCbS,
   ii. the four domains within which the RCbS will be carried out are defined, (DoV, DoP, DoE, DoR),
   iii. the Influence and Predictability Level matrices are defined for the selected ACRs,
   iv. the relevant aircraft design data are collected together with related uncertainties,
   v. preliminary description of expected complexity content for the FSM, FS and FTMS needed to achieve 'sufficient fidelity' for each of the selected ACRs,
   vi. analysis and metrics for fidelity assessment, together with tolerances for sufficiency, are defined, in preparation for meetings with certification authorities,
   vii. definition of test data requirements to characterise the DoV including programme for pre-certification flight trials and ground tests,
   viii. analysis and metrics for uncertainty characterisation and CR for credibility assessment are defined,
   ix. Output; the (preliminary) RCbS Requirements Specification assembled based on the above, using a comprehensive descriptive framework (see Section 2).

4 ROTORCRAFT FLIGHT MODELLING & SIMULATION

4.1 INTRODUCTION

Following a requirements-based development approach ensures that the types of flight simulation conducted are appropriate to the selected ACRs, aircraft configurations and flight conditions of interest. This Section discusses, in general terms, the range of flight modelling and simulation options available in the RCbS process; specifically, real-time pilot-in-the-loop, offline desktop, hardware-in-the-loop, and flight with virtual pilot, prior to the more detailed materials in Section 5 and Section 6.

4.2 SIMULATION TYPE

In the RCbS process, it is likely that a family of FSMs will be used, ranging from moderate to very high levels of complexity. The decision as to which will be used for an application will be driven by the requirements. For example, if closed-loop responses and subjective pilot assessment (e.g. for controllability and manoeuvrability) are important, a real-time pilot-in-the-loop simulation, in a FS, will be required. Conversely, open-loop handling qualities and performance analyses may typically be performed with a standalone FSM in an off-line desktop simulation environment. In certain cases, manoeuvre control by a virtual pilot (see text box) may be advantageous. If pilot-in-the-loop simulation is required, it is necessary to provide not only the capability to simulate with an adequate level of accuracy the aircraft and the environment, but also all the elements of the flight simulator that contribute to the perceptual fidelity, e.g. visual and vestibular motion cues. But even here, the complexity of the FS depends on the application. Handling Qualities (HQs) and human-factors assessments require a cockpit and flight controls that are, at least, substantially equivalent to the certification aircraft. In other cases, a generic engineering flight simulator may provide adequate realism to evaluate or demonstrate compliance and obtain partial or full credit in the conditions of interest. Decisions about the simulation type will be strongly informed by the requirements, which emphasises why the latter need to be sufficiently detailed, i.e. complete, substantiated, measurable etc.

> **The Virtual Pilot**
>
> This Guidance is not prescriptive about the form such a virtual pilot could take, but the intention is that the algorithms running such a computerised pilot need to be sufficiently realistic that meaningful conclusions can be drawn and relevant certification decisions can be made. One benefit of using a virtual-pilot, or indeed any off-line analysis, is that the simulation does not need to run in real-time, so higher-complexity numerical (continuum-mechanics) models can be included, albeit that they also need to be verified and validated. A second benefit of using a virtual pilot is that a massive coverage of the whole flight envelope can be undertaken in batch-mode, isolating critical conditions for further investigation, for example through piloted simulation. The virtual pilot model may also be used to support so-called abuse-case testing to, e.g., evaluate the sensitivity of an emergency operating procedure described in the Rotorcraft Flight Manual to realistic variations representative of the average pilot in operation.
>
> It is recognised that as the applications of RCbS evolve over the coming years, so too will virtual pilot models become more realistic and it is expected that their use in RCbS will expand considerably, for the reasons given above. Future developments of this Guidance should address this evolution. But, with the current state-of-the-art in virtual pilot modelling, whenever the results are close to the certification limits, then a pilot-in-the-loop simulation is likely to be necessary for ultimate proof of compliance testing.

Relating to the selection of the simulation type, an element to consider during Phase 1, requirements capture and build, is whether or not the susceptibility of the aircraft to adverse rotorcraft-pilot-couplings (RPCs) or involuntary Pilot Assisted Oscillations (PAO) [13] warrants specific off-line desktop analyses, or whether piloted simulation with appropriate kinaesthetic and vestibular cueing is required for the selected ACR. While the CSs and FARs do not specifically address this topic, the research to date suggests testing methods that can reveal an aircraft's susceptibilities to such PAOs. In addition, recent work on the susceptibility of tiltrotor aircraft to RPCs is discussed in [14] along with recommendations for testing techniques.

FSMs, particularly those used within a real-time FS environment, typically are not suitable for structural loads analyses, as may be required for proof of compliance with the relevant section of the CS (e.g. CS-29 sub-part C). Nevertheless, such simulations can provide inputs for more detailed off-line analyses using higher order (structural or aeroelastic) models, or may be used to evaluate high-level pass-fail criteria such as touchdown sink rate and ground speed in lieu of a detailed emergency landing gear loads prediction.

HITL simulation can be considered whenever there are vehicle subsystems, that the requirements suggest should be included, e.g. in the real-time simulation flight loop. Alternatively, it may be difficult to build reliable simulation models, due to complexities in the physics, and/or difficulties in collecting the data necessary, e.g. for commercial reasons. In such cases, the requirements on the inputs/outputs and interfaces between the simulator and the hardware components need to be clearly defined and conformity checks must be performed.

4.3 Strengths of M&S

Before progressing to examine the details within the three elements of Phase 2 in the RCbS process, the opportunity is taken to discuss some of the additional merits of using modelling and simulation in the certification process. Some of these may be well known and understood in the design and development departments, but might be less familiar to the testing community. The value to applicants of such discussion within Guidance is that it can open-up new dimensions of awareness during the certification process, important for establishing the goals of the I-P matrix. The real strength of the describe and predict capability of modelling and simulation is that it provides access to robust understandings of the connections between causes and effects; connections that are sometimes very difficult, or impossible, to make by examining the test data themselves (see text box).

> Describe and Predict – mathematics in action
>
> Describe and predict are used to convey the fundamental purposes of modelling and simulation. For example, the trim analysis and solutions *describe* how the controls are used to achieve equilibrium flight conditions. In this sense, the word *describe* carries a general meaning. Trim analysis can also be used to *predict* the minimum-power flight speeds as a function of density altitude. In this sense, the word *predict* carries a specific meaning relevant to the application. Similar examples can be drawn from stability and response analysis.

One example of this strength is brought out through an examination of the changes in the forces and moments on components (or the whole aircraft) following a perturbation in a single state. A small perturbation in sideslip (or sway) velocity can reveal the changes in, say, roll and yaw moments. Increasing the magnitude of the perturbation can reveal the extent of any nonlinearity in these moments and deeper analysis can expose how different components are contributing to the nonlinearities. Ultimately, such analyses can contribute to developing a full understanding of, for example, lateral-directional static and dynamic stability shortcomings. The latter may have been identified as a problem through piloted simulation, or even flight test, but the source of the problem could only be discovered through the kind of diagnostic analysis described above.

Another example of the strength of simulation comes from understanding the sources of problems relating to unexpected increases in main and tail rotor power, at both low and high speed. It is not unusual for poor power predictions to feature in the design and development phases, and often corrected by adjusting parameters in the rotor inflow model (low speed) or fuselage aerodynamic drag model (high speed). The importance of the correct physics in understanding poor predictions in the RCbS application requires a more clinical approach aimed at diagnosing the sources of mismatches between real flight and predictions. Increased effort will normally be required with higher-complexity FSMs and potentially increased pre-certification flight testing. The rewards of the increased efforts are likely to be found in both safety and efficiency during the certification process.

A third example addresses the whole gamut of de-risking, through the computation and management of 'large data' obtained from multiple, offline, simulation runs, aiding the identification of cases for further analysis. The use of algorithms that can search throughout the flight/configuration envelope for boundaries of defined trim, stability or response characteristics or critical cases arising from failure modes analysis, can make such identification very efficient. The design of such algorithms is likely to feature large as modelling and simulation finds its place in the certification world.

The exploration, within the RCbS process, of 'what-if' type questions through offline analysis and piloted simulations can also lead to discoveries that can impact the certification. Such exploration, without constraints, can be particularly valuable during the Phase 3 'Credibility' phase when extrapolation is under the microscope. We return to this in Section 8.

5 FLIGHT SIMULATION MODEL DEVELOPMENT (PHASE 2a)

5.1 INTRODUCTION

Figure 5-1 illustrates the elements of the FSM development phase (Phase 2a), with major inputs from the Requirements Capture/Build phase and the Engineering design data. Inputs from the parallel Phases 2b (FS) and 2c (FTMS) are also shown. The dashed lines indicate iteration pathways within Phase 2a and from outside, in both the parallel phases and the later credibility assessment phase.

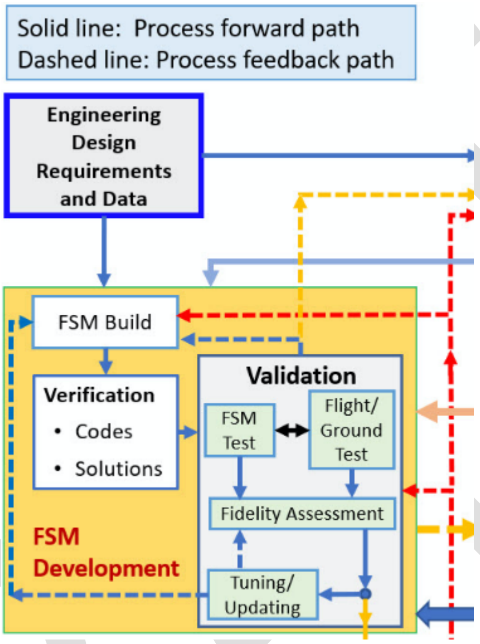

Figure 5-1: The Flight Simulation Model Development; Phase 2a

5.2 FLIGHT SIMULATION MODEL BUILD

5.2.1 Component-based adaptable fidelity modelling

Put simply, an FSM used for certification compliance demonstration purposes should include the physics necessary to achieve sufficient fidelity for the cases and conditions of interest, the ACRs. For a high level of confidence in the results, the FSM is applied within the DoV subset of the DoP. Beyond this, in the DoE, physics should guide the model content, and the levels of confidence in the results will depend on the credibility analysis introduced in Section 3 and expanded on in Section 8. The modelled physics shall describe the behaviour of the aircraft and predict the three essential aspects of flight, i.e. trim, stability and response. The FSM should, therefore, be *physics-based,* i.e., expressed in terms of, or derived from, the physical laws applied in the creation of the mathematical model and in the operation of the numerical simulation. The use of phenomenological sub-models for components is not considered to be prohibited. In some cases, full phenomenological models could be considered if P1 Predictability level, i.e. interpolation only, is sought. However, for those cases, the identification of the associated DoR, and the assurance to not fall outside it, must be undertaken. The use of such models in critical applications is a novelty and should be highlighted to the certification authority. Preliminary guidelines are applicable and are available in [9]. Early coordination with the certification authority is advised.

Appropriate (virtual) flight test monitoring parameters should be included in the FSM to ensure that it is not used beyond the limits of the DoR. Ultimately, the limits of validity of the FSM reflect the DoR boundaries; where the underlying model data and/or the mathematical approximations to the physics break down for modelling the various FSM components. These limits are expressed in terms of both global variables, such as those that define the flight envelope, and local variables, including the mathematical approximations to the physics being modelled for a component. The limits should be reflected in the domains of validation and physical reality for the FSM, with the implication that the aircraft domain of validation should be within the ensemble of component limits of validity.

As alluded to in Section 4.2, it is emphasised that it is not necessary that a single FSM be used throughout the RCbS process to perform all assessments required in demonstrating the fulfilment of the full certification specification. Multiple models, with different complexities and components, may be used, with the complexity driven by, and adapted to, the application. This adaptable-fidelity approach for certification is driven by the requirements on both the content of the modelling, especially but not exclusively for the aerodynamic forces, and the higher-order 'degrees of freedom' necessary to capture flight behaviour correctly. Examples are the importance of main rotor wake – tail rotor interactions for the assessment of low-speed controllability and the impact of dynamic stall on the blade torsion loads and vibration levels at high speed. This adaptable-fidelity approach contrasts with the models typically used for training simulators which are required to have appropriate fidelity (from a training perspective, [15]) over the full flight envelope, but for which non-physical tuning may be acceptable. Guidance for the related process of the configuration management for adaptable-fidelity models is described in Section 9.

Although other approaches may be conceived, a typical rotorcraft flight simulation model is composed of integrated components, or building blocks, assembled together, often following a Multi-Body Dynamic System (MBDS) logic. Figure 5-2 shows components that may be used in a typical helicopter simulation model. Similarly, Figure 5-3 shows components used in a typical tiltrotor simulation model. FSM requirements for both types of rotorcraft will be similar although it is recognised that the latter are not certified according to CS-27/29 standards. A MBDS features multiple degrees of freedom (DoFs), represented typically in the FSM by component motion states and their velocities, or other states representing the evolution of the dynamic system (e.g. dynamic inflow states, pressures in actuators, turbine thermo-states). These would normally include the 6-DoFs of fuselage velocities, coupled with rotor flap and lag or gimbal motions, engine and drive train dynamics etc. In the current state of the art, finite-state rotor inflow models are typically used for real-time applications to capture local rotor blade section incidence and to estimate rotor wake interference on the fuselage and empennage.

Before turning the specific focus to fidelity, it is worth discussing a relatively new development relevant to the RCbS process. This Guidance advocates the application of physics-based modelling for the sake of the credibility of the simulation, particularly for extrapolated conditions. With the advent of Machine Learning (ML), it has become possible to derive rapid-execution, high-dimensionality surrogate models from test data and high-order physical modelling such as CFD. These data-driven methodologies such as Artificial Neural Networks, while not physics-based themselves, rely on training data that stem from testing or physical modelling. In principle, ML methods can be used for extrapolation beyond the training data set. The extent to which this can be done reliably and accurately for rotorcraft flight characteristics is a subject for research. As such, this Guidance does not advocate such techniques for the first practices of RCbS, but early adopters are encouraged to investigate these avenues for exploitation in the future.

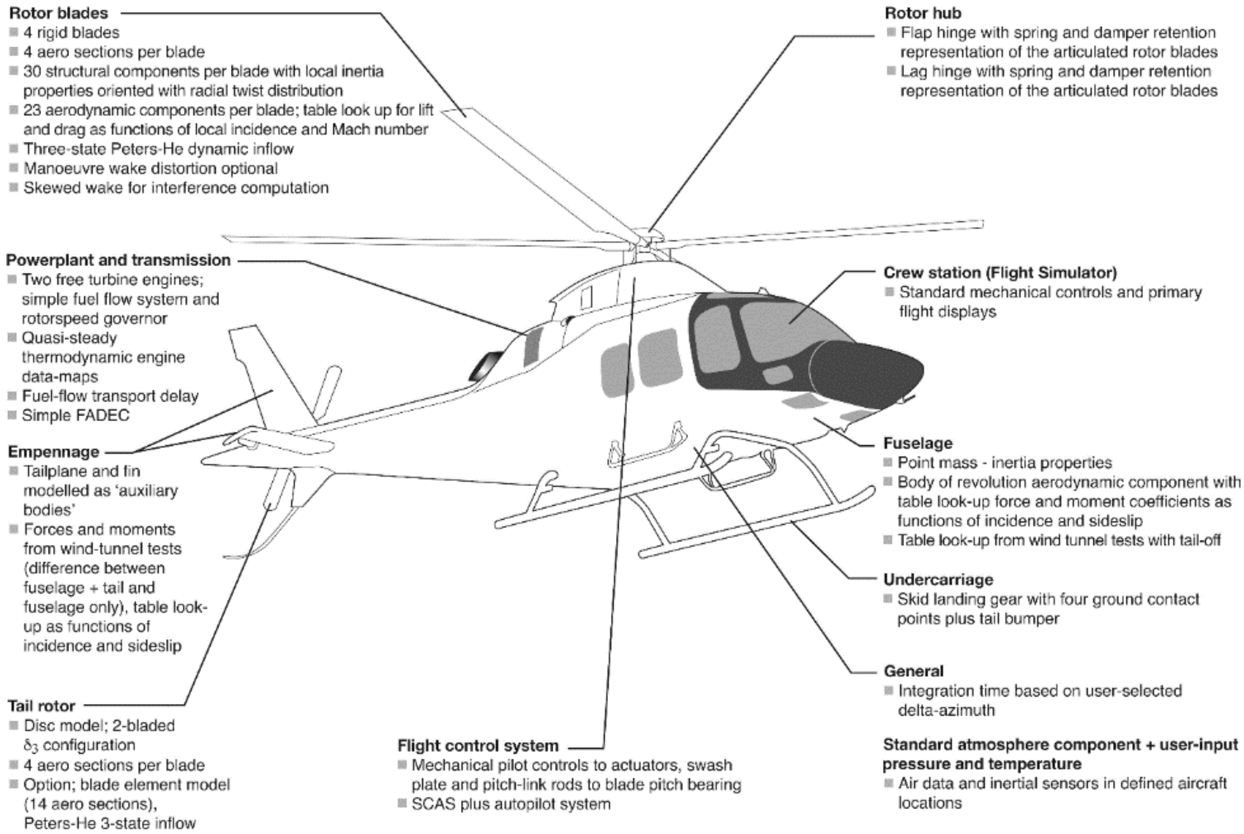

Figure 5-2: A schematic example of a component-based helicopter flight simulation model

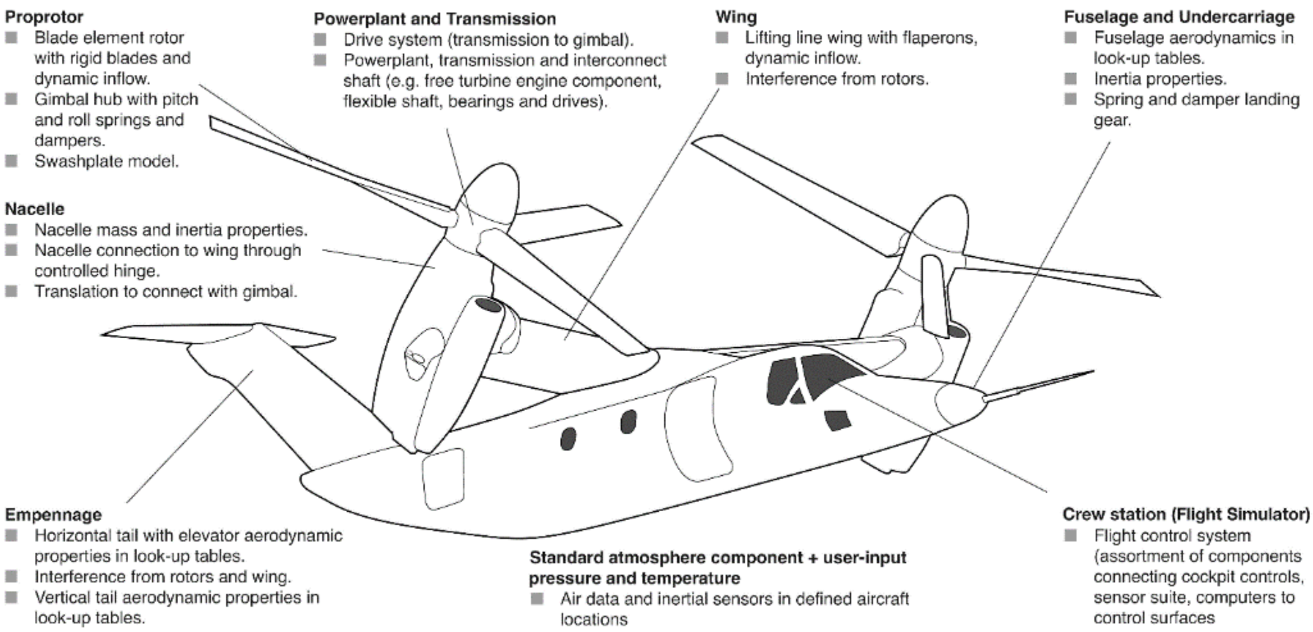

Figure 5-3: A schematic example of a component-based tilt-rotor flight simulation model

5.2.2 Required fidelity; sufficiency

To emphasise, this Guidance advocates that the required fidelity, defined in the Requirements Specification for the relevant ACRs, is what is judged to be sufficient for the RCbS activity by the Applicant and the Authority, and evidenced through metrics across the DoV. What exactly is 'sufficient' will depend on the application and it is the goal of this document to, ultimately, provide guidance in this respect (in terms of DoV metrics and associated tolerances) for specific ACRs for which the RCbS process has been exercised. Nevertheless, expert judgement will be required to ensure that the fidelity is indeed sufficient for the particular configuration and application.

