PRELIMINARY GUIDELINES FOR A REQUIREMENTS-BASED APPROACH TO CERTIFICATION BY SIMULATION FOR ROTORCRAFT

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Abstract

The paper presents an introduction to the preliminary guidelines for rotorcraft certification by simulation developed by the partners of the Clean Sky 2 project Rotorcraft Certification by Simulation – RoCS . The guidelines are primarily aimed at 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). However, the guidelines are also applicable, in principle, to the certification of other types of rotorcraft, including tilt-rotors and e-VTOL configurations. A requirements-based approach is advocated and outlined, acknowledging the profound importance of assembling preliminary requirements, as complete as possible, before embarking on simulation development processes. The proposed approach 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, and therefore ACR-specific. The paper introduces the structure of the proposed Rotorcraft Certification by Simulation process, together with the main concepts that guide applicants to the development of simulations that can be effectively employed to reduce the cost, timescales, complexity and risks that may be associated with certification performed solely though flight tests.

1. INTRODUCTION

Airworthiness certification is the process of demonstrating that an aircraft type, or one component of it, can be safely maintained and operated throughout its approved flight envelope. Nowadays, for rotorcraft, to show compliance with CS-29/27, subparts B on flight and performance, it is necessary to undertake extensive flight test campaigns [1] [2].However, flight testing is costly, time consuming and can carry with it significant risk. Additionally, the limited repeatability, and the constraints in the ability to control the environmental conditions and the test scenarios, hampers both the efficiency and the effectiveness of flight testing for certification. As a matter of fact, the standards state that 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” [1] [2]. As in the US Federal Aviation Administration (FAA) Advisory Circular AC-29.21(a) [3], the term “calculation” includes flight simulation.

The opportunities offered by flight simulation to support design and training, making those processes more effective and reducing costs, are nowadays well-understood, even taken for granted. However, the additional opportunities offered by the extension of virtual engineering [4], or by digital-twins [5], as they are described, for certification purposes, are still in their infancy. Even the most sophisticated flight simulators cannot account for the infinite combination of variables that may be experienced in operational flight. However, it must be acknowledged that the state-of-the-art in flight modelling and simulation fidelity is continuously evolving. Therefore, whereas it cannot be expected that flight simulation will completely replace flight testing in the near term, there is great potential for flight simulation to become an efficient and very effective method to

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evaluate scenarios that are exceedingly costly, dangerous, or even impossible to test in flight.

Therefore, it is conceded that, under the right conditions, compliance demonstration can be carried out through flight simulation, yielding benefits in terms of cost, time and risk reduction. However, to deliver these benefits a concerted effort is required on the part of the applicant to develop, validate, and maintain a credible simulation environment that is of a fidelity suitable to 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 that, for various reasons, are not populated with test data, e.g. Applicable Certification Requirements (ACRs) associated with high-risk failure conditions, or areas of the envelope that require relocation to high-altitude test sites.

Similar ideas are pursued in other fields, such as the automotive industry, that is dealing with the problem of certifying autonomous vehicles [6]. In the specification for the approval of the automated driving system of fully automated vehicles, adopted by the European Parliament, Part 4 lays down the principle of Credibility assessment of models for certification [7].

1.1. Purpose and scope

The RoCS project is ambitious in its scope, with purposeful intent. Acknowledging that simulation has been already considered in a limited case-by-case basis to show compliance with rotorcraft certification specifications [8] [9], the requirements of simulation fidelity, both in terms of the physical characteristics of the flight vehicle and the overall fidelity perceived by the pilot, have yet to be investigated comprehensively in a coordinated effort.

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 [10]. In this case, 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 accurate and 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'. While much material is available on validation and verification for modelling and simulation (M&S) [11] [12] [13] [14], very little of it specifically addresses the usage of M&S for certification purposes. 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.

The Clean Sky 2 project RoCS, Rotorcraft Certification by Simulation, is exploring which are the appropriate methods and processes to be followed when flight simulation is used to support, augment or replace flight testing as an Acceptable Means of Compliance (AMC) for rotorcraft certification [15]. To reach this goal, a first draft guidance material has been produced (Ref. [16]) that has been released here for public consultation on the project website: www.rocs-project.org/guidelines/. The project RoCS is the result of a partnership between Politecnico di Milano, University of Liverpool, Cranfield University, NLR, DLR and Fondazione Politecnico, with Leonardo Helicopter Division acting as Topic Leader, and EASA in an advisory role.

The content of the draft Guidance 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 [17] and the parallel evolution of the Proposed Means of Compliance (MOC) with the Special Condition VTOL (MOC SC-VTOL) [18].