Interpreted in the 'frequency domain', an FSM operates over a wide range of frequencies and amplitudes and typically includes components whose 'natural' frequencies are higher than the range normally associated with flight mechanics and piloted flight control (e.g. 0.1 – 10 rad/sec), e.g. rotorblade aeroelastics, engine/rotorspeed/transmission dynamics, control actuators. The interaction of these components with the aircraft's flight mechanics and control can be important for achieving a 'sufficient' level of fidelity for certification purposes. In this context, a dynamic characterisation (e.g. eigen-analysis) can be carried out to identify the prediction domain in terms of the frequency ranges of component behaviour. Such characteristics are useful for establishing the excitation frequencies in the control-input designs used in the pre-certification flight tests to support flight mechanics model validation. Such results can also be used to compare with frequency response functions derived from test data. Metrics based, for example, on the 'allowable error envelopes' of the so-called 'maximum unnoticeable added dynamics' (MUADs) [16] can then, in principle, be used to quantify what can be considered sufficient fidelity, if the associated envelopes are demonstrated to be applicable to the configuration and flight condition under consideration. Such caveats will apply to all fidelity metrics that require evidence-based justification to use in RCbS. In taking a frequency domain view such as described above, it is important to recognize that it may yet be required to include the higher frequency dynamics in the simulation if relevant for the ACR in question and even if, nominally, it has no dominant role in the flight mechanics of the aircraft.

The degree of complexity in the aerodynamic modelling on all relevant components of an FSM has proved critical to achieving a fidelity sufficient for use in vehicle design, and this is expected to be the case for certification support. Of relevance to fidelity are the range and limits of aerodynamic approximations used in the FSM and these should be clearly defined, with supporting evidence, as part of the definition of the domain of physical reality and the related validation process.

5.2.3 Trim, Stability and Response

The level of FSM fidelity relates to the three aspects of rotorcraft flight dynamics relevant to certification, as discussed in Section 2, namely 1) trim, 2) stability and 3) dynamic response. In general, the fidelity of the FSM for all three aspects should be sufficient for the application, even if the application itself revolves mainly around a single aspect. That is, a model that is able to accurately predict trim for a control margin assessment, but poorly predicts short-term open-loop control response is considered unsuitable for the former application. The FSM fidelity relative to flight test can be quantified with reference to these three aspects, using appropriate metrics. For example:

1. Trim; linking in current certification specifications with, e.g. the control margins throughout the flight envelopes and the static stability characteristics, the latter quantified in terms of control gradients for perturbations in lateral and forward speed. Trim computations are made with the non-linear FSM, to derive the control displacements required to ensure equilibrium flight, e.g. in terms of airspeed, sideslip, vertical velocity and turn rate.

2. Stability; linking in current certification specifications with the dynamic stability characteristics, quantified in terms of the damping and number of oscillations in a period of time. Techniques to establish stability typically involve the pilot/computer applying (open-loop) doublet-type control inputs and allowing the free response to evolve sufficiently long that period and damping can be computed. An FSM can also be linearised by perturbing each state and control in turn and creating a derivative-model, with the eigenvalues of the natural modes computed to provide stability characteristics. The eigenvalues can be plotted on the frequency-damping (eigen) chart for comparison with the

aforementioned open-loop response analysis on the non-linear FSM. Such comparisons can provide information on the impact on stability of any nonlinearities in the FSM. It is noted that the military standard, ADS-33E-PRF (ADS-33) [17] also includes requirements for ‘closed-loop’ stability in terms of attitude bandwidth and phase-delay.

3. Dynamic response (open- and closed-loop); linking, for example, with controllability and manoeuvrability requirements in the current certification specifications. A case might be the response of the rotorcraft to some control input or external disturbance (e.g. gust) computed as transient time-varying evolutions of the aircraft motions. Such cases are typically used in the validation process to establish the quality of the prediction of the short-term response. Another case could be the frequency response, computed in the form of transfer functions, e.g. pitch attitude response to longitudinal cyclic, generated through frequency sweeps on control inputs. Response analysis may also include the evolution of the system to triggering events, or even entire (emergency) procedures, e.g. failure of sub-systems of the rotorcraft. The link with the concepts of controllability and manoeuvrability also emphasise the potential value of pilot-in-the-loop simulation in the compliance demonstration process.

The ‘describe and predict’ strengths of M&S can sometimes weaken because of difficulties in explaining the causes of flight behavioural characteristics through analysis with the coupled, multi-body, nonlinear, dynamic system. Linearisation can be used to provide insight in some cases and it is considered worthwhile as part of this Guidance to expand on this point in the following text box.

The value of linearisation for gaining insight into flight behaviour

The linearised derivative model has been used in aeronautical engineering since the very early days of aviation [40] to facilitate the understanding of complex aerodynamic phenomena. For example, trim gradients can be directly related to static stability derivatives. Furthermore, the nature of derivative variations with flight condition can sometimes reveal the source of, e.g. strong nonlinearities, instabilities or reductions in control margins. Aircraft response to small perturbations can be predicted using a derivative model for comparison with the nonlinear model to aid the investigation of larger amplitude response behaviour. Derivatives provide a microscopic view of FSM validation through comparisons with phenomenological models derived using system-identification techniques from flight test measurements. As discussed later in this section, FSM fidelity can be improved through model-updating using physics-based ‘delta’ derivatives. Rotorcraft differ from fixed-wing aircraft in many respects, including the number of DoFs required to describe behaviour. It is usually necessary to include rotor dynamics and rotor aerodynamic inflows, engine-drive train dynamics and of course the couplings between longitudinal and lateral-directional motions as standard. This multi-DoF model linearisation, therefore, results in a much larger system than the conventional 6DoF description. This formulation facilitates the investigation of important coupling effects that might be hidden in reduced-order forms. So, while the derivative concept is used above in the context of stability analysis, the application in FSM development can be far more extensive. Underpinning this point is that aircraft are generally designed so that cause and effect are linearly related. However, there are situations, commonly at the limits of the flight envelope or during extreme manoeuvres, where nonlinear behaviour prevails, e.g. actuation rate limiting, rotorblade dynamic stall and rotor-wake interactional aerodynamics in low speed manoeuvres. Such phenomena can usually be revealed through comparisons between results from linear and nonlinear models, a valuable exercise in the diagnosis of complex flight behaviour. Conditions under which linear approximations and reduced-order models are valid need to be understood and validated to enhance confidence in the use of linearisation. Such understandings can also play a part in the derivation of confidence ratios for use in credibility assessment (see Section 8).

The question of how to relate the qualitative descriptions of dynamic response into quantifiable requirements for civil rotorcraft certification is a topic of ongoing research; such metrics do not currently feature in the certification specifications. In the military handling qualities/performance standard, ADS-33 [17], the minimum acceptable dynamic response requirements are quantified in terms of parameters such as attitude quickness, control power and inter-axis couplings. Also, the comparison of dynamic response features in the validation of the FSM for use in the certification of training simulators (e.g. FSTD(H) [15], see Section 6).

An important part of the development for an FSM relates to model-updating and tuning (also referred to as calibration in other disciplines (e.g. [3]); i.e. the process of improving the fidelity of the FSM to ensure sufficiency for purpose, e.g. for the use in certification. Complementary fidelity assessments, using trim, stability and response analysis, can provide insight into the required ‘physics-based’ updates in this updating/tuning process.

Before progressing to examine the verification and validation processes relevant to RCbS, some detail on specific components and interactions are discussed.

5.2.4 Flight control and automatic flight control system

The Flight Control System (FCS) interacts with the (real or virtual) pilot and may vary in complexity from a fully Automatic Flight Control System (AFCS) with auto-pilot, to a basic SAS or an unaugmented mechanical system. The pilot is not a component of the FSM (unless it is virtual), but is the centre-of-attention in the FS, as discussed in Section 6. And, as further discussed in Section 6, the data feeding through from the FSM to the FS is a key ingredient of the FS fidelity. The FCS is no different to any other component in the FSM, featuring functional sub-components, inputs and outputs and interfaces with, for example, the rotor systems, aircraft electrical and mechanical power systems and the inertial and air-data sensor systems, as well as the computerised autopilot and SAS. Likewise, simulated FCS sub-components will also have their own domains of prediction, validation, extrapolation and physical reality. The latter needs to take account of nonlinear dynamic characteristics e.g. displacement and rate limits in the electro-mechanical actuation systems, or backlash and stiction in control runs. The ways in which redundancy is achieved and managed is also an important function within the FCS. It is this aspect that becomes crucial when ACRs relating, for example, to AFCS failures are being considered for RCbS. The aircraft failure modes, effects and criticality analysis will have defined the kinds of failure that require recovery action, either by the system itself or the pilot. In this application, the FSM must therefore include these failure modes and the consequent system behaviour will be scrutinised in the validation process. For some failure cases, the absence of validation data, precluded for safety reasons, places them firmly in the domain of extrapolation. As discussed in Section 3, credibility analysis for such cases, including deriving the related confidence ratios, becomes particularly important. One of the case studies reported in Section 10 of this Guidance document explores this topic in more detail.

It should be noted that a significant amount of current certification flight testing is conducted with the AFCS engaged, since this is the normal mode of operation for aircraft certified to CS-29, and in some cases to CS-27. This does not reduce the importance of ensuring that the flight characteristics of the so-called bare-airframe FSM meet the required fidelity standards. However much the AFCS might suppress natural handling qualities deficiencies, understanding the physics at work in the bare-airframe flight behaviour is considered vital in RCbS applications. This is particularly true for failure cases of course but also, more generally, to reinforce credibility of results in the DoE. The presence of an AFCS may, however, significantly reduce the impact of uncertainties related to the bare airframe, making the validation of the FSM more straightforward. So, we acknowledge that in some applications, e.g. AFCS upper-modes analysis and P1 predictability level, the validation of the aircraft with AFCS-on may suffice.

In many practical applications, the applicant might elect to use an exact software copy of the AFCS, or even perform HITL testing, to ensure the fidelity is as high as possible. However, this does not obviate the need for comprehensive V&V analysis for such hardware/software. In a similar vein, it is not uncommon to find that the autopilot or AFCS designs contain proprietary data, so that the exact details of the design are not available, even to the rotorcraft OEM, but only to the AFCS design organisation. This will typically require either black box integration or reverse engineering of the design, effectively a model creation, based on input-output data. The level of complexity can increase significantly if there are multiple functions drawing on the same controls, e.g. stability augmentation, response-type augmentation, load alleviation or flight envelope protection. How the FCS performs when multiple constraints are approached simultaneously should have been addressed in the design specification, produced by the rotorcraft manufacturer. However, such behaviour needs to be verified (does the behaviour meet the design specification?) and validated (is the design specification correct?). Again, the validation of the complete system can be inhibited for flight safety reasons, emphasising the importance of credibility assessment.

5.2.5 Engine, rotorspeed and transmission dynamics

A similar situation, through the potential unavailability of commercially restricted data and the need for reverse-engineering, can arise for the engine component. The main function of the engine is to deliver the required power and torque to the rotors in trims and manoeuvres. The engine also provides power to the mechanical/hydraulic and electrical systems and how this distribution is managed, particularly when close to the power limits needs to be modelled correctly. The inputs to the engine model include fuel flow, with rates controlled by the rotorspeed governor and air from the atmospheric component. The engine intake will ‘shape’ the airflow from the atmospheric model into the compressor stage of a turboshaft engine. These details may point to the need for including models of the thermodynamic processes within the engine, developing through the four thermos processes in the control volumes of the compressor, combustor, gas generator and power turbine. Options here include a fully unsteady dynamic combustion, or a quasi-steady look-up table for the thermodynamics of the compressor-combustion processes. These details will be very important in edge of the envelope performance analysis, but for stability and dynamic response prediction it is the rotorspeed response and torque reaction on the fuselage from both main and tail rotors that are paramount. This is especially true in the simulation of engine failure conditions where it is vital to accurately predict the torque response and available power of the engine(s). The reverse engineering process often assumes a state-space model with variable parameters (e.g. functions of power, hence nonlinear) defining the time constants and gains relating rotorspeed to torque and torque to fuel flow. Elasticity in the drive shafts will impact the natural frequencies within this component and may need inclusion if these fall within the range defined as necessary in the requirements specification.

5.2.6 Environment modelling

Creating a standard atmosphere model is a straightforward task, with air density, ambient pressure and temperature being a function of altitude. The flight simulation validation envelope will be defined by the flight test conditions required and achieved within this atmospheric model, with simulated test points adjusted for the real-world test conditions. Complications occur when, during flight test, the air is moving relative to the Earth’s surface with potential vertical and horizontal shears/gradients. Such ‘winds’ are usually unsteady, containing gusts and turbulence, whose characteristics vary with altitude and proximity to the terrain and objects. Humidity levels impact the density, noting that humid air is less dense than dry air, and the modelling is even more challenging when precipitation occurs. Granted that it is best practice (and at times a firm requirement) to perform flight testing in calm weather conditions, the atmospheric model that forms part of the FSM may need to feature the primary effects of these complications, if they are suspected to have significantly affected the data gathered during the pre-certification flight test campaign and a basis for validation of these effects is available from measurements. Random turbulence can, in principle, be modelled based on extracted air-data system measurements in trim, prior to test inputs being applied. More structured unsteadiness, for example non-idealised gusts, are more difficult to model and can appear as so-called process noise on the signals from the sideslip and incidence vanes. Developing a process for addressing the impact of atmospheric unsteadiness within the RCbS may prove to be important. Moreover, whereas flight testing in closely controlled unsteady atmospheric conditions is not possible in practice, flight simulation, piloted or otherwise, offers the ability to explore the aircraft response to well-defined unsteady conditions in a repeatable manner. For example, the impact of turbulence on controllability and pilot workload is known to be potentially significant and piloted simulation provides the opportunity to quantify this impact directly, rather than, e.g. by requiring a minimum level of residual control authority in trim. Yet another example in which unsteady environmental effects may be important is in the assessment of pilot workload in failure conditions.

It is noted that, although the simulations may be external to the FSM, other elements that fall under the category of ‘environment’, include ground contact/friction and obstacle air wake models, Air Traffic Control (ATC), and other airspace users. The relevance of these will depend on the application scenario and, in case of the latter two elements, whether or not pilot workload is an important aspect in the evaluation being undertaken.

5.2.7 Coupling with the Flight Simulator (Phase 2b)

As shown in Figure 2-1, a primary ‘artery’ from the FSM (Phase 2a) to the FS development (Phase 2b) is a validated FSM. However, the FS will need a ‘prototype’ FSM prior to the formal release at the end of Phase 1a. This would be used to support the development of many of the FS features (if not already developed and verified in prior activities) for which the validated FSM is not critical. The characteristics of such a prototype need to be defined within the FS requirements to ensure that Phases 2a and 2b evolve efficiently. Inevitably, the use of piloted simulation in support of partial or full-credit Influence will need to await results of the FSM fidelity assessment. Of course, certification tests using the FSM and FS take place after the credibility assessments in Phase 3, but there are obvious efficiency benefits in Phases 2a and 2b being completed at the same time. Fidelity assessment will define the domain within which the predictive metrics demonstrate sufficient FSM fidelity for application to the ACR. Consequent FS fidelity assessments will then focus on ensuring that the FS is also suitable for the ACR. These assessments will normally address non-FSM related features, such as visual and vestibular motion cueing, pilot inceptor control forces and cockpit ergonomics critical for flight-related ACRs. However, it may be that pilot feedback, as part of the perceived fidelity assessment, draws attention to some FSM characteristics related, for example, to trim or dynamic response. The FS verification and validation processes should ensure that the FSM is coupled into the FS such that its behaviour is essentially the same as the standalone version documented in the output from the FSM development Phase 2a. The pilot perceives the FSM outputs through the filters of visual and vestibular motion cueing systems in the FS, which themselves need to pass through V&V processes. It is not unusual for a pilot to ‘blame’ the flight model for an FS fidelity deficiency, even though the FSM fidelity assessment has been successfully ‘passed’. There are multiple ways that FS features can contribute to perceived deficiencies that need to be thoroughly investigated before re-visiting the FSM fidelity assessment. This topic is returned to in Section 6.

5.3 VERIFICATION & VALIDATION

5.3.1 Introduction

As described in previous sections, flight simulation attempts to replicate the relevant aircraft flight physics using computer models and, if applicable, simulator hardware. Within the FSM development process illustrated in Fig 5-1, Phase 2a, sit the two ‘checking’ processes that ensure that the FSM build is verified (all model requirements are correctly met) and validated (the model requirements were correct and the replications are successful). The V&V processes are so vital to the success of RCbS that some additional ‘conceptual’ background is considered useful in this Guidance as build-up to the discussion on V&V.

The creation of a simulation in the generic sense may be represented through a triangular process where on one vertex is positioned the real system of interest, on the second vertex there is the conceptual model, i.e. the collection of assumptions and abstractions applied to develop a physical model of the system of interest, and on the third vertex is placed the computational model. In turn, each of these boxes is composed of several sub-boxes that detail the different phases, shown in Figure 5-4.

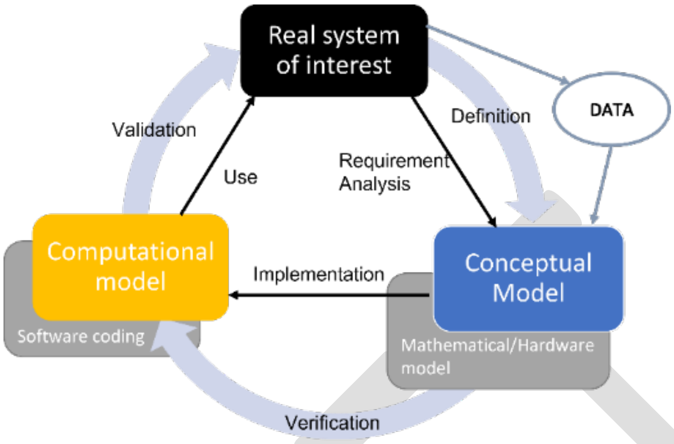

Figure 5-4: Process to create a simulation model

The development process starts at the system of interest, in this case the rotorcraft, or a subsystem thereof. Through requirements analysis, considering the operational conditions under which the system needs to be analysed/simulated, the accuracy required, etc., a conceptual model can be defined. This model can be transformed into a mathematical form, which is converted to a computational model with appropriate numerical discretisation, and finally implemented in the form of a computer code.

It is important to be able to trace back through all the aforementioned steps. This, together with the knowledge of the source of the data that are included in the model, will provide the information required to define the domain within in which the model should function and operate correctly, with the required level of fidelity – the *domain of physical reality,* the DoR.

For physics-based models, the assumptions that define the conceptual model focus on what physical phenomena will be included and what will be ignored. As an example, consider the blades of a helicopter rotor as our real system of interest. Depending on the requirements, the blades can be represented as rigid bodies, as linear elastic beams, or more complex non-linear structures with sophisticated constitutive laws. Each of these conceptual models can then be represented by a variety of mathematical and computational model forms, each one with its own pros and cons that will make it more or less suitable depending on the requirements. At the same time, different sets of data will be required depending on the conceptual model choice. The models will have a different DoR, the limits of which depend on the nature of the loading applied to the blade. For example, the DoR for the structural aspects of an elastic blade element could be related to displacement and stress-strain amplitudes that satisfy linear constitutive equations. The DoR for the aerodynamic blade segment might be expressed in terms of the Mach number and angle of attack range included in the look-up data tables, combined with assumptions on local sweep angle and unsteady aerodynamic effects. Expression in terms of frequency and amplitude of dynamic response is another, general, approach to DoR description. However, since it will usually be difficult, if not impossible, to know exactly how far an approximation is from the DoR boundary, the best that might be achievable is a description based on comparison with a higher-order, more complex numerical model.

A similar process can be followed for the FS software and hardware. In this case, starting from the requirements, the necessary cues can be established for the pilot to acquire the correct awareness of the flight conditions, and up to what degree of realism they must be reproduced. This constitutes the bulk of the conceptual model for the FS. Then, it is necessary to define the software and hardware for the systems used to provide the cues to the pilot. Finally, as described in Section 6, the hardware/software systems are developed to translate the conceptual model into real cues, with associated DoRs for the FS features.

Once a simulation of reality has been built following the process outlined in this Section, the next crucial steps will be the V&V of the simulation. In the context of the above introductory paragraphs, *Verification* is the process of determining that a computational model accurately represents, within the required limits of accuracy, the underlying conceptual and mathematical models and its solution. The process can be divided into two steps: code verification and solution verification. *Validation* is then 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. Usually, validation is performed by comparing the results obtained by the simulation with the results of experiments. However, in some cases, the reference data, or '*the referent',* could be data, information, or knowledge gained by previous experiences, analogous systems, or even by other <u>validated</u> simulation models.

In basic scientific analysis, the predictive capability of a simulation model commonly deals with the ability of the underlying theory to be falsified by experimental observations. However, in engineering, the objective is to check to what extent the predictions meet the accuracy standards set in the requirements. So, the approach to validation is rather based on deciding the acceptable level of disagreement between experiments and simulations. The level of disagreement is a *measure of the fidelity* of the simulation and validation revolves around defined *fidelity metrics* that are used to quantify the degree of accuracy of the model.

5.3.2 Component-based building-block approach

It is advisable to undertake the V&V process, much like the FSM-build, in a hierarchical way starting from the simplest components up to the entire system that will be the object of the analysis, in this case represented by the aircraft. This can be described as a building-block approach, illustrated through a pyramidal structure as shown in Figure 5-5. In this approach one moves from the lowest level, or tier, toward the top, increasing in complexity and the degree of coupling between different components. Validation at the lower levels is based on component-level experiments. In a general sense, rising up the tiers toward the top of the pyramid can obscure the coherence between causes (at low levels) and effects (at high levels), while the errors and uncertainties in measurements and relationships can increase, e.g. through propagation. The systematic step-by-step approach advocated in this Guidance should minimise the risk of this obscurity and ensure a higher control on the quality of the models both from a testing and analysis point of view, and may help in isolating the cause of unexpected or erroneous results and should prevent modelling errors or deficiencies from being masked.

This Guidance recognises the dual nature of top-down and bottom-up perspectives in V&V. In the validation process particularly, the comparisons of greatest interest lie at the highest, aircraft, level. However, mismatches here can normally only be understood, and ultimately resolved, at a deeper, lower-tier or component level. So, the two perspectives go hand in hand and a thorough grasp of the tier-connectivity is considered important in the RCbS process. Ultimately, the applicant shall make a credible case to the authority as to the lowest levels of modelling and validation that must be considered for the application.

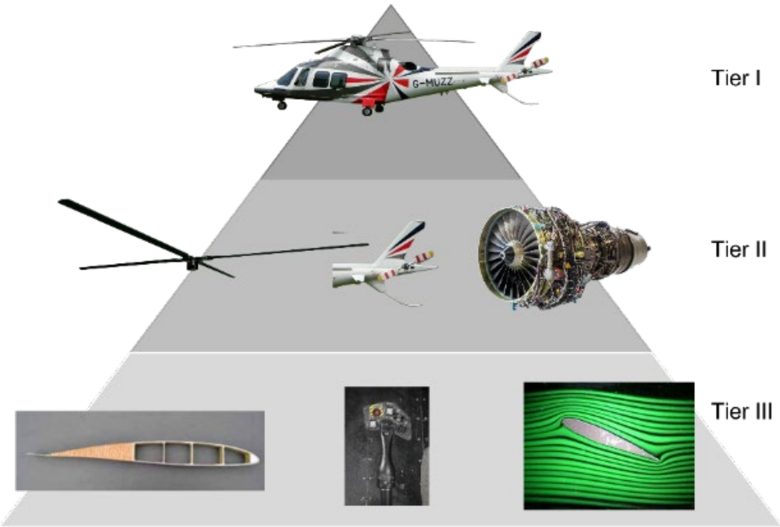

Figure 5-5: Building block approach for an FSM

The requirements-based description of FSM development ensures that all interactions between components and associated tiers are fully defined. In the tier structure, this can be interpreted as couplings between the modelling in the adjacent tiers. In principle, all the coupling should be two-way interactions. However, there are cases where the influence in one 'direction' is much weaker and might be neglected, or where the mathematical and/or computational formulations do not allow the implementation of a two-way coupling. In these cases, a one-way causal coupling is the only available option, e.g. impact of undercarriage with surfaces. The consequences of the introduction of these one-way couplings must be thoroughly assessed, because they may limit the domain of the physical reality of the model and/or affect the component-level validation. Consider, for instance, the case where the model of a helicopter rotor is coupled with the modelling of the aerodynamic forces on the fuselage. The presence of the fuselage affects the rotor flow, but the rotor wake also affects the aerodynamic forces generated on the fuselage. Therefore, even though the isolated fuselage and rotor models may be validated for a large range of flight velocities and incidence angles, the range of conditions for which the prediction error of the coupled model is acceptable, as determined from validation at a higher tier, is likely to be narrower.

It is possible that not all the details of the subcomponents up to the lower level of the pyramid are available to the applicant, e.g. because the aircraft is an assembly of subsystems developed and provided by third parties. This may be the case for instance for the engine, the landing gear, the avionic components, or the flight control systems. In these cases, if detailed modelling is required, it is advisable for the applicant to request a (traceably) validated simulation model from the subsystem providers, developed following requirements and conventions specified by the applicant and transparent in its formulation and implementation, so that it can be integrated into the FSM. If two-way interactions with the subsystem are essential, it is necessary to identify all inputs and outputs of the model required to perform the simulations. It is stressed that the requirements, in terms of V&V and documentation of the supplier subsystem model, are identical to those at the FSM level.

5.3.3 The application domains re-visited

In Section 2, the domains relevant to the RCbS process were introduced. The domains feature large in the V&V and fidelity assessments in Phase 2a. While the definition of the DoP is relatively straightforward since it is derived directly from the requirements, the other domains require more detailed analysis to define. This is aided by Figure 5-6 that illustrates, in 2-dimensional conceptual form, how the domains relate. Generalised flight envelope variables p1 and p2 are used on the axes, but it is noted that the domains are multi-dimensional and should be described as such by the applicants.

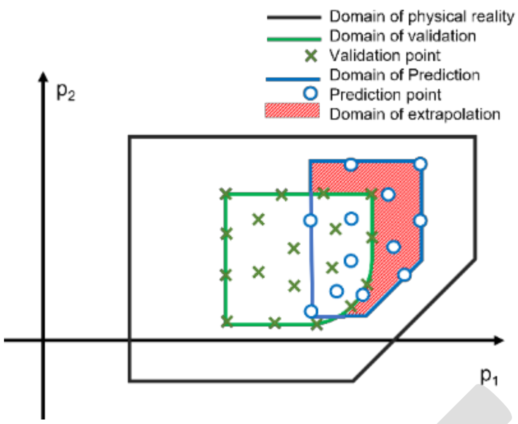

Figure 5-6: Sketch of the application domains and their relationship

To define the DoR of the aircraft, it is useful to follow the building-block pyramid, as this relates the physics used on lower tiers to the coupled components at higher tiers. Typically, for each component at the base of the pyramid it should be straightforward to define the sets of inputs and outputs appropriate for the modelled physics. Then rising to the higher tiers, it is necessary to:

a. Identify the relationships between the input/outputs of the coupled model and the inputs/outputs of its components.
b. Identify the relevant input/output ranges of the coupled model that generate inputs/outputs of the component models that are within the respective domains of physical reality.
c. Verify that the coupling physics in these ranges are correctly represented within the required accuracy. Alternatively, define the ranges over which the coupling effects could be neglected while meeting the requirements in terms of fidelity.

With the adoption of this approach, the coupled models will always have a domain of physical reality that is equal to, or smaller than, the domain of the physical reality of the component models.

In some cases, elements of the building-block pyramid for an FSM may be composed of phenomenological models, i.e., empirical models that are the result of the fitting of experimental data or predictions from higher-order numerical models. If so, care must be taken that these types of models are not used beyond their relevant DoV, i.e., the domain that contains all data used to tune the coefficient of the model [9]. This could be true for the top of the pyramid, if a model with only one level is developed. However, the logical consequence is that such a model will be used only for P1 predictability levels, i.e. interpolation only.

The DoV is determined by the available test data and will be the result of the V&V process. It is, however, important to note that the DoV and DoP must always lie within the DoR. This is particularly important for the DoP, to avoid extrapolation beyond the limits where the model is expected to provide physically meaningful results.

Note that, in many cases, although a simulation might be operating in the global DoE, many of the components will be functioning in their local DoV. However, the inverse may also be true. As such, it is important to trace how component models are operating relative to their local DoP and DoV boundaries.

5.3.4 Verification

The verification sub-phase assures that the implementation of the mathematical model through numerical algorithms is as intended. It is composed of two aspects, code verification and solution verification.

Code verification, establishing the correctness of the code itself, is independent of the physical problem in the RCbS process. In essence, code verification is concerned with ensuring that for a given set of inputs, the coded form of a modelled component generates the intended outputs. The first set of verification operations is described as numerical algorithm verification, usually performed by comparing the solutions computed by the simulation software with solutions generated by so-called *verification benchmarks*. These benchmarks can be: (a) manufactured solutions, (b) analytical solutions, or (c) numerical solutions appropriately generated. Applicants are referred to the literature, e.g. [18] for a thorough discussion on the different options. In general, cross-comparison against other verified codes is not considered the preferred approach, but in some cases may be the only option. By comparing the computed solutions with the benchmarks, it must be shown that by increasing the sampling, the discretization error tends to zero with an appropriate rate of convergence. By its nature, code verification must follow a building block approach, starting from verification of components (e.g. a finite-element flexible beam element) and moving up to include component interactions (e.g. a rotating finite-element rotor blade with aerodynamic loading).

The second set of operations under code verification involves software quality assurance and pertains to verification that the code is reliable and produces repeatable results in a specified hardware and software environment. The bulk of code verification is often performed by the code provider. This is particularly the case when commercial software packages are used, e.g. NASTRAN, FLIGHTLAB [19], in which case, the applicant needs to collect evidence that verification has been undertaken by the code provider. In addition, whenever the hardware or software is modified, it is important to verify that the 'new' code is still generating the results as intended. The latter requirement falls into the category of Configuration Management as addressed in Section 9 of this Guidance. In some cases, it may be useful to ask the software providers to include the documentation to enable the applicant to repeat code verification tests. Finally, it is important that the impact on the FSM predictions of identified or known code defects is assessed as part of the solution verification process.

Solution verification is performed after code verification and is an activity with the objective of *estimating* the discretisation error of the FSM for a specific validation or prediction case. Through solution verification, as shown in detail in Ref. [20] for CFD applications, it is the intention to assess the numerical uncertainty u_{num} of the model in the conditions being assessed. A pragmatic approach is to consider the numerical uncertainty u_{num} as epistemic, i.e., an interval without associated probability distribution, where the bounds of numerical uncertainty for a given output parameter of interest, obtained at a practical level of numerical discretization, are defined equal to ± the magnitude of the error relative to the solution obtained at a higher, ideally asymptotically converged, level of discretization.

The numerical uncertainty, in turn, is one of the ingredients for performing the validation described in the following paragraph, and also the credibility assessment described later in Section 8. In this context, it is important to ensure that the solution verification encompasses the DoV and the DoE.

It is also important to include all supplier and user-defined tools and scripts used to perform the pre- and post-processing activities in the verification process. In the case of time-constrained solutions (e.g. real-time application), there are also time-based convergence constraints in which case the solution iteration may be halted before the established convergence criteria have been met. Requirements for how the solution process deals with such constraints need to be defined and the verification process should check that these requirements are satisfactorily met.

5.3.5 Validation and fidelity assessment

Validation involves the comparison of FSM results with a referent, which generally is the result of an experiment, commonly from flight testing in the RCbS process. The most common aircraft-level referent anticipated in this Guidance will be the prototype of the aircraft to be certified and data gathered during pre-certification flight tests. However, experimental referents may also be obtained from ground tests on components, from scaled models, or from experiments conducted on an analogous system, e.g., flight test results from an aircraft variant that has a similar configuration. In some cases, experimental results may not be available so, other forms of referent can be considered, e.g. results obtained by higher-fidelity continuum mechanics models. However, this Guidance emphasises that comparison with such data is not strictly 'validation'. Such higher-fidelity modelling falls into the FSM toolset in RCbS and should receive the same level of scrutiny, in terms of V&V, as the core FSM.

The goal of the validation process is to ensure the FSM predictions meet the tolerance requirements defined in Phase 1, for the comparison of fidelity metrics with test data. Following on from this, the goal of credibility assessment is to collect enough compelling evidence that would convince, beyond a reasonable doubt, a group of peers that the predictions of an FSM are sufficiently correct. Credibility is returned to in Section 8. In performing validation, it must be remembered that experiments are also affected by errors and uncertainty and that these should also be assessed (see Section 7).

5.3.6 Validation error and uncertainty

Figure 5-7, derived from References 21 and 38, is used to support the description of key errors. So, we see that both the referent (typically experimental data) *R* and the simulation result *S* have errors relative to the 'truth'.

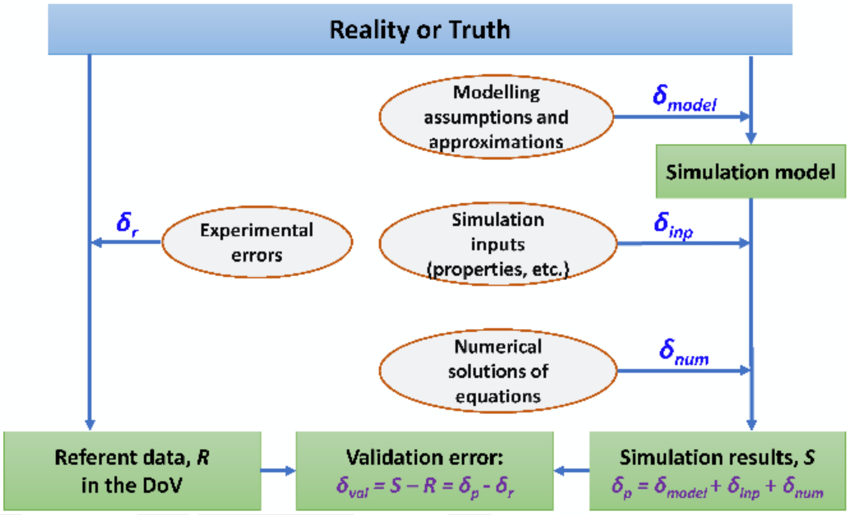

Figure 5-7 Overview of the derivation of the validation or comparison error

As previously discussed in Section 3.2.1, fidelity deficiencies, and hence prediction errors, should be contained within the prediction error uncertainties. Referring to Figure 5-7, this applies for the three elements of the prediction error, δ_p, for the simulation result *S*;

a) the errors due to modelling assumptions δ_{model}, including those generated by the choices made in the conception of the model that are, by nature, related to epistemic uncertainties,

b) the numerical errors, δ_{num}, stemming from the methodology used to solve the underlying equations of the FSM,

c) the errors, δ_{inp}, arising from the input parameters of the FSM. These errors may be related to epistemic or aleatoric uncertainty, or both at the same time.

The validation error δ_{val} refers to the error observed between the referent and the simulation in the DoV. Including the referent error, δ_r, the validation error δ_{val} can be written in the form:

$$\delta_{val} = |\delta_{model} + \delta_{num} + \delta_{inp} - \delta_r| \quad (2)$$

Hence, the error due to modelling assumptions, i.e. the error an applicant needs to quantify and understand in the DoV validation process, can be written as:

$$\delta_{model} = \delta_{val} - \left| \delta_{num} + \delta_{inp} - \delta_r \right| \tag{3}$$

To emphasise, a distinction is made between the validation error δ_{val}, defined with respect to the referent (and featuring only in the DoV), and the prediction error δ_p, defined with respect to the (unknown) truth.

The absolute-value term on the right of (3) is composed of terms that are of unknown magnitude and sign. Assuming the errors are effectively independent (see Reference 38), the associated validation uncertainty u_{val}, can be defined as:

$$u_{val} = \sqrt{u_{inp}^2 + u_{num}^2 + u_r^2} \tag{4}$$

The simulation model error δ_{model} cannot be uniquely identified, but falls within the range:

$$\delta_{model} \in \delta_{val} \pm u_{val} \tag{5}$$

The measurement (referent) or experimental uncertainty u_r is determined by the measurement set-up and encompasses not only systematic and random errors in the data acquisition and instrument calibration, but also random error or variability due to atmospheric conditions and piloting technique. The numerical uncertainty u_{num} is obtained from the solution verification process described in the previous section. Finally, the input uncertainty u_{inp} can be derived through uncertainty quantification methods as discussed in Section 8.

If the validation error is significantly larger than the validation uncertainty, then the error due to modelling assumptions δ_{model} can be expected to be close to δ_{val}, and so the model must be improved. Alternatively, when $|\delta_{val}| \leq u_{val}$, it can be concluded that the model is within the precision achievable given the data and software available. The uncertainty u_{val} provides a target to be reached when performing model validation in the DoV. At the same time, a validation error significantly larger than the uncertainty will be an indicator that something that is relevant has likely been neglected, and so calls for a revision of the setup for the conceptual model used and the associated modelling assumptions. In this process, it should be stressed that characterising the uncertainty of the validation measurements u_r is equally important as characterising the modelling uncertainties.

Although the level of detail in the analysis may vary depending on the ultimate FSM application, it is advised to follow the same hierarchical building-block approach as employed during model development for the validation process. Starting from a robust validation of systems at the base tier, typically characterized by a lower number of relevant parameters, the assessment at higher levels can concentrate on the interactional effects between the subsystems. FSM validation is thus recommended to be performed using this hierarchical approach, focussing on component-level tests and analysis before validation of whole aircraft behaviour against flight test data is attempted. Similarly, the validation of complex manoeuvres should be preceded by tests and analyses in relevant steady-state conditions and simpler manoeuvres. This type of bottom-up approach enables modelling deficiencies to be positively identified and, if possible, remediated. Here, support from diagnostic analysis can be helpful.

5.3.7 Validation in parallel with development

An effective validation process will proceed in parallel with the development of the FSM itself, and also the development of the experimental processes and systems, particularly the FTMS (Section 7). The availability of a prototype model before conducting validation experiments will enable the 'design of experiments' to progress efficiently, e.g. by selecting the relevant points to be tested and the quantities to be measured. This can also provide opportunities to solve problems related to a lack of information on the experimental conditions, quality of the different measures, etc., that are typically encountered when models are developed only after the completion of the test phases. The experiments dedicated to validating the FSM must be planned specifically for this purpose, identifying all quantities that need to be measured accurately to validate the FSM, which in some cases may be only loosely connected with the evaluation of the overall performance of the helicopter. These points are emphasised in this Guidance to alert the applicant to the importance of having the validation data gathering an integral part of the FSM development.

Inherent test variability should always be considered and addressed to avoid the risk of relying on validation based on outlier data points, i.e. data points that fall significantly outside of the typical variability observed during a test or series of tests. Additionally, in these cases, the availability of a model before the test allows the applicant to build up knowledge on expected reference outcomes that can help in identifying possible outliers that require further investigation.

5.3.8 Validation flight testing

To relate to the certification specifications, flight tests for FSM validation should consider both steady-state (trim) and transient (stability and response) phases where relevant. Depending on the application, frequency-domain validation with associated system identification flight testing may be appropriate when the intention is to establish the veracity of the FSM across a frequency range. The bounds and tolerances for the so-called MUADs [16] provide an example metric in this case. Alternatively, transient responses to control inputs can provide insight into short-term damping and control sensitivity comparisons, as well as cross couplings.

When flight test data in the exact conditions of interest are not available or impractical to obtain, validation using interpolation is appropriate in the DoV. In the DoE, validation is more challenging of course but a plan for the credibility assessment and related uncertainty analysis will need to have been laid out in Phase 1. The FSM will, of course, still be governed by the laws of physics in the DoE and the credibility assessment should determine how the flight behaviour might ‘stretch’ the modelling assumptions to their limits. Such analysis will be key to validation and fidelity assessment within the DoE.

5.3.9 Fidelity metrics

While an initial comparison between the referent and the FSM can be qualitative to assess the correctness of the conceptual approach chosen, a quantitative analysis is required to assess the sufficiency of fidelity for the model’s use in RCbS. It is possible to distinguish between different scenarios when defining metrics to quantify fidelity:

a. Cases where the objective is the evaluation of the trim value of a quantity of interest, e.g. a control margin. Here, the fidelity can be measured through the percentage errors between the referent and the result of the simulation. Ideally, the allowable error is referred to a meaningful performance characteristic related to the ACR, e.g., the minimum control margin for manoeuvrability or gust tolerance.
b. Cases where the objective is to compare the evaluation of a response over time, e.g. in dynamic stability assessment where period and damping are computed. Percentage errors across the time response, or metrics based on peak errors can be considered. The choice in metric should be strongly influenced by the nature of the ACR being addressed.
c. Cases where the objective is the comparison of frequency response functions, e.g. to characterise and validate the frequency content of the various FSM components. The cited MUAD metric [16] has been established to connect with a pilot’s perception of modelling errors across the frequency range of interest in pilot simulations.
d. Cases where the aircraft behaviour in an ACR involves large excursions from a trim condition, e.g. following failures or when pilots need to exercise the full manoeuvrability of the aircraft, e.g. for

obstacle avoidance. The moderate-large amplitude response quickness metric from ADS-33 is an option for fidelity assessment in such cases [21].

In cases where there are multiple quantities of interest in the fidelity assessment, it is possible to define a weighted sum of all quantities with the weights reflecting the relative importance of the different quantities [22].