The Guidance is presented in the form of a structured 'Rotorcraft Certification by Simulation' (RCbS) 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.

The objective of this paper is summarising the main content of such guidance material and to present some very preliminary examples of application.

The Guidance [16] expands on the important concept of 'sufficiency', and the various 'domains' in which M&S is used. 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. 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 and demonstrating simulation Credibility. As such, the requirements for pre-certification testing become part of the process required to follow to perform RCbS.

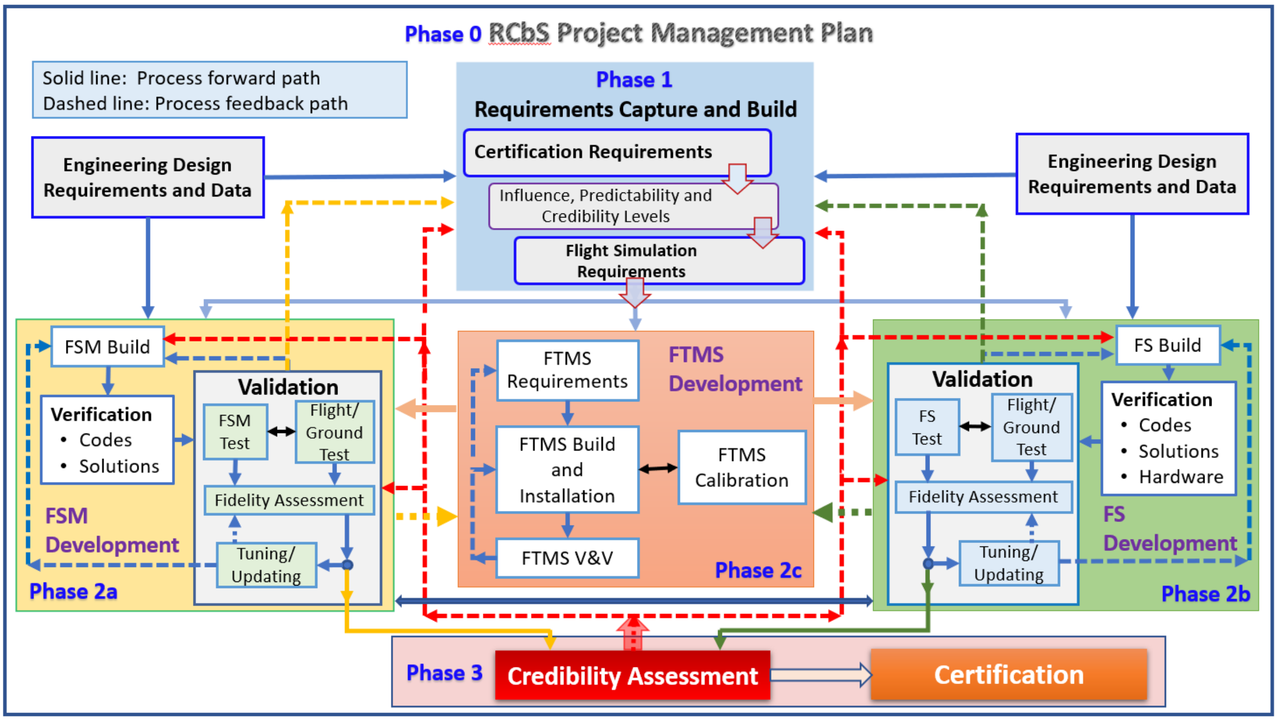


Figure 1 Overall structure of the Certification by Simulation Process. FSM (Flight Simulation Model), FTMS (Flight Test Measurement System, FS (Flight Simulator).

The RoCS Guidance [16] 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 in the Guidance 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.

2. STRUCTURE OF THE PROCESS

The proposed comprehensive and structured RCbS process is illustrated in Figure 1. 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 the 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 acts 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. 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 the validation and Credibility assessments.

It is recommended that, in the early adoption of this RCbS process, progress from one phase of the process to the next is 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.

3. PHASE 1 – REQUIREMENTS-CAPTURE

Before commencing the development of the RCbS process, it is necessary to understand the problem under consideration and determine the objectives of the analyses 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.

The requirements-capture phase is intended to ensure that the (complexity) content within the FSM, the FS and the FTMS is appropriate to achieve the essential fidelity requirements that are sufficient for application to certification. The concept of sufficient fidelity has two dimensions; a predictive dimension, quantified by metrics and associated tolerances and a perceived dimension, where, as appropriate, 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.

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 to be measured, and their associated accuracies, and analyses to be performed
d. Required qualitative information, such as pilot or test engineer commentary,
e. Flight test monitoring parameters and associated Do-Not-Exceed limits.