As illustrated in Figure 5-1, validation and fidelity assessment should be considered an iterative process that starts with the fidelity requirements and associated flight test points (both defined in Phase 1) and advances to a tuned/updated model that meets the sufficiency requirements. The model updating process is also likely to be iterative, as fidelity at aircraft-level is derived from component-level assessment and developments.

It is emphasised here that the sufficiency criteria in terms of FSM fidelity in the DoV should be defined in Phase 1, based on the Influence/Predictability for the ACR and agreed with the certification authority. In principle, the 'acceptable' FSM mismatch-tolerances require a degree of engineering judgment based on the experience from other applications. For example, error tolerances from the certification specifications for flight simulation training devices may be used as a guideline where appropriate. More generally, a systematic approach is recommended to connect the physics-based nature of the FSM **with the requirements of the ACR.**

5.3.10 Investigating FSM error

One of the challenges in the validation and fidelity assessment of an FSM lies in the systematic exploration of the model error δ_{model} and related (epistemic) uncertainties in the predictions. That is, those errors and uncertainties relating to approximations in the mathematical expressions used to model the underlying physics. The following deals with the qualitative exploration of the model error, whereas quantification is discussed in Section 8.

The engineer knows that their model is not perfect. He/She may have some knowledge of the imperfections and so should be able to estimate the boundary of the DoR, to try to ensure that predictions do not cross this. However, in several respects, the engineer will be uncertain about the location of this multi-dimensional boundary. Also, in the DoR, and even within the DoV, he/she will likely have different degrees of uncertainty about the accuracy, the predictive ability, of their model. Such uncertainties will be well informed by experience and, although experience is a good teacher, it can also deceive. As with most aspects of the Guidance, there is no substitute for a systematic process to assessing these kinds of uncertainties. Herein are suggestions for the elements of such a process.

Every input-output (mathematical) relationship in a FSM approximates reality. The mathematical approximations are reflected in assumptions about how the physical processes work. Here, for the benefit of clarity, we distinguish between (mathematical) approximations and (physical) assumptions. Understanding the physical assumptions and how they are represented by the mathematical approximations is part of the foundation for exploring the modelling errors in an FSM. This understanding is considered critical to the successful application of RCbS.

A significant benefit accruing from the use of an FSM, for both design and certification, is the ability to explore, identify and quantify the physical sources of the contributions to input-output relationships. Predictive capability has long been underpinned by understandings of the relationship between a cause and effect (the physical manifestations of input and output). In the limit, such cause-effect analyses can be used to quantify the impact of all modelling assumptions, and their approximant parameters, on mismatches between test and FSM predictions, i.e. the fidelity of the FSM. Of course, on their own, such diagnostic investigations do not necessarily identify the specific source or complete cause of a mismatch, but they can be used to compute sensitivities and, hence, point to likely suspects in the search for modelling errors.

At the global level, FSM fidelity can be expressed in terms of the relationships between the forces and moments acting at the aircraft centre of gravity and the resultant evolution of aircraft motion states. For small perturbations, the relationships are traditionally quantified in the form of 6-DoF stability and control derivatives, or more generally, N-DoF generalised force and moment derivatives (e.g. including rotor dynamic and aerodynamics states). Such global analysis is also possible using test data, creating phenomenological models (p-models) e.g. using System Identification techniques to support fidelity assessment. As discussed in Section 5.3.6, and later in Section 10, component-based force and moment derivatives can be used as a guide to FSM updating through fidelity renovation.

An FSM contains a myriad of computational pathways from interconnected local components to the global flight behaviour in the form of trim, stability and response predictions. Along these pathways, throughout the process network, data flows that provide the source of information that can be used in uncertainty analysis. Virtual (diagnostic) sensors within the network allow the user, or computer associate, to interrogate very detailed behaviour to establish where processes are relative to the boundaries of the DoP and DoV.

The sources of modelling deficiencies lie at the local level, propagating errors along the various pathways to the global level, e.g. in the magnitudes and directions of local flowfield or in the way that component forces and moments react to the flowfield. Another example might be the way that a control actuation system might saturate because of demands from the pilot/autopilot on the one side and/or loads induced by rotor-blade torsion on the other. Some of the usual suspects of modelling deficiencies are shown later in Table 8-2.

Once the primary source(s) of FSM error have been identified, the question becomes how to repair or renovate the deficiencies in fidelity. That brings us to the model tuning/updating process in Figure 5-1.

5.3.11 Model tuning and updating

In pre-certification FSM development, it is not unusual for fidelity to be insufficient for the intended RCbS ACR. In the event the validation against test data reveals unacceptable discrepancies, the first step should be to investigate and reveal the cause of the discrepancy and postulate physics-based updates to the FSM. The update process could include modifying the modelling assumptions and/or adding previously un-modelled dynamics. Both might require the gathering of additional experimental data as illustrated by the iteration with flight testing in Figure 5-1. Another option is to tune the FSM parameters to achieve the required sufficiency. Every design parameter in the FSM will have a degree of uncertainty and, within this established measure of uncertainty, sensitivity analysis can reveal the limits for parameter modification, or tuning, to increase fidelity. In the process care must be taken to keep all parameters within physically meaningful bounds and to ensure that the aircraft-level tuning does not deteriorate the correlation against component-level test data. In case of doubt, it may be necessary to explore the limits of validity of a given parameter by comparison against a higher fidelity simulation approach. It is noted that, when taking into account simulation model validation uncertainty, the DoFs for improving the correlation with test data through input parameter variations (i.e. tuning) are naturally exercised and finding the unique combination of parameters that provides the ‘best’ match is not necessarily of particular value.

If a system-level p-model is used, then all possible model-updating techniques could be applied, keeping always in mind that such model can be used only for P1 predictability levels, i.e. interpolation only, since its DoR cannot extend, by definition, beyond the DoV.

A wide range of model-updating methods has been explored and documented by the NATO Research Task Group AVT-296 [22]. AVT-296 explored a range of different approaches applicable across the life-cycle of a rotorcraft, including for use in improving FSM fidelity for training simulators and for certification. The physics-based update methods (Methods 3–6 in [22]) are generally applicable to the certification process if applied within appropriate limits. AVT-296 also documented a variety of fidelity metrics commonly used as a part of the update process.

Many of the methods described in the NATO report make use of System Identification methods to create a p-model, derived from flight test measurements. Comparison of the parameters identified in the p-model structure with the equivalent parameters extracted from the FSM then provide the basis for fidelity improvement activity. Example parameters are the 6DoF stability and control derivatives (see text in Section 5.2.1), rotor inflow deformation parameters, or constants in the rotorblade retention modelling. Clearly, as with FSM parameter tuning, any adjustments to the FSM parameters based on such comparisons must be fully justified.

Finally, if the simulation model is used to obtain proof of compliance in the DoE, the credibility of the simulation model and validity of the underlying tuning must be explained and demonstrated. Credibility assessment is the topic of Section 8.

5.4 SUMMARY: PHASE 2a

To summarise, activities in Phase 2a, development of the FSM based on the (preliminary) Requirements Specification, include:

i. FSM build, verification and validation and fidelity assessment, including updating/tuning,
ii. Prototype FSM supplied to the FS and FTMS developers to support parallel activities,
iii. Input of pre-certification ground and flight test programme to support validation of FSM,
iv. Multiple iterative pathways managed and exercised as required throughout Phase 2a,
v. Updates to Requirements Specification based on Phase 2a activities,
vi. Outputs; FSM validated for intended purpose, documented in fidelity assessment reports.

6 FLIGHT SIMULATOR DEVELOPMENT (PHASE 2b)

6.1 INTRODUCTION

The focus of the Guidance in this Section is on real-time, piloted simulations. The FS is intended to create an illusion of reality for the crew, so that they behave, react and perform as if they were in the real aircraft. Many factors contribute to this illusion. The fidelity of the various simulator features are obvious contributors, but also the protocols around how tests are conducted can reinforce or spoil the illusion. The test team must 'pretend' that they are conducting a real flight test and, as far as possible, engage in communications as if it was 'for real'. Even with a perfect FSM fidelity, the pilot's reactions, for example to failures, will depend on the cueing fidelity, not exaggerated, such that the failure identification, control strategy reactions and closed-loop recovery strategies are realistic. Achieving this kind of realism is no easy task, but rather calls for a development and validation discipline matching that described for the FSM. With the pilot in-the-loop, the term 'behavioural fidelity' is also considered appropriate.

Figure 6-1 illustrates the elements of the FS development phase (Phase 2b), with major inputs from the Requirements Capture/Build phase and the Engineering Design Data. Inputs from parallel Phases 2a (FSM) and 2c (FTMS) are also shown. The dashed lines indicate iteration pathways within Phase 2b and from outside, in the parallel phases and the later credibility phase. The steps required in the FS Development are:

1. Flight Simulator Build
2. Flight Simulator Verification
3. Flight Simulator Validation, including fidelity assessment.

It is acknowledged that there may be legacy FS facilities available to the applicant. In this case, the FS Build phase may be non-existent and the V&V activities may rely, in part, on past efforts, given appropriate configuration management practices are in place. The remainder of the activities within Phase 2b will then focus on the assessment and, if needed, the updating of the FS for the selected ACR.

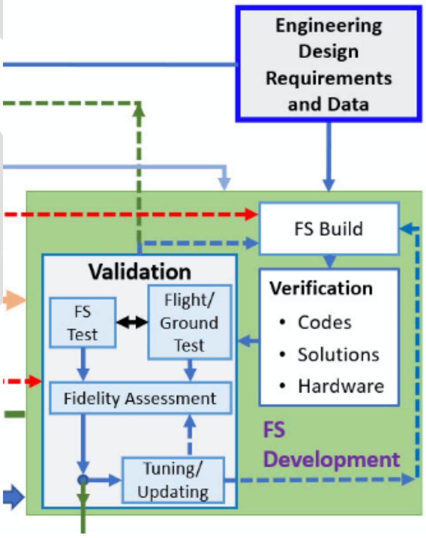

Figure 6-1: The Flight Simulator Development; Phase 2b

An FS is comprised of different features (Figure 6-2) which provide cues to the Evaluation Pilot EP enabling them to undertake an ACR. This Guidance draws on the definitions in Notice of Proposed Amendment - "Update of the flight simulation training device requirements" [12] and ICAO 9625 [11] for ten FS features. The FSM feature developed in Phase 2a is a key component of the FS development as it provides inputs to the other FS features, e.g., the vestibular motion cueing system (VeMCS), and receives outputs from features, e.g., the flight control positions and forces. The FSM content is discussed in detail in Section 5 and only the inputs/outputs to other FS features are discussed in this section. For some ACRs, not all FS features will be required and these will be addressed in the following sections.

The Operator Station (OS) is the outer region of the FS schematic and interacts with the FSM and other features. The FSM provides inputs to the other FS features to generate cues to the EP who is at the centre of the FS schematic. The cues that can be provided to the EP are visual (sense of sight), auditory (sense of hearing), vestibular (sense of balance and orientation in space), proprioceptive and kinaesthetic (awareness of position and movement of joints respectively), and tactile (sense of touch). Each FS feature may generate one or more of these types of cues.

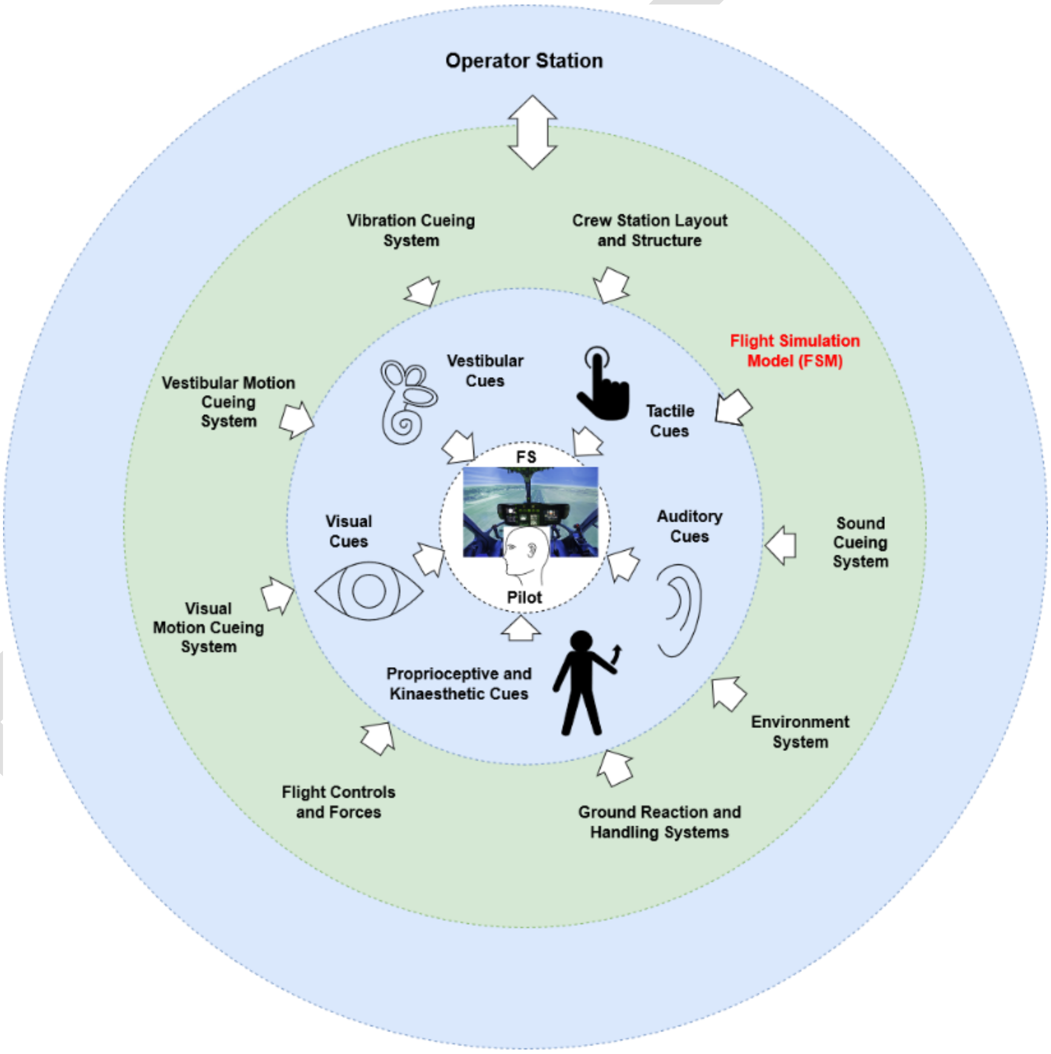

Figure 6-2: Schematic of FS Features

During the fidelity assessment, predicted and perceptual fidelity metrics, defined in Phase 1, will be employed. The fidelity of the FS features should be sufficient to provide an EP with the cues needed to undertake an ACR without ‘significant’ adaptation. An example of a perceptual (behavioural) fidelity metric is the Simulation Fidelity Rating (SFR) scale [23]. The SFR scale requires the EP to compare the task performance achieved and the task strategy used between flight and simulation to assess the fidelity of the FS. Quantifying task performance is normally straightforward, but strategy is more complex. An example of an adaptation metric, based on changes in control compensation is described in Refs [24], [25]. The SFR method differs from current flight simulator training guidance [15] which defines Levels of Fidelity, e.g. specific, generic, and representative to clearly differentiate certification guidance and allow more nuance in feature requirements. The content of the FS features should be such that they provide cues with sufficient fidelity for an ACR. Examples of the FS feature-content information are provided in the next sub-section.

6.2 FLIGHT SIMULATOR BUILD

The design and build activities of the FS are based on the requirements specification for the selected ACRs. It is crucial to ensure all FS features have sufficient fidelity to generate the cues needed by an EP to undertake ACR testing with representative task performance and without significant adaptation. Cue fidelity is further facilitated through a fidelity assessment in the validation step of FS development. The Guidance in this section discusses the kinds of feature content that might be considered for an ACR.

The FSM is considered to be one of the features of the FS, but since its development and fidelity assessment are undertaken in parallel with Phase 2a (Section 4), it is not detailed here. A 'prototype' FSM, supplied by Phase 2a, can be used in the FS development to examine the sufficiency (or necessity) of cues such as the vestibular motion cues provided by the VeMCS.

An FS may be used for more than one ACR, so it is necessary to consider the fidelity requirements of multiple ACRs during the build step of the FS development process. Use of Engineering Design Requirements and Data from the real aircraft, e.g. an aircraft cockpit Field of View (FoV) diagram, is also required during the FS build, to ensure sufficient fidelity of the FS cues.

It is recommended that applicants consider the design requirements for each FS feature in a structured way as detailed in Section 3 (Phase 1), where the following characteristics are considered:

1. Function
2. Operational modes
3. Data structures
4. Inputs
5. Outputs
6. Interfaces
7. Constraints
8. Domains of prediction and validation

It is acknowledged that the concept of the domains of prediction and validation becomes somewhat nebulous when considering a FS feature rather than the FSM. Consider the following example; piloted FS validation has been performed for a specific ACR resulting in a certain range of motion inputs from the VeMCS, thereby defining the DoV for the VeMCS. It is then found that the compliance demonstration trials in the simulator result in motion amplitudes/rates that are larger, i.e., the DoP exceeds the DoV. In this case, the applicant will need to show, e.g., by validation at FS feature level to extend the DoV, that the fidelity of the cueing from the VeMCS is sufficient within the full DoP.

The following sections define the nine FS features (not including the FSM) and discuss feature-content considerations for an ACR. The data structures and communication protocols for sharing information across features must be defined during the FS Build process.

Transmission of data between simulation features, and the time taken for a feature to cycle the data through a computation step, will introduce time delays in the FS environment, namely latency and transport delays. Latency is defined in CS-FSTD(H) [15] as the difference in the time taken for a real aircraft's system to respond and that taken for an FS feature to respond. The time taken for an FS feature to process an input signal from the EP's controls is defined as a transport delay. Transport delays will affect any solution produced by an FS feature, or collection of features, and must be quantified in the verification of the FS solutions. Recommendations for maximum transport delay values, also considered applicable for RCbS, can be found in documents such as CS-FSTD(H).

6.2.1 Operator Station

Definition: The Operator Station (OS) is comprised of the computer terminal(s) from which the FS features are initialised, managed and monitored by the operator. The OS feature is not defined in [12], but for a certification FS the OS has content that needs consideration.

Design Considerations: The OS must enable the certification team, including the EP, flight test engineer, and the engineers operating and monitoring the FS, to gather data from the FS to demonstrate that the aircraft performance and piloting requirements for the ACR have been achieved. To support this process, the FS OS can be utilised to trim the FSM with the pre-certification flight test conditions flown (e.g. airspeed, weight, altitude, environment conditions) and record data from the simulated task. For example, in demonstrating compliance with ACR 29.143 (Controllability and Manoeuvrability) the OS can be used to interact with the Environment System (ES) feature to load the required visual database, and with the FSM to trim the model in a ground referenced hover in the presence of 17kts winds for a range of azimuths.

The OS can record data obtained from the FSM, e.g. aircraft states, and the Flight Controls and Forces feature, e.g. pilot inceptor positions, for use in FSM and FS validation, fidelity and credibility assessment. The OS could include a real-time visualisation of the simulated aircraft's performance and the EP's control activity to enable the certification team to assess whether performance criteria have been met and/or whether the test point quality satisfies the ACR or if it needs to be repeated.

6.2.2 Environment System

Definition: The Environment System (ES) feature represents the FS components needed for the ACR which are not part of the FSM, but are configured through the OS. These ATC, navigation signals, atmosphere and weather effects on the visual conditions (e.g. fog), as well as surface features such as aerodromes and terrain/landscape.

Design Considerations: The required characteristics of the ES are dependent on the ACR. For example, in CS-29, Appendix B, VII for IFR flight, the 'Environment – Atmosphere and Weather' characteristic should be able to represent Instrument Meteorological Conditions (IMC) in the Visual Motion Cueing System (VzMCS), including, visual range and precipitation effects, which are controlled by the OS. When the ACR includes navigation tasks, navigational data should be included to provide inputs to the instrument panel in the Helicopter Systems feature. The ES feature includes the visual terrain database which comprises visual models of the terrain and provides height above terrain inputs to the Ground Reaction and Handling System, Crew Station and Layout Structure features, as well as to the FSM. If required for an ACR, landing areas and ground markings should be modelled with a sufficient level of detail, texture and contrast.

6.2.3 Ground Reaction and Handling System

Definition: Helicopter ground reaction and (ground) handling responses in an FS which are derived from the FSM.

Design Considerations: Although the landing gear/undercarriage component is a part of the FSM, it is included here as a separate FS feature as the input/output relationship needed for its operation, e.g. input from the ES system feature to the FSM and vice versa, must be considered during the FS design and build. The ES system feature will provide height above terrain information as an input to the FSM to calculate the undercarriage deflections, friction and side forces. The outputs from these calculations are conveyed to the EP through the VeMCS and the VzMCS to aid in identifying the ground state of the aircraft, e.g. skidding or rolling motions. The height above terrain information is also needed for aerodynamic ground effect modelling in the FSM, which in turn affects the ground handling simulation. This simulator feature is not required for any ACR that does not involve landing, taxiing, contact with the terrain surface, or In Ground Effect (IGE) operations.

6.2.4 Crew Station Layout and Structure

Definition: The Crew Station is defined as the area in an aircraft where the flight crew members work and where the EP's inceptors, flight instruments and interfaces to helicopter systems such as the engine controls, are located.

Design Considerations: The content of this feature includes flight instruments, caution and warning displays, secondary aircraft controls such as buttons and switches to power and electrical systems, and navigation and communication systems. Some elements of the helicopter system, such as the SCAS and autopilot, are components of the FSM, and appropriate interfaces in the FS will be required to enable the EP to provide inputs to the FSM.

The construction, positioning and configuration of the content of this feature should be such that they do not significantly modify the task strategy employed by an EP while performing an ACR, e.g., change in visual cues due to crew station framing and seating position. This feature could be developed with the use of a physical replica of flight hardware, or via a virtual representation of the cockpit. Engineering Design data are required to enable the fabrication of the cockpit, or the generation of a 3D model for virtual applications.

The crew station layout and structure feature design will depend on the configuration of the VzMCS. A Virtual Reality (VR) VzMCS will require a digital recreation of the crew station, rather than a physical one. This may reduce the required complexity of the crew station significantly, but increase the complexity of the VzMCS in turn.

All aircraft systems required for an ACR should be available and appropriately located in the Crew Station, especially for tasks that include emergency procedures. It should enable any interactions required by the EP during the ACR with relevant aircraft systems. All systems required for accomplishing an ACR should be operable by the flight crew with no input from the simulator OS required.

6.2.5 Flight Controls and Forces

Definition: This feature is defined as the physical control inceptors used by the EP in the Crew Station and their force and damping characteristics.

Design Considerations: The FS inceptors can be broadly divided between 'unloaded' and 'loaded' (also known as 'force-feedback') systems. The former is typically associated with desktop simulation and will generally not represent the control ranges and forces that a pilot would experience in the aircraft. As such, their use would not normally be expected in the RCbS use of a FS, and must be justified if used for an ACR. Loaded systems can allow customisable mechanical characteristics of the inceptors, e.g. breakout force and spring force gradient, to be generated to represent those of the aircraft. The requirements for sufficiency of the fidelity of these characteristics will be dependent on the ACR being assessed. The characteristics of the inceptors are typically provided by a control loading system, including control loading computer and motor, and can be configured through the OS.

The EP should be able to apply control inputs in terms of amplitudes, forces and frequencies in a manner that is required for the ACR and that satisfy fidelity requirements. The output from the movement of the FS inceptors are inputs to the FSM's FCS component which, in turn, provides inputs to the FSM rotor components and SCAS/autopilot.

6.2.6 Visual Motion Cueing System

Definition: The VzMCS is any type of display technology including dome projection and virtual, augmented and mixed reality (VR/AR/MR), that provides out-the-window (OTW) visual motion cues that the EP uses for an ACR.

Design Considerations: Development of the visual cueing system must consider the required FoV, Field of Regard (FoR) (the total area that can be captured by a movable sensor), and appropriate levels of lighting and contrast to provide the EP with 'useful' visual flow information to attempt an ACR. For example, to enable ACR 29.143 (Controllability and Manoeuvrability) to be undertaken, the FoV and display resolution should provide sufficient visual motion cues to enable the EP to perceive similar height above ground and vehicle drift cues to that experienced in real flight.

For a projection system, the design eye-point is required from the Engineering Design Data to locate the pilot's head in the FS. For multi-channel projection systems, blending and warping of the visual channels on the projection screen/dome should not introduce any perceivable distortion in the OTW visual scene.

Although currently considered immature for use in certification, VR systems have been certified for use in rotorcraft simulator training [26]. It is anticipated that suitable options for creating the OTW visuals using VR, AR or MR systems will be commercially available in the future, and a brief description is included here. In VR, all visual cues are provided to the EP through a headset that generates the OTW cues and, possibly, a virtual cockpit (VR). In the case of VR, the EP does not see the physical simulator cockpit structure, nor their limbs and hands. Unless hand tracking and hand visualisation is included, a VR solution can only be used in ACRs where EP interaction with cockpit content other than the main inceptors (collective, cyclic and pedals) is not required, e.g. button presses. In the AR case, the EP can see the Crew Station Layout and Structure through the AR headset, while the OTW view is 'augmented' using a 'black mask'. In the AR case the Crew Station windows need to be blanked with black material or the room around the Crew Station needs to be dark or heavily dimmed. In the MR case, the real-time video image from two cameras mounted on the headset (one per eye) is mixed with a virtual representation of the OTW view (using a mask of the Crew Station or making use of chroma-key techniques). In the MR case, specific aspects of the video pass-through need to be considered, such as time delay of the video image, degradation of the image quality and the distortion caused by the offset between the pilot's eye location and the camera position in front of them.

With AR/VR/MR devices the following aspects need to be considered when choosing the hardware. The vision of the pilot is restricted by the FoV of the headset, while in simulators with a projection system the OTW FoV is restricted by the projection system. On the other hand, the FoR of head-mounted devices (AR/VR/MR) is 360°, whereas the FoR of a projection system is limited by the physical structure. The minimum FoV/FoR required for an ACR demands specific consideration. Too small a vertical FoV can lead to adaptation of the EP's eye scanning and increased head movements and discomfort. The latency between tracking of head movement and image rendering can cause 'cybersickness'. Furthermore, reference [27] suggests that having a frame rate less than 90 frames per second can cause misperception of motion also leading to cybersickness. A mismatch of the distance between the centres of the EP's eyes, the inter-pupillary distance, and that set in the hardware can cause fatigue and cybersickness. For the MR case, care needs to be taken with the camera position to prevent and parallax issues and false motion perception during head rotation. Further guidance related to reducing cybersickness in VR is provided in [27].

These emerging technologies are being investigated and their utility will be evaluated in a case study in Section 10.

6.2.7 Sound Cueing System

Definition: The sound cueing system is any technology that provides auditory cues to the EP.

Design Considerations: In flight, the EP receives sound cues from several sources, providing feedback on the helicopter's state, e.g. engine/rotor speed, gearbox whine and indications such as audio cautions and warnings, e.g. low rotor speed warning. The inputs to sound cueing system are provided by the FSM and other features, such as ATC communications from the ES. The presence of unrealistic, or incoherent, sound content can impact an EP's situational awareness and sense of realism, and the sufficiency of the sound cue feature in the FS must be considered for each ACR. Particularly in failure cases where the pilot's attention is focussed on the outside world visual cues, such a during a Category A rejected take-off, sound cues may have an impact on task performance. Sound cueing systems should also include intercom facilities that allow the EP to communicate with other crew members and the FS operator. Tones and voices from the avionic system are a source of information for the pilot, and, in several situations, being able to 'pick-up' rotorspeed changes from the rotor/engine/gearbox tones will be important.

6.2.8 Vestibular Motion Cueing System

Definition: The VeMCS provides angular/linear displacement, rate and acceleration cues to the EP.

Design Considerations: The human vestibular system contains two important motion sensors, located in the inner ear: the semi-circular canals for rotational cues, and the otoliths for translational cues. The semi-circular canals are sensitive to angular velocities and accelerations, while the otoliths sense specific force, i.e. the non-gravitational forces acting on the body per unit mass. The latter are often simplified as (lateral or longitudinal) accelerations, but this simplification only holds when the aircraft or simulator is not tilted relative to the gravity vector. A human in a tilted aircraft without any acceleration (e.g. a hovering helicopter) will still experience a non-zero specific force cue. The VeMCS produces the vestibular cues through the Motion Drive Algorithms (MDA), or motion filters. By tuning the parameters of the MDA, the fidelity of the vestibular cues can be optimised with the need to keep the movable cabin of the VeMCS within its available motion space.

A wide range of VeMCSs may be employed that can vary in the number of the Degrees of Freedom (DoF) they provide, the maximum velocities and accelerations they can produce, and the envelope of the system, i.e. the maximum linear or angular displacements achievable by the moving platform. The VeMCS is driven with the linear accelerations and angular rates calculated by the FSM which are scaled and filtered, using the MDA, to keep the resulting platform motion within its operating envelope. The MDA filters have coefficients that can be used to tune the response of the VeMCS.

> Considerations in the tuning of the MDAs with a small-medium motion system
>
> The tuning parameters within the motion drive laws can be optimised for individual test manoeuvres. Failure to do this introduces the risk that adverse motion cues might reduce perceived fidelity below sufficiency level. Aspects that need to be considered in this tuning process include:
>
> a. Envelope of expected motion in a flight task about each axis in terms of accelerations and rates,
> b. Distinguish between primary and secondary motion/control axes; this supports optimising the distribution of MDA commands to platform 'legs',
> c. How might translational-rotational motion compensation be achieved to correct for adverse cueing in a task, e.g. roll-sway or pitch/surge,
> d. Define expected ranges of pilot 'gains' in the task. This can be useful in the tuning to optimise for medium gain levels (e.g. moderate level aggression),
> e. Ensure the matching of transport delays in the visual and vestibular motion systems.

Careful considerations of the MDA filter coefficients, the gains and break-frequencies, are needed to ensure the EP receives correct and sufficient vestibular cues for an ACR. The VeMCS should not provide any adverse cues as perceived by the EP. Ideally an MDA should use a high gain to provide sufficient onset cues, whilst also having a low phase shift to reduce adverse cues. Sinacori [28] proposed a set of predictive VeMCS fidelity levels using gain and phase criteria. Use of a high gain will result in more of the motion platform envelope being utilised, potentially reaching a limit, and will also require more motion washout, resulting in a larger phase shift between the flight-model output and the motion platform response, to return the platform to the platform's neutral position. The motion platform washout should occur at a level that is not 'intrusive' to the EP and that keeps the phase shift at an 'acceptable' level. More recently, the Objective Motion Cueing Test (OMCT) [11] has been proposed as a predictive fidelity metric. It compares the calculated motion response of a flight model (motion system input) to the actual movement of the VeMCS (output) as modified by the MDA. The MDA coefficients will need to be tuned for each motion platform DoF or combination of DoFs, according to the ACR, to provide sufficient positive cues to an EP. An example of a process that could be used to determine MDA filter coefficients is provided in [29] where it was shown that sufficient vestibular motion cues could be achieved by careful harmonisation of the 2 DoF motion filter gains for a roll-sway task, outside of the criteria defined by Sinacori.

6.2.9 Vibration Cueing Systems

Definition: Vibration cueing systems are any technology that provides proprioceptive, tactile and vestibular motion cues to the EP in the frequency and amplitude range associated with pilot seat vibrations.

Design Considerations: The motion frequency range that a VeMCS can produce is normally limited (0-10Hz in the heave axis and lower in the surge and sway axes [15]). High-frequency VeMCS motion can put additional unwanted loading on other FS features such as the VzMCS. To generate higher-frequency vestibular motion cues that may be associated with, e.g. retreating blade stall or vortex interactions in the translational lift phase, a separate Vibration Cueing system, e.g. in the form of a vibration seat or platform, could be included in the FS. The DoFs in the Vibration System will be dependent on the ACR.

6.3 Flight Simulator Verification

The codes, solutions and hardware of each FS feature must be verified during the FS development process, i.e. the construction, functionality and operation of each feature must be consistent with the requirements of the FS specified in Phase 1. Each feature will have inputs to/from other features in the FS, e.g. the FSM provides inputs to the VeMCS to generate vestibular motion cues, the ES and the Ground Reaction and Handling System both have inputs to the FSM to produce ground contact responses using height above terrain information. The applicant needs to demonstrate the requirements specified in Phase 1 have been correctly realised during the FS verification assessment.

6.3.1 Codes

The FS features will have associated computer codes which must be verified. The applicant should ensure that any codes that operate on an input correctly produce the expected output. This process identifies errors that might occur due to, for example, inconsistency of units used, rounding errors in calculations and definitions of axis reference systems. The applicant needs to demonstrate that they have an appropriate configuration management process (see Section 8) in place so that the effect of any updates to codes are verified before implementation into an FS feature. Codes are typically compiled into a real-time version and the data generated by the real-time version should be compared with the data generated by the source code to ensure they agree.

An example of the verification process is provided as follows. The FS requirements related to testing for an ACR might dictate the use of a motion platform to provide vestibular motion cueing for the EP. Outputs from the

FSM are inputs to the MDA, which in turn drives the motion platform actuators. A simulation model of the motion platform response to actuator demands could be independently developed and the response of the FS VeCMS compared for verification. This could be achieved by inputting step or sinusoidal signals into the MDA and comparing the response with the input demand. This approach has been proposed in the OMCT in [11].

6.3.2 Solutions

Most FS code is deterministic. However, with an FS having multiple interacting features, using different time clocks to produce solutions, this may result in non-deterministic behaviours, or behaviour that is very difficult to predict. A check is required to ensure that these solutions are as expected and permit execution in real-time.

For example, the ES provides height above terrain information to the FSM. Contact between the undercarriage component of the FSM and the terrain surface must be detected and then trigger a series of calculations to compute forces and moments on the undercarriage and the resulting vehicle motions. The output from the FSM is then transmitted to other features such as the VzMCS, VeMCS and the sound cueing systems. These complex interactions must be verified to produce consistent solutions, if these effects are required for the ACR being simulated.

Within a single feature, there may also be ‘variability’ in solutions based on inputs. For example, the graphics engine in the ES will require computation time to produce a solution following an input from the FSM, i.e. an update of the aircraft inertial position. The computation time, and the resulting framerate of the graphics signal produced, may vary based on the detail in the visual scene, for example, the number of polygons used to represent macro-textures, and the resolution of micro-textures. The framerate should be maintained above requirements defined in Phase 1 of the RCbS process, informed, for example, by values contained in documents such as CS-FSTD(H) [15].

6.3.3 Hardware

The construction and function of any FS feature hardware must be verified to match the requirement specification for that feature. This process may include the following:

1. Checking physical dimensions and movement ranges of inceptors against technical drawings,
2. Checking that ‘input’ functions of hardware devices drive the intended mechanical or computational response, e.g. a button press generates an on/off signal as required,
3. Checking that ‘output’ functions of hardware devices respond to commands as intended, such as speakers playing a sound, without unexpected distortion, at an appropriate volume.

Relevant delays that exist in the real-world system, e.g. pressure instrument lag, should be appropriately modelled in the FSM, or associated FS feature, and verified in the FS. The output from an FS feature such as the displacement of an EP’s inceptor, should be verified against the value received and used by the FSM FCS component.

If Phase 1 (FS requirements) specifies the use of a VeMCS for an ACR, its response to input commands should be verified. An example of this process is given in ICAO 9625 in the form of the OMCT [11]. The OMCT defines a matrix of translational and rotational inputs, of varying amplitude and frequency, to evaluate the ability of the VeMCS to reproduce these commands. The resulting platform motion can be verified using accelerometer measurements.

In case of an existing FS, part of the hardware verification can be derived from documentation from past activities assuming proper configuration management has been exercised.

6.4 FLIGHT SIMULATOR VALIDATION

The FS validation process is intended to ensure that the cues that the FS features generate are of sufficient fidelity to enable the EP to undertake an ACR realistically, i.e. effectively equivalent to flight. At its heart, the sufficiency assessment is, therefore, a comparison between task performance achieved and control strategy employed in the FS and the real aircraft. The validation process illustrated in Figure 6-1 is divided into three iterative steps:

1. Testing
    a. FS Test
    b. Flight/Ground Test
2. Fidelity Assessment
3. Tuning & Updating

The testing step is divided between flight/ground test of the aircraft, and testing using the FS. These steps can take place in parallel, but it is expected that they will be informed by a common strategy. The following sections will address each of these steps in more detail.

It is assumed at this stage that the FSM is sufficiently 'mature' to conduct FS validation. As mentioned previously, a prototype FSM can be used during the FS development. However, it is recognised that the validation processes may take place in parallel to some degree, and the FS development can also support the FSM validation process through subjective evaluation if FSM tuning/updating is required.

6.4.1 FS Test

FS testing is used to assess the features of the simulator and the cues that they produce to enable step 2 of the FS validation process, the fidelity assessment. It is expected that applicants will use a structured approach to planning a FS test campaign to design repeatable, performance-bounded tasks relevant to an ACR. This starts by defining the aim of the testing, descriptions of the manoeuvres to be flown, aircraft test configuration, and the data to be gathered. In Phase 1 of the RCbS process, objective and subjective metrics will have been defined to assess FS fidelity, which are then adopted in the FS test campaign.

A process for designing flying tasks is provided in ADS-33 [17], where performance requirements for Mission Task Elements (MTEs) are defined based on the role of the aircraft. It is suggested here that a similar approach is adopted to develop performance requirements for tasks associated with an ACR.

It is recommended that a FS test trial document is developed and reviewed by the test team prior to testing. It is suggested that, where possible, EPs are selected that have flight experience of the ACR and on the aircraft to be certified to provide 'informed' feedback during the validation process. It is expected that a trial briefing is completed prior to any testing so that it is clear to the test team what tasks will be flown and that any clarifications on test requirements are addressed, e.g. task performance, control strategy.

The task and aircraft configuration are controlled using the FS OS feature. During testing, the EP can be reminded of the task description and performance requirements prior to undertaking a test point. Feedback can be provided to the EP regarding the task performance achieved using data recorded by the OS. It is recommended that EP feedback is sought and recorded on all elements of the FS test campaign, in support of validation.

A subsequent de-brief session enables the test team to review the results of the tasks flown, the EP feedback including any ratings awarded, and to provide supporting data for use in the Credibility Assessment, Phase 3. A trial report should be produced to collate this information.

6.4.2 Flight/Ground Test

Data should be gathered from flight/ground testing, within the domain of validation, to support FS fidelity assessment. It is suggested that tests are designed to enable comparisons with FS testing, where it is safe to do so. The aircraft should be instrumented, as defined in the Requirements Specification, to provide data for both FSM and FS fidelity assessments; more information on the FTMS is provided in Section 7. Data for FS fidelity assessment could include measurements of control activity, or subjective handling qualities ratings for MTEs related to the ACR.

A similar process to that defined in Section 6.4.1 can be used for testing on the aircraft. However, the ground testing procedure may differ if a pilot is not required. For example, for some aircraft the mechanical characteristics of the flight controls can be validated via ground test measurements. However, for aircraft with changing mechanical characteristics over the flight envelope (e.g. due to force feedback through pitch-link rods), additional measurements during flight might be required.

6.4.3 Fidelity Assessment

The fidelity assessment process evaluates whether the FS fidelity is sufficient for the relevant ACRs and I-P Levels. It uses outputs from the FS and flight/ground testing to compare objective and subjective metrics. If fidelity of the FS is assessed as sufficient, then the applicant can proceed to the Credibility Assessment phase. If FS fidelity is lacking after assessment, then a 'tuning/updating' process should be undertaken to correct identified deficiencies for use in future iterations of the FS validation process.

The fidelity assessment process is informed by objective and subjective metrics and associated tolerance margins, defined in Phase 1 of the RCbS process. Unless deficiencies are encountered and tuning/updating of a specific FS feature is required (Section 6.4.4), the FS fidelity assessment, in principle, only considers the full aircraft and the interactions with the pilot. The related metrics fall into two categories:

1. Task performance
2. Task strategy

For objective measures, a comparison of the task performance achieved in flight and simulation cover parameters specified in the task definition for FS and flight/ground test. For example, the task developed for CS 29.62 Rejected take-off: Category A, may have performance requirements on the touchdown conditions of the aircraft, which can be directly compared between FS and FTMS data.

Task strategy can be quantified through analysis of the pilot's control activity. Biometric measures can also be used to inform such comparisons. For example, pilot control strategy can be quantified by computing control input displacement/rate using the so-called attack activity [30] or other time- and frequency-domain metrics [25]. Biometric measures may include head and eye tracking data, heart rate, or brain activity (electroencephalography), and an applicant would need to demonstrate that these measurements indicate sufficiency of the FS fidelity for an ACR in terms of comparative pilot compensation, FS vs FT.

Subjective methods should also be used during the fidelity assessment to capture the EP's experience. These methods rely on feedback from the EP on the sufficiency of the FS fidelity for an ACR. This feedback can be sought through, e.g., the use of subjective rating scales, such as the Cooper-Harper Handling Qualities Rating (HQR) scale [31], or the Bedford workload rating scale [32]. These scales allow an EP to assess the level of performance achieved and the associated compensation required (HQR scale) or the spare capacity for a task. Comparisons of such ratings, awarded in FT and FS testing, allow a fidelity assessment to be made. In addition, it is recommended that the SFR scale [23] is used in the fidelity assessment process as it was specifically developed to provide a framework for FS fidelity evaluations. Whilst the SFR scale was initially developed for application to training tasks, there is a direct read-across for RCbS. Use of the SFR scale addresses two aspects:

1. Comparisons between flight and simulation task performance, i.e. the precision with which a task is completed, and,
2. Task strategy adaptation, i.e. the degree to which the pilot is required to modify their behaviour (change the form of compensation) when transferring from simulator to flight and vice versa.