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 proposed 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.

3.1. The four domains

Using modelling and simulation to describe and predict flight behaviour, four domains are considered (Figure 2). These domains have to be defined in Phase 1. 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, the domain concept 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 and use these predictions to achieve certification at the defined Influence levels for an ACR.

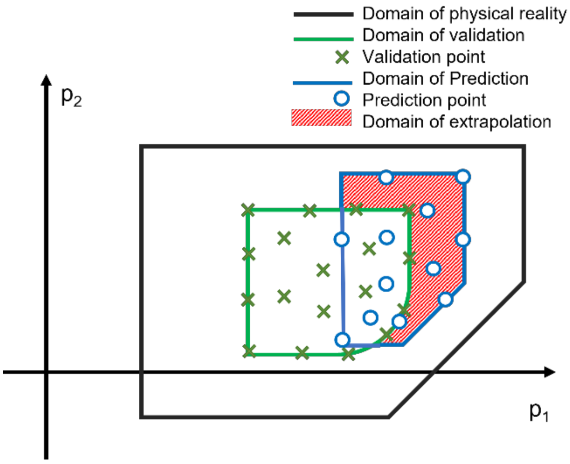


Figure 2 : Illustrating the Domains concept in RCbS

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. 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 model are still valid. For instance, 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 M&S, 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.

3.2. Influence, Predictability and Credibility

The 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. The 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 simulation, will then impact the level of effort required throughout the entire RCbS process, similar to the approach presented in [13].

The levels of Influence on certification decisions are described by the four options in Table 1.

Table 1 Influence levels for use in RCbS

Influence levels		**Description**
I	De-risking	The simulation is used to develop/familiarise with flight test procedures. No certification credit is obtained.
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.
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.

The outputs of RCbS are distributed throughout the DoP and may extend beyond the DoV into the DoE. This distribution is described in terms of the levels of Predictability, as illustrated in Table 2. The assigned Influence and Predictability levels influence the Credibility required of the simulation as discussed further in section 5.

Table 2 Predictability levels for use in RCbS

Predictability levels		**Description**
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 Means of Compliance (MoC) are of predictability level P2
P3	Limited interpolation in the DoV and extensive extrapolation in the DoE	When an extrapolation model can be built from validation data that do not fall in the P2 level
P4	Full extrapolation	All points used in simulated tests are outside the DoV and so no direct comparison of the complete FSM with flight test data is available, e.g. failure testing.

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, simulation 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 the FSM and FS.

Several factors will impact the simulation Credibility, or the requirements thereupon, including,

a. The Influence and Predictability levels.
b. The M&S capability of the applicant, documented in reports and papers, international recognition of subject-matter-experts.
c. Extent of previous experience with the prediction of the specific behaviours related to an ACR.
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 or from the results of M&S at various levels of complexity. Evolutions that feature strongly non-uniform or non-linear effects should attract detailed scrutiny to establish Credibility.
e. The confidence in the underpinning flight model tuning and updating methods used within the DoV and extended into the DoE.
f. 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.

Figure 4 illustrates the Confidence Ratio (CR) concept used in the RoCS Guidance [16] to quantify the Credibility assessment relating to the prediction of a 'margin' (e.g. control or performance margin). M is the margin, or the generalised 'distance', between the quantified performance requirement and the FSM prediction, i.e. the performance assessment. The CR is defined as the ratio between the margin and the uncertainty U:

$$\mathrm{CR} = \frac{\mathrm{M}}{\mathrm{U}}$$

Note that CR concept relates to the use of simulation for prediction (Phase 3), not validation (Phase 2), and is applied to the parameters of interest for which performance requirements exist or can be defined. For example, in the case of a control margin assessment, CRs may logically be computed for the pilot control positions. Performance requirements could also be defined for the body pitch and roll attitudes (ensuring adequate situational awareness). However, the CR concept says nothing about the interrelation between the parameters. For that, the assessment relies upon the Phase 2 validation performed within the DoV.

Credibility assessments are concerned with deriving, and ultimately ensuring the sufficiency of, the variety of margins related to an ACR, taking into account the level of uncertainty. A different threshold for the CR will be required depending on the Credibility necessitated of the model. In the above context, the CR concept only applies to situations and parameters where there is a defined performance requirement. 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.