The robustness of the awarded SFR will depend on the pilot's ability to reflect on their task strategy and the achieved task performance. Therefore, the pilot must be proficient in both the vehicle and the task, and must also have operational currency so that a meaningful fidelity assessment can be made. Caution is advised during the fidelity assessment process, as a pilot can quickly adapt to FS deficiencies. Capturing this adaptation via pilot reflection needs to take this into account. A fidelity questionnaire is useful in the assessment process to identify any FS deficiencies.

6.4.4 FS Tuning/Updating

The source of any perceived FS fidelity deficiency needs to be unambiguously traced to the related FS feature to support FS tuning/updating. For example, the FS fidelity requirements defined in Phase 1 might dictate the use of a specific feature e.g. a VeMCS, and during the ACR fidelity assessment the EP might perceive false 'motion' cueing. This can arise due to VeMCS content deficiencies, e.g. in the motion filter gain and break frequency, but also due to deficiencies in the FSM or VzMCS. In some cases, subjective fidelity assessment of the related feature(s) can be conducted using an appropriate rating scale, such as a motion fidelity rating scale [33], to aid in identifying and correcting the feature content. It is recognised that tracing the source of FS fidelity deficiencies can be challenging, but this Guidance stresses the importance of facing such challenges purposefully.

The results of any tuning of the FSM would need to be assessed in the FSM development phase (2a) prior to re-evaluation in the FS fidelity assessment process.

6.5 Summary: Phase 2b

Summarising the activities in Phase 2b, development of the FS based on the (preliminary) Requirements Specification:

i. Prototype FSM supplied to the FS to support parallel activities,
ii. FS build, verification and validation and fidelity assessment,
iii. Draw on pre-certification flight test programme to support validation of the FS,
iv. Multiple iterative pathways managed and exercised as required throughout Phase 2b,
v. Updates to Requirements Specification based on Phase 2b activities,
vi. Outputs; FS validated for intended purpose, included in fidelity assessment reports

7 FLIGHT TEST MEASUREMENTS FOR FSM/FS DEVELOPMENT (PHASE 2c)

7.1 INTRODUCTION

Critical to the success in the validation process of both the FSM and FS is the quality of the flight test measurements used in the comparisons between reality and simulation. To set the scene, we recall a famous adage, of unknown origin (although something similar has been attributed to Albert Einstein), related to the development and validation of rotorcraft simulation models.

> *No-one believes the simulation result, except the person who created it,*
>
> *while everyone believes the flight test data except the person who measured it.*

The message here is that, while there will always be doubts about the fidelity of simulation, and while we expect flight test measurements to be the 'truth', those who have been closely involved in designing, building and using an FTMS, understand the meaning of the second part of the adage. They are aware of the significant number of pitfalls involved in the design and build of an FTMS, and they understand the importance of the care and attention to detail required to mitigate or avoid these pitfalls and to minimize measurement uncertainty.

The increased use of M&S in support of certification will require not only increases in FSM/FS fidelity but also a sustained emphasis on the quality of the test data used in pre-certification validation activity. Another important point to make is that the achievement of the envisaged levels of fidelity and credibility are likely to require in-flight measurements from the rotor systems, to support validation and understanding of physics-based model updates. To emphasise this point, it is no exaggeration to state that the lack of rotor measurements can sometimes make it very difficult, if not impossible, to determine the cause of flight behaviour poorly predicted by the FSM.

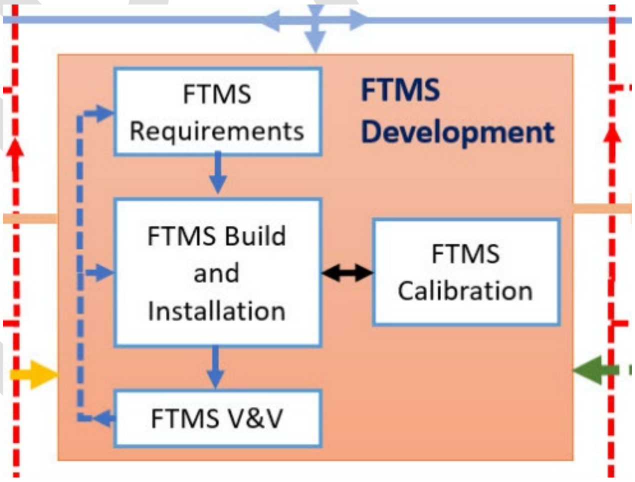

Figure 7-1: Phase 2c in the RCbS process; FTMS development

Figure 7-1 shows the sub-phase from Figure 2-1. Although requirements for the FTMS will have been developed in Phase 1, along with requirements for the FSM and FS, the inclusion of a Requirements 'box' within the FTMS development acknowledges the potential for some of these to be augmented once the on-board environment is quantified. In this Section, we describe some of the important issues to be addressed when designing, building, calibrating, installing and using a FTMS, including the extraction of data from the system and its use by the FSM/FS engineers. The five topics will be addressed separately, noting that at each stage, quality can be preserved or degraded through the decision making and practice of the FTMS engineers or shortcomings in the initial FTMS requirements specification. This Section ends with a discussion on the expected content of a pre-certification FTG, noting that the certification FTG will also be augmented by companion testing with the FSM and FS.

The V&V for the FTMS follows a similar process to the FS. In a general sense, the integrated H/W+S/W FTMS must be proven to meet the documented requirements (Verification) and must operate such that it provides the intended outputs (Validation), i.e. the requirements were correct. The calibration process (Section 7.4) is critical in this regard as it is where physical quantities of interest (e.g. accelerations, aerodynamic velocities, rotor flap motion) are sensed and converted into electronic information for comparison with a 'validated' benchmarks, e.g. instrumented inertial platform. The FTMS is the source of validation data for both the FSM and FS and S/W that converts raw measurements into the information required for the validation must pass thorough a V&V process.

7.2 FTMS Design

As emphasised for the creation of the FSM, the design specification of the FTMS should be based on requirements. The requirements must address the measurement functions, their precision, resolution and range, allowable levels of measurement and process noise, methods of calibration and installation, and the process of data capture; including sampling rates, synchronization, any relevant analogue-to-digital signal conversion, associated filtering and the interface of the FTMS with the crew and ground station. The design specification should also include requirements relating to the building of the FTMS. Measurement redundancy should be taken advantage of in the design of the system and associated data processing (e.g. velocities from air data, inertial data and satellite navigation data). The requirements set for a comprehensive rotorcraft FTMS will be extensive and need to be developed in close collaboration with the developers of the FSM itself. Depending on the FSM requirements set in Phase 1 and the validation activities foreseen, it may be necessary to include a model of the FTMS (a virtual prototype), as part of the FSM, featuring sensor locations, updateable calibrations and data processing. The same argument applies for embodying a prototype FSM within the FTMS development of course. A plan for verifying and validating the design should be included as part of the design (e.g. as in [34]).

7.3 FTMS Build

The requirements for the building of a FTMS should emphasise the integrated nature of the system, maintenance requirements and usability; and the purpose of the system, which will include the acquisition of data for use by flight simulation experts in model validation. The FTMS will be built as an integrated set of sub-systems; e.g. the air data, the inertial data, flight controls, rotor flap and lag dynamics, rotor loads, engine/transmission, satellite navigation and so on. There will likely be a requirement to include measurements used by any control augmentation system, e.g. stability, autopilot, load alleviation, as well as flight information available to the crew, e.g. presented by a glass-cockpit system, noting the challenges involved in accessing data from proprietary systems. The integration process should ensure that the FSM expert is presented with a coherent, consistent set of data, digitized to the same real time. A common clock for all sub-systems is normally required to ensure measurements can be related coherently but, even then, time shifts in sampling will result in time shifts in time histories. The maximum time shift between two time histories is likely to be related to the minimum sampling rate. For example, if blade flap and lag angles are required every 5° of rotor azimuth to capture dynamic stall effects, a sample rate of several hundred Hz will be required; the same for the tail rotor might increase by a factor of 5. In contrast, an adequate sampling rate for dynamic pressure, sideslip and incidence, normally measured on a boom attached to the front fuselage, might be 100 Hz or lower. The variable sampling rates mean it is important to consider the post-measurement data integration processing as part of the FTMS. The need for data in the 'rotating system' should be addressed in the design specification including how these are transmitted to the recording system (e.g. through slip-rings or radio transmission), and synchronised with non-rotating data.

7.4 CALIBRATION

Calibration requirements fall into two categories; off-board and on-board. For example, inertial measurement systems are commonly calibrated on an off-board motion table, while rotorblade flap angles usually require on-board calibration. If two different sources of calibration are available, it is advisable to compare the two, and quantify the levels and characteristics of the measurement and process noise present in the on-board data. This particularly applies to air data measurements using a boom. For example, a pitot-static and vane system can be calibrated in a wind tunnel for comparison with on-board calibration data. The latter can be derived from flights in still air involving tracking a ground pace vehicle, with the aircraft trimmed at various pitch/incidence and heading/sideslip angles. The wind-tunnel calibrations will need to take account of the process noise due to tunnel wall effects. The on-board system measurements will include the effects of rotor wake impingement on the boom, a source of process noise that is difficult to quantify. At some speed, the level of such process noise will be so large that confidence in the measurements becomes too low for use in validation. If low airspeed measurements, and related sideslip and incidence, are critical to the fidelity level required, then an appropriate sensor system must be used. Calibration of controls should consider the pathway from the pilot station, through the powered actuation system(s), the swashplate and control linkages to individual blade pitch angles; a set of measurements that may have different static and dynamic behaviours. Accurate measurement calibration is clearly critical to the successful use of a FSM in certification.

7.5 INSTALLATION

The locations and attachment methods used for the FTMS and its sub-systems are also important. For example, fuselage motion sensors are best located close to a nominal centre of mass, with translational motion sensors, e.g. accelerometers, isolated from translational vibration and the anti-nodes of structural bending, while rotational motion sensors, e.g. rate gyros, isolated from rotational vibration and the nodes of structural bending. Requirements for the installation of sensors that capture control motions and rotor system behaviour should address the acceptable levels of 'intrusion' to preserve the integrity of the measurements. The interfaces of the data capture system with the crew and ground stations are important for real-time monitoring and review of data quality, involving the installation of dedicated telemetry and cockpit display systems. These aspects are further considered in the next section.

7.6 USAGE, INCLUDING FLIGHT TESTING

The stage is set as they say; the FTMS design, build and calibration is complete and the system, having met the design requirements, is installed in the aircraft and on-board calibrations are completed. The productive part of the process now begins with the FTMS usage and FT campaign. As already emphasised, pre-certification flight trials to validate the FSM will take on a new level of importance as they gradually replace the certification trials themselves. The pre-certification flight test campaign will be defined in a comprehensive trial plan, including aircraft configurations to be tested, coverage of the flight envelope and, critically, crew instructions for the characterisation of aircraft behaviour in terms of trim, stability and response in defined weather conditions. The test campaign should involve close coordination with the development of the FSM and FS. Effectively, test points flown in the real aircraft can be pre-tested with the FSM, either offline or in a piloted simulation environment, as appropriate. Comparisons between the FSM and FT enable the identification of FSM flaws and the assessment of potential updates. This integration of the FT campaign with the FSM development can have a major impact on progress, but is so important, to the avoidance of nugatory testing on the one hand, and to facilitate efficient model-updating on the other, that it should be embraced as a fundamental aspect of pre-certification flight trials. The need, and scope, for innovation in this area is significant. In this respect, it is anticipated that a more detailed FTG will be developed in collaboration with certification agencies and applicants and included in a future release of these preliminary guidelines. In advance of this, the following sub-section discusses key aspects of the content of the FTG.

7.6.1 Pre-certification Flight Test Guide

As with all activities within the RCbS process, the pre-certification FTG must be based on, and reflect, the requirements of the FSM/FS validation and fidelity assessment processes. The close-coupling between requirements for the FTMS with those for the FSM and FS is reinforced within the content of the FTG and documented within the context of the DoV relevant to the ACR under consideration. For example, in the 4-dimensional matrix of design conditions for quantifying static and dynamic stability (airspeed, density altitude, c.g. location and aircraft mass), 70% might be selected for the DoV (30% in the DoE). Of these DoV points, 60% might be selected for CbS. With this plan, across the whole of the DoP (DoV + DoE), only 28% of points would be flight tested in Certification. In the pre-certification testing, a subset of such points might also be selected for fidelity assessment.

In support of FSM validation and fidelity assessment, linking with the content of Section 5, a typical set of test points at each flight condition/aircraft configuration might include:

a) Step/pulse control inputs to exercise the air data measurement system across its anticipated range of variation. This provides the core data for the so-called kinematic consistency analysis intended to ensure that air data system and inertial data system measurements of aircraft velocities form a consistent set. Any calibration error corrections derived from this analysis will need to be applied to data derived during sorties to capture data for fidelity metrics in the DoV.
b) Trims across the required ranges of incidence and sideslip to provide the core data for quantifying static stability or controllability in low speed manoeuvres.
c) Control frequency sweeps (one control axis in turn) that provide the core data for system identification analysis to create p-models for use in the fidelity assessment and updating of the FSM. Real-time, or post-run, analysis to check the coherency across the frequency of interest should be conducted and the sweeps repeated until input-output coherence, and hence the test data, meets the defined quality requirements.
d) Multi-step control inputs (one control at a time) to provide the core data, for example for frequency and damping of the lateral-directional oscillation to derive its stability characteristics using pedal control doublets. Another example might be related to the RTO, recording responses to collective and cyclic control in steep descent conditions. Data from, for example, 2311-type multi-steps can be used in the 'validation' of the p-models before they are used to support the FSM fidelity assessment.
e) Two repeats of test points for all the above are advisable to support the resolution of any anomalies.

In addition, flight test points in support of the FS validation and fidelity assessment will be required, linking with the content of Section 6. These could include:

f) Tests to exercise failure modes in cases where the expected severity level is 'minor', e.g. SCAS lane failures. In addition to capturing data for the FSM (response) fidelity assessment, such tests would enable the pilot to assess the various failure cues, including vestibular motion, in support of the FS fidelity assessment.

g) Mission-task-element testing to support the FS fidelity assessment for ACRs that involve task flying, e.g. CAT A rejected take off, controllability and manoeuvrability in cross-wind hover. Such examples could involve the use of the SFR scale to enable evaluation pilots to quantify the sufficiency of the FS cueing.

It is suggested that the FTG be written by the RCbS engineer in close collaboration with the evaluation pilot(s) and FTMS engineering team. Agreed criteria for test point quality and success/failure need to be defined and in-flight judgements and decisions made, based on such criteria. Evaluation team training in the application of (open-loop) test inputs can be conducted in the FS to ensure maximum data quality, e.g. duration and steadiness of trim prior to control input, input magnitude and shaping, input and response duration, criteria for recovery.

It is recognised that 'pre-certification' testing implies that additional flight and simulation testing will be required for the Certification process itself, conducted at the selected DoV points. Some of these points may be the same as those already flown in the pre-certification tests, while others will form the matrix of points 'within' which interpolation will be performed using the FSM/FS. The distribution of the pre-cert and cert points in the DoV will be established as discussed in the first paragraph to this sub-section and will be influenced by the Influence Level(s) selected for the ACR. The extent of the DoE will also be a factor in establishing the distribution of points in the DoV, since an understanding of the trends in fidelity and the extent of fidelity updating within the DoV will be factors in quantifying uncertainty and hence confidence in the DoE results.

The significance, and hence importance, of flight test data quality is highlighted here, recognising that the distribution of RCbS points across the DoP, although initially defined by the I-P matrix in Phase 1, will probably not be finalised until the fidelity assessment within the DoV is complete. The FTG should be written to accommodate this flexibility.

7.7 Summary: Phase 2c

To summarise, activities in Phase 2c, development of the FTMS based on the (preliminary) Requirements Specification, include:

i. FTMS design, build, calibration and installation,
ii. Alignment between FSM/FS validation needs and FTMS,
iii. Create the pre-certification Flight Test Guide,
iv. Execution of pre-certification ground and flight test programme to support validation of FSM,
v. Multiple iterative pathways managed and exercised as required throughout Phase 2c,
vi. Updates to Requirements Specification based on Phase 2c activities,
vii. Outputs; FTMS and validation test data for Phase 2a and 2b.

8 Credibility Assessment and Certification (Phase 3)

8.1 Introduction

With Phase 2 and the initial fidelity assessments of both the FSM and FS complete, the applicant moves into Phase 3, Credibility Assessment and Certification (Figure 8-1). Within this phase are the defining moments for the achievement of certification, so it is expected that Certification Authorities will be even more closely involved. Credibility addresses the complete set of RCbS results for the chosen ACRs across all I-P Levels (Table 3-2 and 3-4).

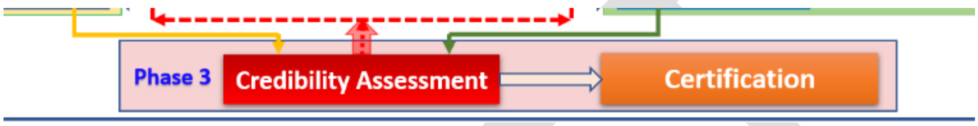

Figure 8-1: Entering Phase 3, Credibility Assessment and Certification

Demonstrating credibility within the DoV (using interpolation) is anticipated to be relatively straightforward, and rooted in the results of fidelity assessment and FSM/FS validation, including updating/tuning. In the DoV, the uncertainty analysis can give the model developer a scale to assess the fidelity, noting that when the comparison error is comparable with the uncertainty the model is within the precision achievable given the data and software available (see Section 5.3).

Results within the DoE, however, will need further evaluation in Phase 3 before the case for Certification can be sufficiently well evidenced and this Section discusses how such evidence may be presented.

Several general kinds of extrapolation can be considered. The first, typically in Predictability Levels 2 and 3 (Table 3-2), involves cases where the extrapolations consist of extensions of fidelity assessments made within the DoV, e.g. based on a validated model with proven physics-based updates. Extrapolating assessments made at low-altitude into the high-altitude regime could be an example here. Another might be the extrapolation of level flight dynamic stability to climbing/descending or turning flight. Three considerations are suggested to maximise confidence and the credibility of these kinds of extrapolations:

a) Develop an extrapolation from a sufficient number of points within the DoV,
b) Understand, through analysis, the physical sources of variation in predictions in the DoV (e.g. of performance margins or fidelity deficiencies),
c) Understand, through analysis, how these physical sources may change in the DoE and what other kinds of physical sources might need to be considered (e.g., dynamic stall).

The second kind of extrapolation, typically in predictability Level 4 (Table 3-2), involves cases where the ACR being considered is not supported by directly comparable results in the DoV, e.g. landing following total power loss. But even in such cases, there are likely to be fidelity analyses that can be drawn on from the DoV that inform fidelity assessment and credibility, e.g. results from autorotation flight tests conducted at altitude, including entry and recovery.

A third, and special, kind of extrapolation could relate to STC applications, e.g. hoist or external protuberance installations, maximum take-off weight extensions, or additional flight control modes for specialist operations, for which the compliance demonstration may in certain cases partly rely on similarity. While this Guidance does not feature examples or case studies in this category, it is envisaged that the proposed RCbS process will still need to be followed, and founded on the original certification process. Close collaboration with the OEM will be required to enable such STC applications. More generally, having established an RCbS basis for a rotorcraft, the application of the process for any such life-cycle developments by the OEM is likely to be very efficient.

For all kinds of extrapolation, applicants need to describe the location within the DoE, relative to the boundaries of the DoV and the DoP.

The credibility of the results from extrapolation can be informed by Uncertainty Analysis and Quantification (UAQ), a topic touched on briefly in Sections 3 and 5, and expanded on in this Section.

As with fidelity, the notion of sufficiency is also important for Credibility. To emphasise the point, at the RCbS process point reached by Phase 3, to achieve sufficient simulation Credibility, it is essential that;

1) A thorough verification and validation has been conducted to identify and address, to the extent possible, the various sources of simulation error that might influence prediction accuracy.

2) Fidelity within the DoV has been quantified and errors and uncertainties for the FSM/FS predictions and FTMS are characterised.

3) Extrapolations into the DoE are informed by the three considerations, a), b) and c) described above, as well as past-experience from the applicant regarding the evolution of simulation model error and uncertainty along the extrapolation dimension (if any).

4) The development and exploitation of the simulation framework has been performed by a team with the necessary expertise and experience following a controlled development process, akin to what is proposed in this Guidance.

The fourth point has already been highlighted on several occasions in this Guidance and its importance will feature strongly as the results of the Credibility Assessment are presented to the certification authority.