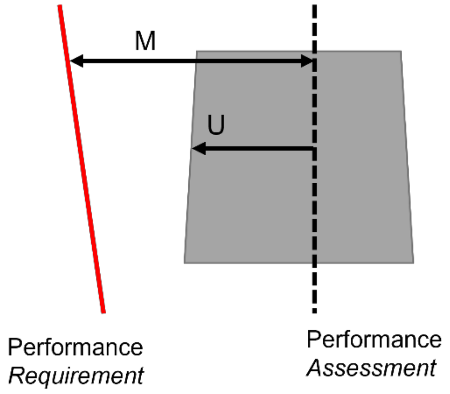


Figure 3 Conceptualisation of the confidence ratio

Using as input, information from the set of certification requirements, the relevant engineering design requirements and data, and outputs from the 'levelling' process 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 ground and flight test data required to support validation, and consequent fidelity and Credibility assessments.

4. PHASE 2 – SIMULATION DEVELOPMENT

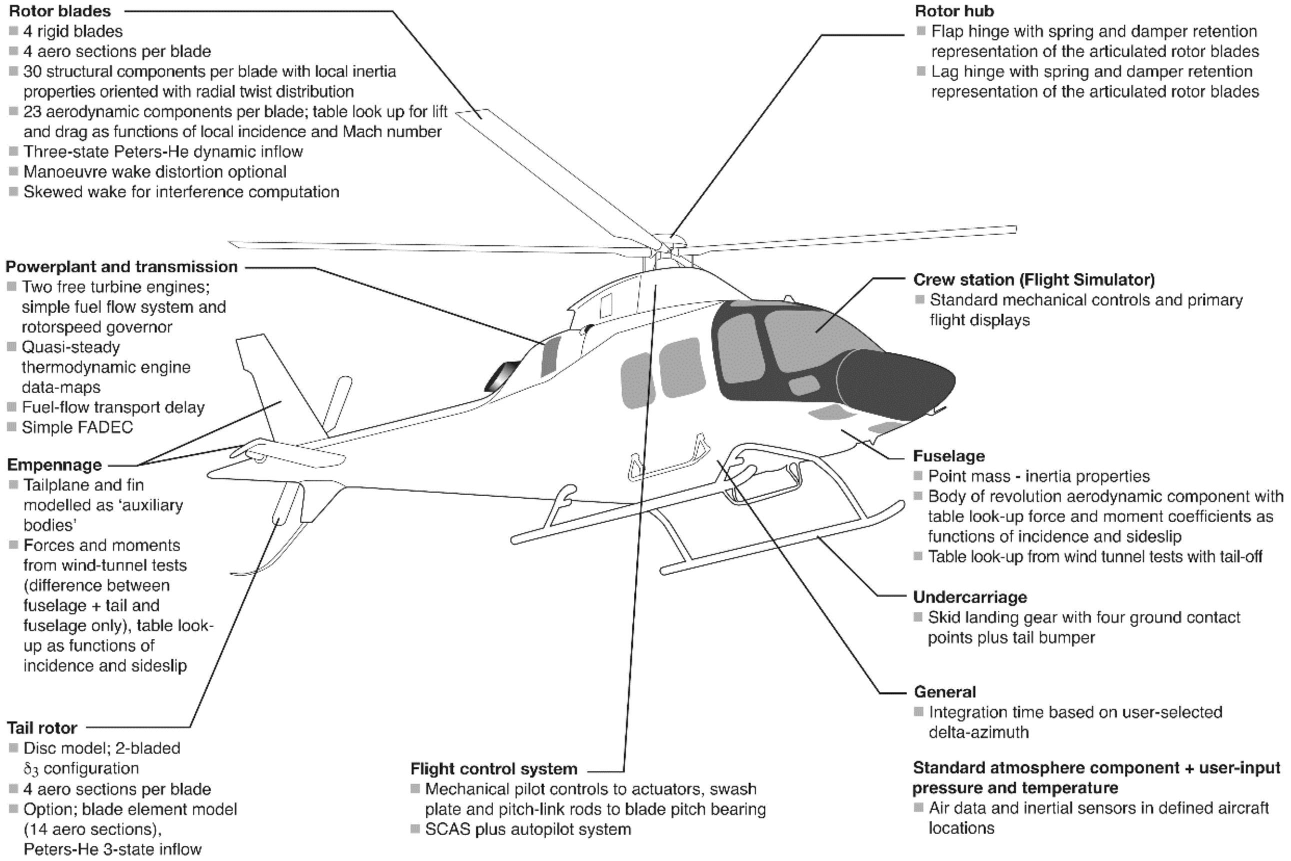
In the RCbS process, it is likely that a family of flight simulation models will be used, ranging from moderate to very high levels of complexity. The decision as to which will be used for an application will be driven by the requirements.

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 may be advantageous.

4.1. Flight Simulation Model

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 as defined by the ACRs. For a high level of confidence in the results, the FSM is applied within the DoV as a 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. 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 (e.g. stitched system-identified models [19] could be considered if P1 predictability level, i.e. interpolation only, is sought. However, for those cases, the identification of the associated domain of physical reality, and the assurance to not fall outside it, must be undertaken. This is, of course, the case for all FSM analysis, and 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.

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 4 shows components that may be used in a typical helicopter simulation model.



Rotor blades
- 4 rigid blades
- 4 aero sections per blade
- 30 structural components per blade with local inertia properties oriented with radial twist distribution
- 23 aerodynamic components per blade; table look up for lift and drag as functions of local incidence and Mach number
- Three-state Peters-He dynamic inflow
- Manoeuvre wake distortion optional
- Skewed wake for interference computation

Powerplant and transmission
- Two free turbine engines; simple fuel flow system and rotorspeed governor
- Quasi-steady thermodynamic engine data-maps
- Fuel-flow transport delay
- Simple FADEC

Empennage
- Tailplane and fin modelled as 'auxiliary bodies'
- Forces and moments from wind-tunnel tests (difference between fuselage + tail and fuselage only), table look-up as functions of incidence and sideslip

Tail rotor
- Disc model; 2-bladed δ_3 configuration
- 4 aero sections per blade
- Option; blade element model (14 aero sections), Peters-He 3-state inflow

Flight control system
- Mechanical pilot controls to actuators, swash plate and pitch-link rods to blade pitch bearing
- SCAS plus autopilot system

Rotor hub
- Flap hinge with spring and damper retention representation of the articulated rotor blades
- Lag hinge with spring and damper retention representation of the articulated rotor blades

Crew station (Flight Simulator)
- Standard mechanical controls and primary flight displays

Fuselage
- Point mass - inertia properties
- Body of revolution aerodynamic component with table look-up force and moment coefficients as functions of incidence and sideslip
- Table look-up from wind tunnel tests with tail-off

Undercarriage
- Skid landing gear with four ground contact points plus tail bumper

General
- Integration time based on user-selected delta-azimuth

Standard atmosphere component + user-input pressure and temperature
- Air data and inertial sensors in defined aircraft locations

Figure 4 Components in a typical rotorcraft FSM

The required fidelity, defined in the requirements specification defined in Phase 1 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 DoP. What exactly is 'sufficient' will depend on the application and it is the goal of [16] to, ultimately, provide guidance in this respect 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 particular configurations and applications.

The creation of a simulation in the generic sense may be represented through a triangular process where on one vertex represents 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 model of the system of interest, and on the third vertex is placed the computational model. In turn, each of these corner points and their interconnections is composed of several activities, as shown in Figure 5.

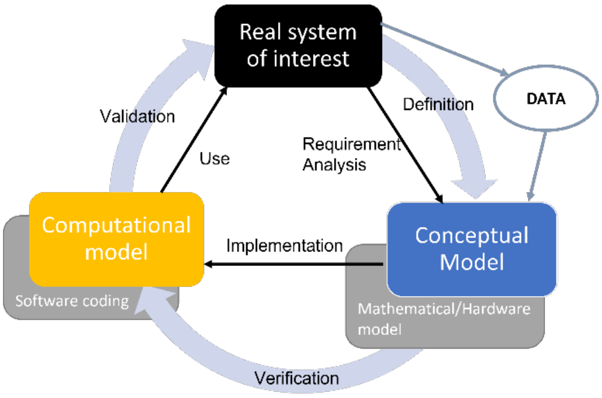


Figure 5 Generic process of creating a simulation model

For physics-based models, the assumptions that define the conceptual model focus on what physical phenomena will be included, how they will be approximated mathematically, 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.

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, 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, the next crucial steps will be the Verification and Validation (V&V) of the simulation. In the context of Figure 4, 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 the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended usage. 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 validated 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.

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. Validation at the lower levels is based on component-level experiments. In a general sense, rising up the tiers from components to the whole aircraft 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 the RoCS Guidance [16] 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. A systematic approach can also help in isolating the cause of unexpected or erroneous results and should prevent modelling errors or deficiencies from being masked.

Following a building-block ‘pyramid’ approach also helps to define the DoR of the aircraft, 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. 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.

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, i.e. meets the requirements.

Solution verification is performed after code verification with the primary objective of estimating the discretisation error of the FSM for a specific validation or prediction case. Through solution verification, it is the intention to assess the numerical uncertainty u_{num} of the model in the conditions being assessed.

Validation error and uncertainty In simulation Credibility and fidelity assessment, errors and uncertainties are quantified in the same units but analysed differently. Following the approach presented in [11], the validation or comparison error, δ_c, between test and simulation, is the difference between the simulation error δ_s, and the experimental error δ_r i.e. $\delta_c = |\delta_s - \delta_r|$. The simulation error is composed of three elements;

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

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

c) δ_{inp}, arising from errors in the input parameters of the FSM. These errors may relate to both epistemic and aleatoric uncertainties.