The various sources of test data error and simulation error addressed in the validation process have been discussed in Sections 5–7 of this Guidance. The current section deals with how believable the results of simulation are, their Credibility, along with the evidential basis, simulation uncertainty and its characterisation. As recommended throughout this Guidance, it is assumed that the applicant has employed physics-based modelling and updating for the FSM, exercised throughout the DoR.

It is important to re-emphasise at this point that the V&V processes within the FMS, FS and FTMS developments (Phase 2) are intended to ensure that, first, the three elements, the FMS, FS and FTMS, all meet their requirements defined in Phase 1 (verification) and, second, that the functions and operations within the three elements meet the fidelity requirements defined in Phase 1 (validation). In this way, applicants are expected to strengthen confidence in their ability to quantify uncertainty through the V&V and fidelity assessment processes, and hence credibility in predictions.

8.2 Simulation Credibility and Uncertainty

8.2.1 Simulation credibility assessment

In the current context, simulation credibility refers to the extent to which the predictions from the FSM or FS can be relied upon to assess the compliance of the aircraft to the selected ACRs, considering the potential uncertainties of the simulation. The essential elements of a credibility assessment have been enumerated above, and previously in Section 3. To re-iterate, the concept of simulation credibility is particularly (but not exclusively) relevant in a certification context where the DoP extends beyond the DoV into the DoE, a region where the simulation error cannot be fully assessed based on a comparison with test data, and so extrapolation is required, considering simulation uncertainty. Credibility in the DoE relies on the applicant's perception, ultimately shared by the certification authority, that they are addressing what are normally described as known-unknowns (as opposed to so-called unknown-unknowns), that inform and underpin the quantification of confidence.

While a generally accepted framework for flight simulation credibility assessment currently does not exist, numerous efforts have been made in various fields of science and engineering [10], [20], [35], [36], [37]. There is also an ASCE/ME Journal of Risk and Uncertainty in Engineering Systems dedicated to this topic, that would be expected to report up-to-date research relating to mechanical and civil engineering. It is emphasised that the Guidance herein does not advocate any particular method. What is important from a regulatory perspective is that the essential elements of simulation credibility assessment are adequately addressed by the applicant.

One of the essential elements expanded on here is the use of uncertainty analysis and quantification.

8.2.2 Uncertainty analysis and quantification

In [35], uncertainty quantification is expressed in terms of four elements;

a) *Identification (Where are the major sources of uncertainty?),*

b) *Characterization (What form are they, and what are their mathematical descriptions?),*

c) *Propagation and Aggregation (How do they combine to determine total uncertainty in the analysis results?), and*

d) *Analysis (What are their impacts and implications?)*

Reference [35] discusses these four elements in detail and makes an important point relevant to RCbS; *"Community-wide adoption of addressing analysis uncertainty using the structure of these four elements will facilitate clear communication between applicants, regulatory authorities and other industry stakeholders."* This Guidance therefore endorses this recommendation in pursuit of the same communication goal.

In Section 5, the three important elements of validation uncertainty were introduced: the uncertainties due to numerical errors u_{num}, those associated with experimental error u_r, and those due to uncertainty in the input parameters u_{inp}. Solution verification is the process by which u_{num} is estimated (see Section 5.3.4). Regarding flight test data, the experimental uncertainty should be determined within the FTMS development and calibrations. Uncertainty due to input parameters should be part of the data provided at the initial stages of RCbS from the design department, supplemented with expert insights on the type of modelling included in the FSM.

Typical FSM computational models make use of parameters that are quantified through specific experiments or in some cases inferred from design requirements and data. In principle, all these data should have uncertainties associated with them that could either be of an epistemic nature, with no knowledge of the probability distribution, or aleatory due to known random variations that exist from one aircraft or component to another or from time to time. In any case, given estimates of these data uncertainties, it is possible to estimate the effect on the output quantity of interest that is connected with u_{inp}. Two different types of approaches can be used to obtain such estimates:

a. Local linear analyses using, e.g., Taylor series expansions for the simulation result of interest to determine the (linear) sensitivity coefficient derived from the FSM. The input parameter uncertainty u_{Xi} must also be estimated. This approach leads to a local assessment, i.e. close to the values of the nominal parameters values.

b. A more general, global, statistical approach without assumptions of linearity, based on Monte Carlo or other similar stochastic methods. Typically, the required numerical effort is higher, and, as with sensitivity analysis, the input parameter uncertainty must be estimated a priori, in this case in the form of probability distributions. The numerical burden falls on the computer, of course, and it is the physical interpretation of the results that enables the user to draw meaningful conclusions.

Input parameter uncertainties can sometimes be estimated from prior experiments, and, for an input X_i, u_{Xi} may be characterised not only in terms of an interval (epistemic uncertainty), but also in terms of a statistical distribution. Lacking more detailed information, the simplest assumption is a uniform distribution, i.e., an interval within which all values are equally likely. The assumption of a Gaussian distribution requires the definition of a mean and standard deviation. Finally, rather than a specified uncertainty, one could assume the (conservative) worst-case parameter value, if indeed this limit can be justified (e.g., minimum specification engine power, or conservative control rigging). The concept of Conservatism is further discussed later in this Section. If statistical data are lacking, it is useful to seek expert opinions to gain, e.g. information on intervals. Even in their simplest forms, these approaches provide the applicant (and certification authority) with an understanding of the simulation output variability and primary parameters of influence which need to be characterised with a high degree of certainty.

It is worth noting that the input parameter uncertainty analyses described above also extend to the virtual pilot (see Section 5). In this case, the analyses may be used to explore the effects of the uncertainty in piloting strategy. The approach may be akin to a form of so-called ‘Abuse Case Testing’ in which deviations from the Rotorcraft Flight Manual specified procedures are deliberately introduced to verify the efficacy of the specified alternate procedures. In taking this route, the applicant must carefully consider the interrelationship between aircraft model input uncertainty and the uncertainty due to the virtual pilot model and its parameters.

For cases where the simulation is applied in the DoE, an assessment must be made on how the prediction errors and uncertainties from the DoV are expected to evolve along the extrapolation dimension. This assessment may be aided by, for example, access to historical (flight test and simulation) data, or comparisons with higher-order numerical prediction methods. The extrapolation limits specified in the FAA’s AC 29.45 [5] have been established based on historical flight test experience and contemporary analytical and simulation methods; e.g. “a predicted controllability model developed for high altitude may be used if verified by limited flight testing with steady ambient winds. The extrapolation guidelines in AC 29.45 b(2) are still applicable. These high-altitude controllability tests could typically be conducted in conjunction with take-off, landing and performance tests.” and “Controllability can usually be extrapolated up to a maximum of 2,000 feet above the highest test site altitude.” It is noted that the FAA refer to ‘verification by limited flight data’, using the term verification rather than validation as used in this Guidance. As required in the FAA/EASA standards, the present Guidance advocates that applicants exercise engineering judgement to evaluate whether the defined limits for extrapolation are applicable, particularly for novel aircraft configurations and advanced analytical and simulation techniques.

It is essential, for the assessment of simulation credibility, that the uncertainty throughout the prediction domain is adequately characterised. Within this context, it is useful to again make the distinction between aleatory and epistemic uncertainty. Epistemic uncertainty (EpU) is present in the simulation if there is a specific lack of knowledge, or shortcomings in understanding, about the physical processes being modelled. Included in this definition are model-form/structure uncertainties due to the approximate representation of reality, e.g., in the form of the rotor wake and interference modelling. In principle, epistemic uncertainties can be reduced by gathering additional test data or by using increased complexity, or higher-order, numerical tools such as Computation Fluid/Structural Dynamics to gain further insight into the physics being simulated. In the latter case, the knowledge gathered from the higher-order solution may, e.g., be used to reduce the uncertainty bounds on specific input parameters.

Aleatory uncertainty (AlU) is due to the (multiple) inherent variations in the physical system and its parameters and is probabilistic in nature. This type of uncertainty might include variations in aerofoil properties (due to manufacturing tolerances, erosion and repairs), vehicle moments of inertia, control riggings, atmospheric turbulence, etc. AIUs can be addressed in several ways, typically requiring many simulations to be run. In fact, this is a clear benefit from the use of the structured RCbS process to replace flight test, given that simulation provides an efficient means of evaluating a very large number of variations on a given scenario.

AIU can, in principle, be addressed in a probabilistic manner using Uncertainty Quantification (UQ) techniques [35]. This approach relies on the identification and characterisation of the sources of uncertainty in the modelling and aggregating and propagating these throughout the model to obtain output probability distributions. The benefits of this approach to UQ can only be fully realised when the capability to interpret such distributions, in the context of extrapolation, are well developed by the applicant.

Another approach to dealing with uncertainty (in an input parameter or at prediction level) can be described as conservatism. That is, by introducing conservative or worst-case assumptions and/or limitations in the FSM or FS cueing environment, leading e.g. to under-prediction of margins, or by imposing conservative limits of acceptability on the compliance parameters. In this case, it must be shown that the assumptions are indeed worst-case and/or that the effect of the assumptions are large enough to account for the prediction uncertainty. The problem with this approach is, of course, that it may lead to suboptimal, or unnecessarily reduced, aircraft performance if used excessively. Furthermore, it needs to be shown that the conservatism does not invalidate the physical modelling. That is, the conservative assumptions must be physically meaningful so that the simulation does not deviate from the DoR. The approach of dealing with uncertainty through conservative assumptions is not uncommon to the AMCs, as illustrated in AMC25.1309 11.e.4c, which states that “uncertainty should be accounted for in a way that does not compromise safety”.

8.2.3 Confidence ratio

Within the broader concept of simulation credibility, the predictive quality of the simulation hinges on the extent of both the simulation error and predictive uncertainty. Increasing the credibility of the prediction requires reducing both the error and the uncertainty, e.g. by FSM updating, or by reducing the uncertainties in the various input parameters.

The required level of credibility of the simulation prediction (initially estimated in Phase 1, see Section 3.2) is tied to the proximity to non-compliance, i.e. the margin between the prediction and the boundary of the performance requirement. Thus, the closer the case is to being non-compliant (small *M*), the lower the required uncertainty *U* of the simulation. As discussed in Sections 3 and 5, this dependency can be captured using the concept of the Confidence Ratio, *CR,* illustrated again in Figure 8-2, and generally defined in terms of the ratio of the ‘distance’ between the FSM prediction and the performance requirement, or the margin *M*, to the uncertainty *U* in the prediction.

$$CR = M/U \qquad (6)$$

So, as the uncertainty *U* increases, confidence reduces. A large *CR* implies either that the case is far from being non-compliant (large *M*), or that the combined uncertainties (*U*) in the simulation prediction are low compared to the distance to the performance requirement. In Figure 8-2 the ‘estimated experimental result’, and related (estimated) comparison/simulation prediction error δ_p, have been added for reference. The estimated experimental result in the DoE might be derived from extrapolation of the test data in the DoV. As discussed previously, this error, unknown in the DoE of course, should be embedded in the uncertainty *U*. The embedding can lead to increased or reduced *CR*, depending on whether the trend in the DoV was for under-prediction or over-prediction of the margin *M*. This will be returned to when discussing stability margins later in this Section.

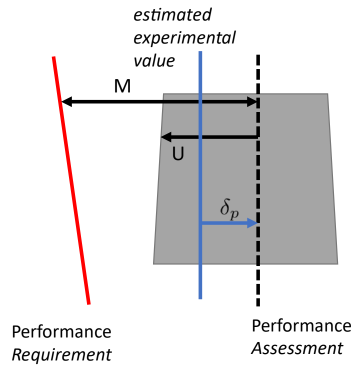

Figure 8-2 Schematic illustration of Confidence Ratio Parameters

The *CR* was first introduced in Section 3 since applicants must make their initial estimates of credibility and related uncertainties for the Requirements Specification. There, in Table 3-3 reproduced below as Table 8-1, the relationships between the *CR* and an applicant's confidence in the results of simulation for a specific ACR were suggested. In turn, how this confidence translates into the RCbS activity for particular ACRs was illustrated in Table 3-4. The case was speculative but reinforces the point already made that the closer the case is to being non-compliant, the higher should be the required confidence (i.e. the lower uncertainty), and therefore the credibility, in the conclusions drawn from simulation. Even if it may prove infeasible to define *CR* requirements that hold universally true, the concept does provide an intuitive normalized quantification of the confidence in the simulation predictions.

Table 8-1: Suggested Confidence Ratio (CR) ranges

1.0<CR<1.1	Low confidence (L)
1.1<*CR*<*1.25*	Medium confidence (M)
1.25<*CR*<*1.4*	High confidence (H)
1.4>*CR*	Very High confidence (VH)

To emphasise, the *CR* concept described above applies to those parameters for which a performance requirement, and therefore a margin, exists within the ACR, e.g., the control margin for a controllability assessment, or the damping of an oscillation for a dynamic stability assessment, and is particularly relevant, but not exclusively, to cases in the DoE. It is anticipated that requirements on the *CR* should be ACR-specific. Generally, a *CR* greater than unity is required to account for "unknown unknowns" not featured in the uncertainty quantification efforts and thus included in *U*. Finally, as extrapolation will increase the uncertainty in the predictions, this will automatically be reflected in a reduction of the CR for cases of extensive extrapolation.

An example is now presented to provide insight into how the *CR* might be used in practice.

ACR 29.143(c) (Controllability and Manoeuvrability) requires that the *"wind velocities from zero to at least 31 km/h (17 knots), from all azimuths, must be established in which the rotorcraft can be operated without loss of control on or near the ground in any manoeuvre appropriate to the type."* The applicant has proposed that simulation is used to compute the trim pedal margins up to the maximum take-off and landing altitude for the so-called critical azimuth. The safe margin (i.e. the performance limit) is defined by the red line in Figure 8-3 and has been established based on flight testing in the DoV, demonstrating that the indicated margin ensures adequate control authority. The applicant is seeking partial-credit for this ACR, limiting the use of simulation to the prediction of the control margin.

Figure 8-3 illustrates a possible set of results. The top two graphs present the outcome of the validation analysis in the DoV, expressed as a function of the intended extrapolation dimension (density altitude). The first graph plots the comparison between flight test and simulation with the uncertainty bars generally indicating an interval, or probability bounds, depending on the nature of the uncertainties. The uncertainty for the simulation predictions in the DoV, as plotted, reflects the sum of the numerical and input uncertainties. The associated model structure/form error δ_{model}, and validation uncertainty u_{val}, are plotted in the second graph. The third graph shows the result of linear extrapolation of the validation (or model form) uncertainty into the DoE. The fourth and final graph then presents the result of subsequent application of the extrapolated model form uncertainty to the total prediction uncertainty u_p as computed by the expression:

$$u_p = \left(\sqrt{u_{num}^2 + u_{inp}^2 + u_{model}^2}\right)_p \qquad (7)$$

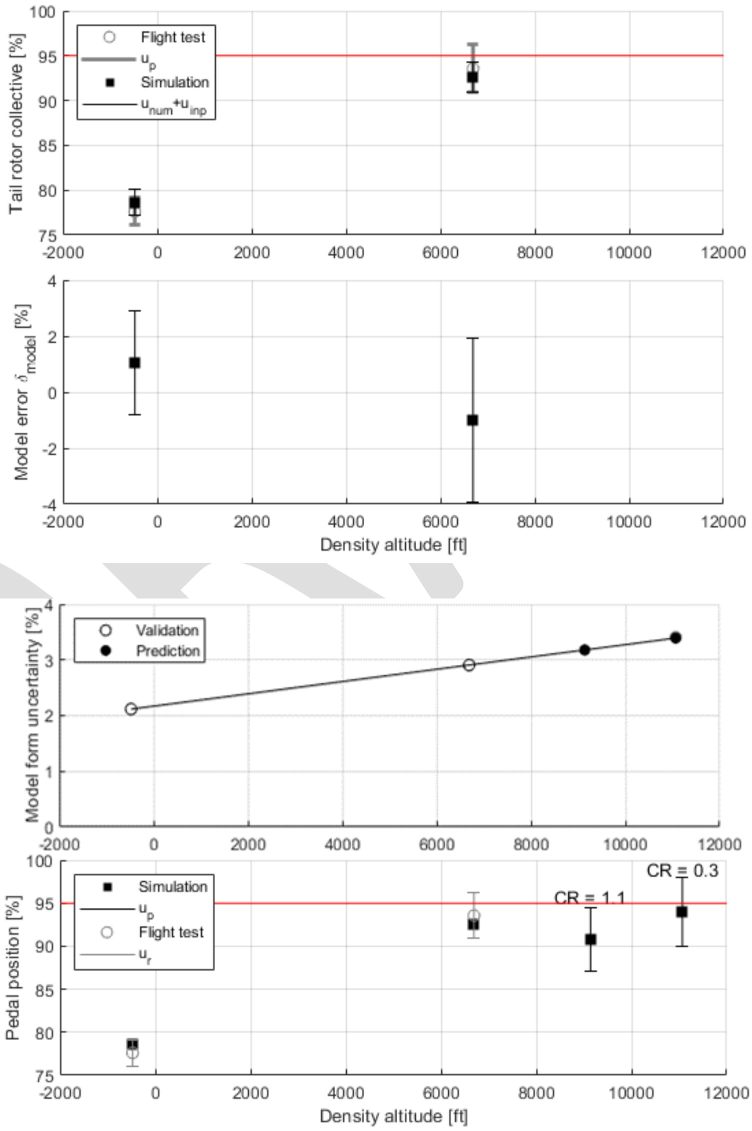

Figure 8-3: Example of CR analysis; pedal margin for critical azimuth test in the DoE

In this particular example, the simulation prediction clearly does not meet the minimum requirement of a *CR* greater than unity. At this point, the applicant is faced with the choice of accepting a take-off gross weight restriction, or improving the modelling and/or reducing the prediction uncertainty. That latter may be achieved by gathering additional flight test data to reduce the amount of extrapolation, updating the model form of the simulation, or by endeavouring to reduce the input uncertainties to which the prediction is most sensitive.

Note that the extrapolation of the model form uncertainty does not inherently result in increased uncertainty, though the data trends in that direction in this example.

8.3 Exploring DoV fidelity assessments extrapolated into the DoE

Test data define the boundaries of, and are scattered throughout, the DoV, but uncertainties prevail. Two such examples involving epistemic uncertainty are,

a) Using the metrics defined in Phase 1, the initial comparison between flight and simulation show insufficient fidelity at an ACR condition. A model update process is undertaken to reduce the mismatch to within tolerance; but there is no statistical information available on the input parameters exploited in the model updating.
b) Interpolation is used to derive fidelity at condition Y based on validation at conditions X and Z, where fidelity has been deemed sufficient. Uncertainty surrounds whether the (potentially different) model updates applicable at conditions X and Z, or some combination of both, will also be applicable at condition Y.

The potential for gaining insight into fidelity uncertainties is much greater in the DoV due to the multiple validation points analysed. A technique that has proved useful for the *analysis and characterisation* of epistemic uncertainty in fidelity assessment is described as ‘renovation’. First, stability and control derivatives (Section 5.2.3) predicted by the FSM are compared with those estimated from flight, e.g. using System Identification (SySID) techniques. Based on the comparisons, a subset of derivatives is selected that time and frequency domain response metrics are shown to be particularly sensitive to; the sensitivity being quantified by user-defined cost functions [38]. Delta derivatives can then be formed to augment the nonlinear FSM, and thence to improve fidelity. In a further step, an examination of the component (e.g., main rotor, fuselage, tail rotor, see Figure 5-2, Figure 5-3) breakdown of the predicted FSM stability and control derivatives can potentially provide the required insight into the physical sources of modelling errors. Through this process, judgements can be made on the sources of modelling deficiencies. In principle, if the renovation can be shown to be suitable also at extrapolated conditions within the DoE, it can be used to minimise simulation error as well. This process is exercised in the case studies in Section 10 but here an example is presented to assess the effectiveness of a renovation made at one flight condition, applied to another.

***8.3.1 Example scenario*, CS-29 requirements for dynamic stability.**

“CS 29.181 Dynamic stability: Category A rotorcraft; Any short period oscillation occurring at any speed from V_Y (best rate of climb speed*) to V_{NE}* (never exceed speed*) must be positively damped with the primary flight controls free and in a fixed position.”*

This ACR also applies for VFR flight, the requirement being that short-period oscillations should be stable. The standards set for IFR flight (CS 29, Appendix B) are more demanding and specify stability requirements in terms of damping ratio of an oscillation (see Figure 8-4). Figure 8-4, the boundaries for the various certification standards are shown on the frequency-damping chart, together with data points for the RoCS AW109 case study on Dynamic Stability (DS), expanded on in Section 10. For this example, the validation process at one (altitude-velocity) point (3000ft, 120kts) in the DoV revealed that the FSM prediction for the Lateral Directional Oscillation (LDO) was just outside the CS-27/29 boundary (x, TD F-AW109), while estimates from flight test showed the LDO to be just inside the certification boundary (*, TD FT DB Esti). A simple renovation determined that an FSM-update involving a 10% increase in the yaw damping derivative was sufficient to bring this fidelity metric (+, RF-AW109(3000ft)) into the sufficiency range, defined in this example as a 10% (blue-dashed) 'box' around the mean flight test point The figure also shows uncertainty boxes wrapped around the flight test and simulation test points, based on the varying computations of frequency and damping using different sections of the pedal doublet-induced yaw response test data[4]. In the case of the simulation data, this included data derived from different control input magnitudes.