The comparison error δ_c can then be written in the form:

$$\delta_c = \delta_{model} + |\delta_{num} + \delta_{inp} - \delta_r|$$

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

$$\delta_{model} = \delta_c - |\delta_{num} + \delta_{inp} - \delta_r|$$

The absolute-value term is composed of terms that are of unknown magnitude and sign. Assuming the errors are effectively independent, the associated standard validation uncertainty u_{val} can be defined as:

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

The measurement (referent) uncertainty u_r is determined by the measurement set-up. The numerical uncertainty u_{num} is obtained from the solution verification process. Finally, the input uncertainty u_{inp} can be derived through uncertainty quantification methods as discussed in Section 5.

If the comparison error is significantly larger than the standard validation uncertainty, then the error due to modelling assumptions δ_{model} can be expected to be close to δ_c and so the model must be improved. Alternatively, when $|\delta_c| \leq u_{val}$, 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. At the same time, a comparison error significantly larger than the uncertainty will be an indicator that something that is relevant has been neglected, and so calls for a revision of the setup for the conceptual model used and the associated modelling assumptions. In this process, characterising the uncertainty of the validation measurements u_r is equally important as characterising the modelling uncertainties (see section 4.3). Uncertainty quantification is returned to in section 5.

Fidelity metrics 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:

- 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.
- 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.

- 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.
- 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.. The moderate-large amplitude response quickness metric from ADS-33 is an option for fidelity assessment in such cases [20].

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 Level for the ACR and agreed with the certification authority. In principle, '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.**

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 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. It is emphasised that 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. If a system-level phenomenological 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 [19].

4.2. Flight Simulator

An 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.

An FS is comprised of different features (Figure 5) 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" [21] and ICAO 9625 [22] for ten FS features. The FSM feature developed in Phase 2a (see Figure 1) 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 FS features, e.g., the flight control positions and forces.

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.

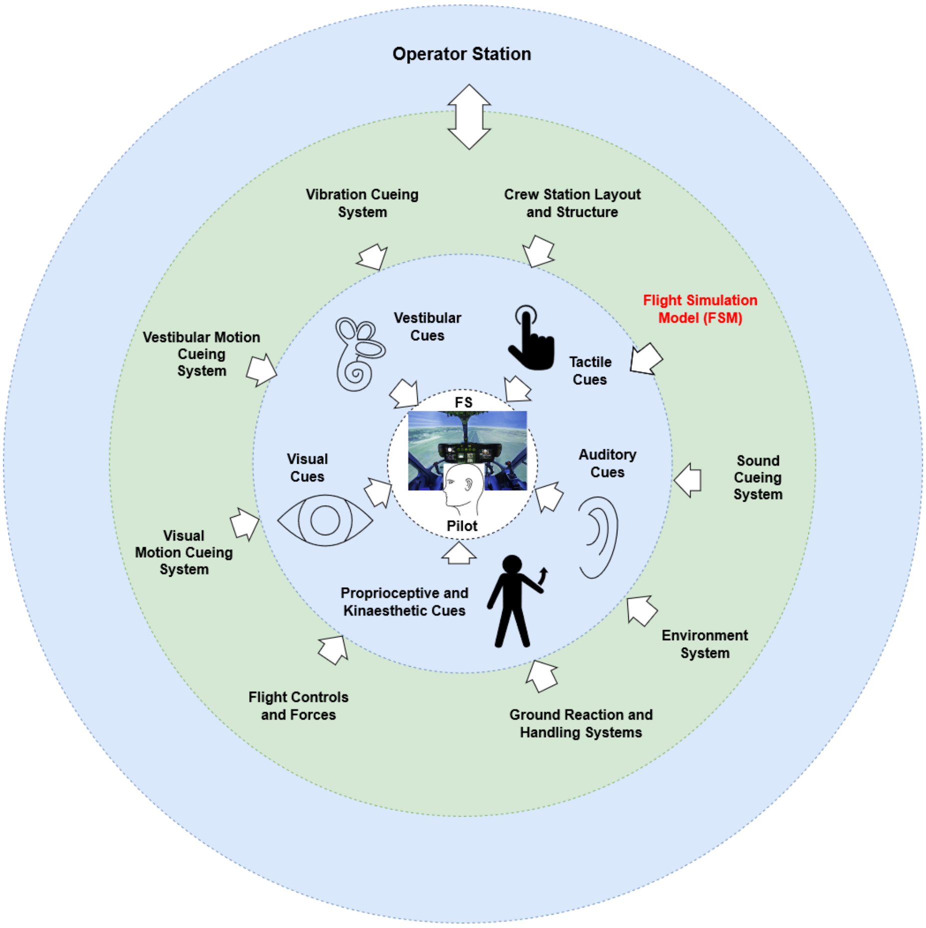


Figure 6 Schematic of Flight Simulator (FS) Features

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 definition and design consideration of each of the nine features is described in detail in the first draft of the guidance material [16]. As an example, the feature Visual Motion Cueing System (VzMCS) is outlined here:

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 (see Figure 1) 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, Virtual Reality (VR) systems have been certified for use in rotorcraft simulator training [23]. It is anticipated that suitable options for creating the OTW visuals using VR, augmented reality (AR) or mixed reality (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 generate the OTW cues (AR) and, possibly, a virtual cockpit (VR). In 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 and degradation of the image quality.

With AR/VR/MR devices, 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.

FS Verification and Validation 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.

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 FS validation process illustrated in Figure 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.

It is assumed at this stage that the FSM is sufficiently 'mature' to conduct FS validation. 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. 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.

4.3. Flight Test Measurement System

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. The increased use of M&S in support of certification will require not only increases in fidelity but also a sustained emphasis on the quality of the test data used in pre-certification validation activity. In this section are described 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.

FTMS design and build As emphasised for the creation of the FSM, the design specification of the FTMS should be based on requirements, addressing 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, synchronisation, 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 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, 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.

Calibration and installation. The calibration process is critical to V&V, as it is where physical quantities of interest (e.g. accelerations, aerodynamic velocities) are sensed and converted into electronic information for comparison with a 'validated' benchmarks, e.g. instrumented inertial platform. 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.

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. Rotational motion sensors, e.g. rate gyros, shall be 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.

Flight tests 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 for the different I-P levels, including aircraft configurations to be tested and coverage of the flight envelope. The test campaign should involve close coordination with the development of the FSM itself. Effectively, test points flown in the real aircraft can be pre-tested with the FSM (P1 level), either offline or in a piloted simulation environment, as appropriate. The integration of the flight test 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.

5. 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.

Results within the DoE, however, will need further evaluation in Phase 3 before the case for Certification can be sufficiently well evidenced.

Several general kinds of extrapolation can be considered. The first, typically in Predictability levels 2 and 3 (Table 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. Three considerations are suggested to maximise confidence and the Credibility of these kinds of extrapolations.

a. Develop an extrapolation from an appropriate 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 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. The three important elements of validation uncertainty were introduced in section 4: 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. The experimental uncertainty should be determined within the FTMS development and calibration. 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, e.g. those where more precise experimental procedures could be considered, or aleatoric due to random/unpredictable 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, in this case in the form of a probability distribution (which may be uniform if no other data is available).

The required level of Credibility of the simulation prediction (initially estimated in Phase 1) 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. This dependency can be captured using the concept of the Confidence Ratio, *CR,* illustrated in Figure 4, and generally defined in terms of the ratio of the 'distance' or margin *M* between the FSM prediction and the performance requirement, to the uncertainty *U* in the prediction. 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 uncertainties in the simulation (*U*) are low compared to the distance to the performance requirement.

The minimum requirement for the performance metric assessment is for positive confidence, i.e. *CR*>1. For added assurance, values of *CR* in higher ranges could be used, e.g. as shown in Table 3.

Table 3 Suggested 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)

Here, the uncertainty is reflected in the level of confidence an applicant will have in the FSM prediction of the margin; the smaller uncertainty reflecting a higher confidence level. It is emphasised that, at this stage in the Guidance development, the limits of these levels are purely illustrative and are not based on a rigorous assessment or theory.

Table 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)

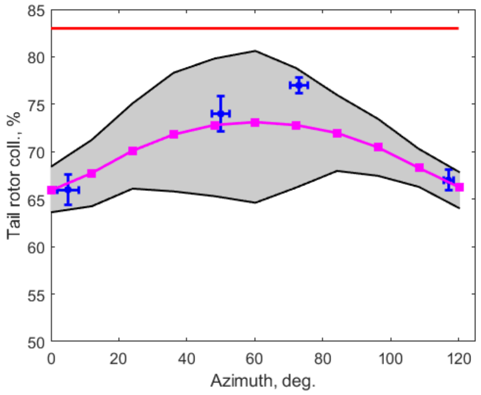
Bringing the *CR* metric into the I-P matrix allows for requirements to be set on the minimum levels of confidence in the predictive capability of the modelling and simulation. An example is shown in which the matrix is colour-coded with the levels of confidence suggested in Table 4. Once again, the 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.