Figure 8-4 also shows the FSM prediction (LF-AW109) for the 10000ft case, together with the renovation (RF-AW109) after application of the same 10% yaw damping improvement that was effective at the lower altitude. The applicant might argue that there were no significant differences in the flight characteristics (and hence FSM structure/form) at the two altitudes to justify a more extensive update, but they would, of course, need to offer explanations for the damping deficiency.

The data points discussed above are for the bare airframe, or SAS-off, configuration. As shown in the figure, there is a significant stability margin for the CS29 VFR ACR, and CS27 VFR ACR, for which there is no quantified stability requirement. However, uncertainties for the 3kft case would make IFR certification questionable, with such a small stability 'margin'. The data suggest that, at the higher altitude, the aircraft would fail the IFR certification. This is, of course, not untypical of helicopters without stability augmentation.

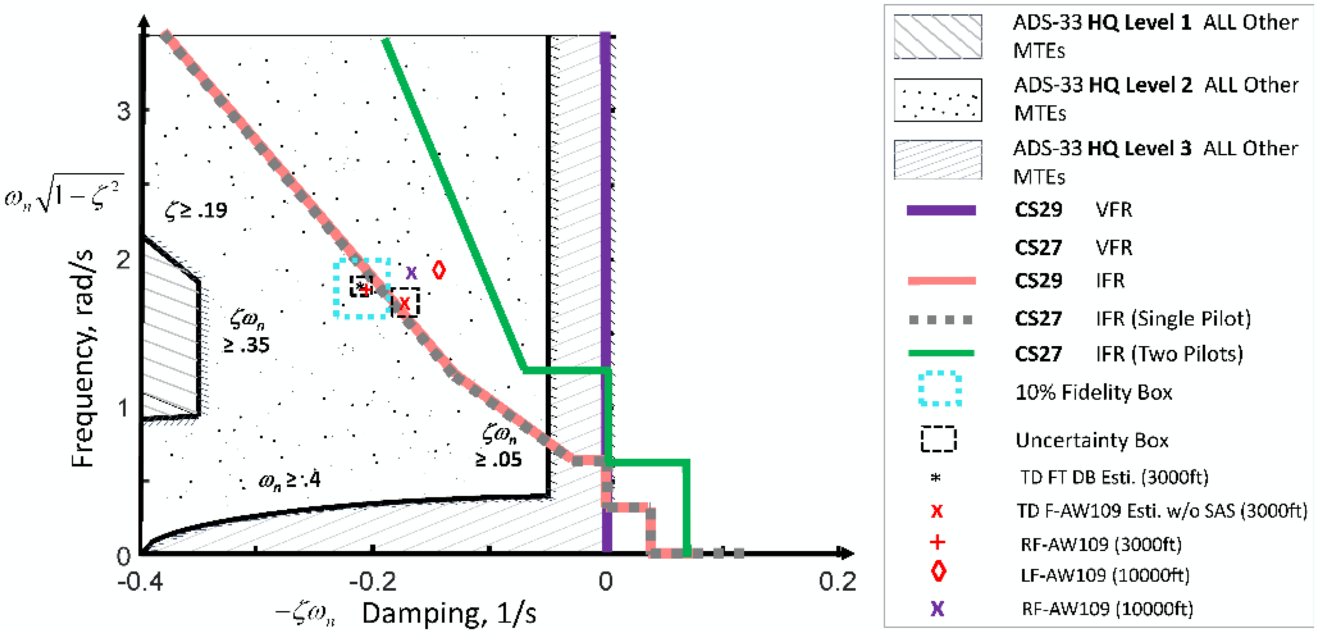

Figure 8-4: FSM renovation to achieve sufficient fidelity for dynamic stability at 120kts, with the corresponding DS boundaries; 3kft result compared with flight test, and 10kft result with extrapolated renovation

In the above case, the renovations, or updates, were made using a single 'delta' derivative, augmenting the nonlinear FSM yaw damping with a 10% increase in N_r. A plausible physical explanation for this is that the wind tunnel tests to derive fuselage and empennage forces did not capture the interference/blockage effects correctly, both statically and dynamically. In addition, there are uncertainties regarding the modelling of the blockage effects on the tail rotor in the FSM. Uncertainty analysis could include varying interference modelling

[4] In this example, the FSM and FT frequency-damping points for the 3kft case on the eigenchart were both derived from time-domain computations of the yaw response to pedal doublet inputs. In Section 10, the effectiveness of SysID techniques is explored to provide more extensive renovation.

parameters, within the DoR range, to explore sensitivities, coupled with additional CFD analysis to compare with the wind tunnel test data.

8.3.2 *Typical sources of FSM uncertainties*

Within the rotorcraft FSM, there are several sources of potential mismatch that have featured in the limited public-domain references on simulation fidelity. Table 8-2 describes these as the 'usual suspects', but the list is far from exhaustive and can be modified or added to as experience is gained with the application of the RCbS process.

Table 8-2: Some of the Usual Suspects contributing to mismatches between simulation and test

Usual Suspects	EpU or AIU	Issues and impact
Blade torsion dynamics	EpU	• Offsets between blade section cg, ac, tc give rise to couplings between flap, lag and (particularly) pitch/torsion • Cambered sections have pitching moment as function of velocity (dynamic pressure) as well as incidence and M, causing torsion dynamics even in steady flight • Change in 0/rev twist due to aerodynamic moment can require more or less collective in trim; impacts power • 2/rev Coriolis components in loads evidence for this effect
Aircraft inertias	EpU but treated as AIU	• Usually not measured so estimated from mass distributions; considered to be unreliable, particularly for old types where no digital data are available
Stick to blade calibrations	EpU but may vary from blade to blade and A/C to A/C so aspects of AIU also	• Calibrations usually made on the ground with auxiliary power unit (so actuation hydraulic pressure can be different from in-flight) • Feedback of rotor torsion aerodynamic loads through pitch-links to swashplate in flight will distort relationships
Delta3 Flap-pitch coupling	EpU	• Sometimes deliberately designed in (especially on tail rotor) but needs careful checking during calibration, so need flap measurements to be sure.
Wake decay and contraction	EpU	• One of the most challenging aeromechanics prediction problems • Typical finite-state dynamic wake model has several 'tuning' parameters to shape results but these need to be physically realistic • Major impact on interference effects
Hub retention – flap, lag and torsion	EpU	• Modelling an elastic blade with a rigid blade, the hub retention structure is very important and dominates the hub moment predictions • Validation with blade tip and hub moment measurements can reveal how accurate the rigid blade approximation can be
Fuselage blockage on tail, tail rotor and variations with incidence and sideslip	EpU	• Known to be a significant contribution to reducing dynamic stability in forward flight • Variations with sideslip and incidence significant and has a dynamic component (hysteretic) gives rise to strong nonlinearities
Radial distribution of rotor dynamic inflow	EpU but usually no measurements for validation	• Significant impact on performance since induced drag/power impacted by loss of bound circulation radially • Variations during manoeuvres can impact dynamic response, particularly off-axis (e.g. Manoeuvre Wake Distortion) • Strong impact in vortex ring state

Usual Suspects	EpU or AlU	Issues and impact
Measurements of V, α and β conversion to u, v and w	AlU and EpU	• Problem in low speed but also higher speeds • Impact of rotor wake can be significant and won't be captured in, e.g., wind tunnel calibrations • V, α and β vary at different points of the aircraft but usually measured at a single point, ahead of the nose on a boom
Kinematic consistency	EpU and AlU	• Crucial to undertake analysis to ensure that the measurements of re-constructed states u, v, w, p, q, r and θ, ϕ, ψ form a consistent set that satisfy the 6DoF equations • Scale factor and bias errors are common for accelerations, angular rates and air-data measurements and can vary from flight to flight
Main rotor wake interference on tail rotor	EpU	• Can have major impact on yaw control in low speed manoeuvres with certain wind azimuth conditions; difficult to predict correctly without some form of vortex wake model
Tail rotor vortex ring state (VRS)	EpU	• Evident with winds from port side (anti-clockwise main rotor); requires significant corrections to tail rotor dynamic inflow model to predict the adverse effects of VRS
Dynamic stall	EpU	• Can impact the performance and flight stability particularly for flight at high Mach number (forward speed, altitude) • Complex phenomena that triggers local unsteady rotor blade lift and pitching moment changes; stall characteristics quite different from quasi-steady stall and involve hysteresis
Yawed flow and reversed flow effects	EpU	• Complex nonlinear 3-dimensional effects that require aero data tables for sections that include large incidence and sideslip • Can lead to changes in aircraft flight behaviour at higher airspeeds

8.4 CONCLUDING REMARKS

This Guidance suggests that Credibility Assessment should be contained within the final Certification activity of the RCbS process. As such, the way results are presented to certification authorities needs to be documented in the PMP, the subject of the next Section. It is acknowledged that the initial publication of these guidelines is far from complete or comprehensive in this regard. As with other elements of the RCbS process, the guidelines emphasise early-adopter practice to be shared community-wide to maximise the capturing of lessons-learned as the guidelines evolve.

8.5 SUMMARY: PHASE 3

To summarise, activities in Phase 3, Credibility assessment and certification, include:

i. RCbS certification tests performed for relevant ACRs
ii. uncertainty characterisation undertaken throughout the domain of prediction,
iii. credibility analysis and assessments undertaken on the results of i. and ii.,
iv. results assembled and presented to certification authorities to make case for certification,
v. based on the feedback from Phases 2 and 3, the Requirements Specification is updated to constitute a formal element of the case for RCbS for the selected ACRs.
vi. Outputs; updated RCbS Requirements Specification and Type/Supplemental-Type Certificate documentation.

9 PROCESS DOCUMENTATION; THE PROJECT MANAGEMENT PLAN, CONTROLLED DEVELOPMENT AND CONFIGURATION & DATA MANAGEMENT

9.1 INTRODUCTION

This Section addresses what might be described as the administrative aspects of the RCbS process and application. Sometimes, and mistakenly, considered as 'second order' to the main development and creative activities, these aspects are, in this Guidance, put forward as equally critical to achieving success. Although there are currently no formal standards for the qualification of the tools and data of the RCbS process, this situation may change as the experience builds. In such a scenario, methods, data management, standards and practices adopted will need to be fully documented to establish an applicant's credibility, while providing evidence of such for certification authorities. This Guidance therefore recommends a fully transparent and comprehensive approach to developing the PMP, the controlled development of the FSM, FS and FTMS and the associated configuration/data management; described as Phase 0 of the RCbS process.

As highlighted in the Executive Summary, the Phase 0 development of the PMP should address, for each selected ACR,

i. Resources and timescales,
ii. Dependencies and constraints,
iii. Risks and mitigations,
iv. Process control, documentation, configuration and data management,
v. Preparation for documenting the RCbS certification case.

The first three bullets are standard in project management; as is the fourth, but because of the potential evolution of requirements and configurations in RCbS, perhaps has added importance. It should also satisfy the dual purpose of providing comprehensive documentation of the applicant's RCbS process, and how it is managed, for the benefit of both the applicant and the certification authority. The process control and materiel management will underpin any required 'qualification' of flight simulation models and flight simulators for use in RCbS. Applicants shall therefore formalise a controlled development and configuration/data management process, mirroring the phases described in this Guidance. This includes the systematic documentation of all relevant information necessary to enable the authority to understand the methodologies used, the underlying assumptions and limitations involved in Phase 2 developments, and to assess the validity of the simulation results and consequent credibility analysis in Phase 3.

The emphasis on creating a requirements-based framework for developing and validating, in parallel with pre-certification flight testing (Section 7), facilitates such a formalised approach. The requirements for the FSM and FS and their V&V, as well as a documented narrative on how the requirements have been met, or not, must be captured in a configuration/data management process.

The formal practice of (FSM/FS) configuration/data management facilitates appropriate representations with respect to the expected certification configuration(s), traceability of the results, and repeatability for future analyses and tests. The requirement for configuration/data management extends to the simulator hardware, even if generic subsystems are used (e.g. reconfigurable control loading system). Deviations from the expected certification configuration should be documented and justified. Records of the relevant information and data shall be retained as, e.g. Part 21.A.55 requirements [39].

Items to be addressed in the RCbS configuration/data management documentation are:

a) FSM/FS requirements specification, including how different variants are to be used and relate to one another
b) Data structures and related sources and uncertainties
c) V&V process and results, including model tuning/updating
d) Definition and rationale/justification for the four domains (DoV, DoP, DoE, DoR)
e) Problems relating to FSM and FS, e.g. configuration data and physics modelling
f) Interpolation, extrapolation and similarity
g) Experience and expertise being applied to RCbS by the applicant
h) Documentation and record keeping processes

Known problems, as referred to under e), would typically include deficiencies, process deviations and errors in definition or implementation of the FS & FSM. These problems and their impact and/or mitigation should be documented and communicated in dedicated Problem Reports.

As described in Sections 5 and 6, it is acknowledged that several versions of the FSM and FS are likely to be used in the RCbS process, addressing different Influence-Predictability combinations. It is recommended that a common framework for the different variants is used, that forms a core in the configuration management. The documentation of the V&V process includes details on the relevance and robustness of the selected metrics, and the model-updating methods that have been or will be applied. The overall documentation shall also include a description of the flight simulation model and the simulator hardware. As noted in Sections 5 and 6, the components of the model and simulator can be described in terms of the requirements that the component is serving, addressing functions, modes of operation, data structures, inputs and outputs, constraints and interfaces with other components.

The configuration/data management documentation covers a wide range of topics, in many ways mirroring the structure of this Guidance material. The early adopters of the use of M&S in support of certification will have the opportunity to shape the development of this approach, identify the critical issues, and highlight strengths and weaknesses of different methods.

9.2 Resourcing the RCbS Process

It is recognised that building a capability able to fully embrace virtual engineering in certification, as summarised in Figure 2-1, and expanded on throughout this guidance, will take time and dedicated resources. The emphasis on ‘dedicated’ is part of a recommendation of these guidelines, to ensure that sufficient time is allowed to grow capabilities without the constraints and pressures of current programs. The technical capabilities will include the disciplines of flight dynamics and control and associated multi-body dynamic modelling, aerodynamics/structural dynamics and associated numerical modelling, flight simulation and associated flight simulator technologies, system identification methods and applications, flight and wind tunnel testing and measurement techniques etc. Of course, these technical capabilities will exist in various depth levels within a modern rotorcraft industry and be applied throughout the life cycle of numerous ‘projects’ concurrently. A major challenge is to establish what is required to achieve ‘sufficient’ fidelity and credibility in the company’s flight simulation models, flight simulators and flight test measurement systems, to make a significant impact on certification costs, timescales and safety. Developing a profound understanding of what is meant by sufficient and credible, is part of this challenge.

Such a challenge can be approached by first applying the RCbS process at various I-P levels, and for specific ACRs, to existing, certified, products taking advantage of existing flight test databases. This would also provide opportunities to train new engineers in the exercising of the RCbS phases. In this way, the existing ‘operational’ capabilities can be drawn on, providing a framework for the RCbS process development; also extant capabilities can be improved as new methods, focused on the certification application, are developed. As the process matures to the point where it is applied to a new application, a question that might arise is ‘how deep should the RCbS capability be’? Because of the importance or the V&V processes in Phase 2, a strong argument could be made for at least duplex in each discipline. This would enable a progressive and independent checking of any analysis and the results of simulation. This duality would also extend to the simulation tools adopted in the process, e.g. CFD codes, flight models, SySID techniques. The dedicated RCbS team will also face a significant challenge when faced with using ‘existing’ flight test data, usually captured for unrelated purposes. It is suggested that dedicated test programs in support of RCbS capability development will also be required to ensure that validation and fidelity assessment processes can be productively exercised and refined.

Early applications are likely to be modest in their aims, but it is strongly recommended that the long-term aspiration to achieve the I-P full credit goals define the backbone of the capability development. We elaborate on these aspects later, in Section 11 of the Guidance.

10 GUIDANCE FOR SPECIFIC ACRS WITHIN THE CERTIFICATION SPECIFICATIONS

10.1 INTRODUCTION

10.2 CONTROLLABILITY AND MANOEUVRABILITY: LOW-SPEED

Applicable sections: §29.143(c-d)

…important to emphasise here the importance of hi-fi aerodynamics derived from, e.g. CFD results, in the FSM and challenges of how to turn these into real-time data-maps that provide the pilot with realistic effects in the FS

10.3 VFR/IFR DYNAMIC STABILITY

Applicable sections: §29.181, App. B §VI

…

10.4 CATEGORY A TAKE-OFF AND LANDING

Applicable sections: §29.49, §29.53-62, §29.67, §29.77-81, §29.85, §29.141(b), §29.143(e)

…

10.5 SAS FAILURES

Applicable sections: …

10.6 POWER-OFF LANDING

Applicable sections: …

11 WHAT NEXT? ROUTES TO THE ADOPTION OF RCbS

11.1 INTRODUCTION

Here, in this final Section of the Guidance, the RoCS team outline some potential routes forward, and how the first steps along these might be taken, for early adopters of the RCbS process. In Section 9, 'resourcing the process' was discussed and a key point was made that, "*early applications are likely to be modest in their aims,* *but it is strongly recommended that the long-term aspiration to achieve the I-P full credit goals define the backbone of the capability development*." This is reinforced here because, while there may be opportunities for short term success, the 'quick-wins' as they are sometimes described, the more extensive benefits from RCbS, the full vision, can only be realised by building a strong foundation and comprehensive framework as put forward in this Guidance. Any route forward must be safe (risks quantified and pitfalls avoidable), reliable (well defined with uncertainties quantified), ambitious (acknowledging the challenges) and ultimately affordable (clear returns on investment). Milestones along the route need to reflect growth in capability in harmony with success in application. The RoCS team stress these points in view of the strategic role that CbS will play during the evolution of virtual engineering within the aviation industry.

So, the Guidance advocates small steps in the pursuance of big goals, with examples described below.

11.2 What Next for Early Applications?

Some suggestions for early adopters of RCbS to pick up on are listed below.

a) Study and understand the RCbS process set out in this Guidance, particularly the value of the iterative pathways between phases,
b) Undertake a thorough assessment, a calibration/valuation, of your existing FSM/FS/FTMS capabilities, in terms of both models and facilities and human skills and experience; calibrations referred to above could relate to the use of both interpolation and extrapolation, and draw on existing test data,
c) Build capability around cases, by selecting ACRs that enable the full RCbS process to be exercised, albeit at reduced levels; include uncertainty quantification in this capability development,
d) As recommended in Section 9, apply the RCbS process at various I-P levels, and for specific ACRs, to existing, certified, products; exercising extrapolation in such cases could be particularly valuable, pinning the corners of the DoP using certified flight test points,
e) For any application (e.g. from c) or d)) assess carefully the levels of uncertainty of your M&S predictions to provide users of these results an indication of the credibility levels,
f) Consider the potential utility of flight test data for M&S validation purposes as a standard part of development/envelope expansion flight test preparation activities,
g) Scope out what a 'fully-operational' RCbS team might look like; how it might fit into the Company structure and how capabilities can be sustained for the long term,
h) Train your engineering team to develop and report certification-ready M&S results with a section in the report dedicated to evidence that support the credibility of the results,
i) Consider how your applications might need to comply with 'industry-wide' standards and the importance of knowledge-sharing in this context; the Guidance has been specific in its recommendation that early-adopters are pro-active in sharing good practice throughout the community,
j) Seek support from relevant certification authorities who also need to develop a deep understanding of the RCbS process,

In Section 9, we briefly touched on the types of skills and experience that would be required in a RoCS team. Technical capabilities will feature large, but other skills and experience will also be important. Individuals whose strength is in finishing a task, deciding when enough is enough, or writing the PMP, or designing/conducting the flight trials, won't be the same people who write the CFD codes or UQ algorithms or try to make sense of the results of validation or credibility. The RCbS team will have strength in breadth and depth, and to be fully effective, will need to operate as a team, across multiple disciplines and departments, with heightened awareness of important synergies and the need to adopt a systems-engineering discipline.

As these guidelines are being written, it is evident that they are being considered, wholly or in part, by others whose focus is not on the CS-27/29 requirements, including players in the emerging eVTOL industry. This is welcomed by the RoCS team, who are, in principle, available to advise on how the process might be adopted or adapted to these applications during the remaining tenure of the project (30th November 2023).

2023-03

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