Finally, a fictitious example is presented to provide insight into how the *CR* might be used in practice

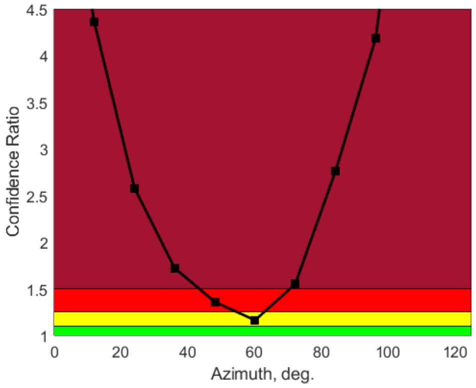
6. EXAMPLE; ACR 29.143(C) (CONTROLLABILITY AND MANOEUVRABILITY

CS-29 ACR 29.143(c) (Controllability and Manoeuvrability, Ref 2) 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 for the so-called critical azimuth. The applicant is seeking partial-credit for this ACR. There may be uncertainty about whether this margin will be sufficient to ensure operation without the risk of loss of control, as a predefined pedal margin does not necessarily ensure a certain amount of control power, in addition to the uncertainty concerning the prediction. However, the advantage of the RCbS approach could be exploited in this case by performing additional tests, with the pilot in the loop, and with the inclusion of appropriate perturbations to evaluate if the proposed margins provide the necessary control power.

Figure 7(a) and 7(b) illustrate a possible set of results. The prediction uncertainty band (grey area) has been derived from a fictitious sensitivity analysis. Similarly, fictitious flight data points are included in the figure, presumed to be gathered from tests on the pre-production aircraft during development. The blue crosses indicate uncertainty in the measurements of both azimuth and tail rotor collective (the uncertainty in wind speed is not shown, but implied). It is known that the test data are not fully representative of the aircraft being certified (e.g. mass, c.g. locations, atmospheric conditions), so strictly the certification case is in the DoE, in level I3-P2. Nevertheless, the applicant will draw some evidence from these results relating to the Credibility of the simulation.



(a) control margin



(b) confidence ratio

Figure 7 Example of CR analysis; pedal margin for critical azimuth test in the DoE

From Figure 7(a), the applicant considers that the maximum uncertainty will occur in a hover with starboard winds between 45-75°. Initial predictions of the FSM (magenta line) suggest a pedal margin of nearly 10% in this condition relative to the defined limit (red line). Model updating following validation uncertainty analysis has included augmenting the model with a higher fidelity representation of the main rotor wake – tail rotor interaction. The impact on the pedal margin depends on several parameters in the interference model, relating to the decay in strength of the main rotor tip vortices, and how this distorts the distribution of inflow at the tail rotor disc. While these parameters reflect EpUs, the lack of data led to the applicant conducting a sensitivity analysis to discover worst case scenarios. The uncertainty band in Figure 7(a) and, consequently, the CR variations in Figure 7(b), reflect these analyses as well as other sources of uncertainty. The combination of the test data and uncertainty analysis result in the applicant's CR reducing to about 1.2 at the critical condition. Whether this will be sufficient for certification is likely to be a subject of negotiation with the certification authority. Furthermore, the question of whether this margin (or the associated limit) is sufficient to retain controllability in conditions where there are atmospheric disturbances is likely to require piloted simulation to achieve resolution.

7. CONCLUDING REMARKS

The paper has presented a summary of the content of the preliminary *Guidelines for Certification by Simulation* developed within the RoCS project. The Guidelines have the ambition of providing a general framework to guide future applicants in the set-up of a simulation campaign for certification by simulation. Given the level of fidelity achieved by contemporary state-of-the-art simulation tools, a steep increase if foreseen in applications that will exploit, for partial or full credit, flight simulation as a mean of compliance. This prospect promises not only to make certification less costly, time-consuming and risky, but will open up the possibility to set up more systematic approaches to compliance demonstration, exploiting the greater repeatability and control that flight simulation offers. It is expected that the systematic approach outlined in the RoCS Guidance, if properly used, will allow a faster introduction of new technologies, contributing to the improvements in safety that the rotorcraft community has been seeking.

It is duly acknowledged that the RoCS Guidance in its current form is only a first step in this direction. Input from the rotorcraft community, and in particular early industry adopters of the RCbS process, is necessary to improve and consolidate the concepts (and thresholds) that are included in the first draft of the Guidance.

Following the public consultation period, a second edition of the Guidance, a formal output of the RoCS project, will be published, including examples of applications to specific ACRs. The consultation period is planned to be closed through a public workshop to be held at the 2022 European Rotors conference in Cologne, Germany.

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