CHALLENGES AND OPPORTUNITIES OFFERED BY FLIGHT CERTIFICATION OF ROTORCRAFT BY SIMULATION

Giuseppe Quaranta, giuseppe.quaranta@polimi.it, Politecnico di Milano (Italy)

Stefan van't Hoff, stefan.van.t.hoff@nlr.nl, NLR (The Netherland)

Michael Jones, Michael.jones@dlr.de, DLR (Germany)

Linghai Lu, linghai.lu@cranfield.ac.uk, Cranfield University (United Kingdom)

Mark White, mark.white@liverpool.ac.uk, University of Liverpool (United Kingdom)

Abstract
Newly developed aircraft must obtain a type certificate from the responsible aviation regulatory authority. This certificate testifies that the type of aircraft meets the safety requirements set by the authority. The compliance demonstration itself is the lengthiest and most expensive part of the certification process. The driving factor for the cost and duration of the compliance demonstration is the amount of ground and flight testing required. Moreover, certain certification flight test activities, particularly those involving demonstrations of control system or engine failures, can be classified as high-risk in terms of flight safety. The ROtorcraft Certification by Simulation (RoCS) project aims to explore the possibilities, limitations, and guidelines for best practices for the application of flight simulation to demonstrate compliance to the airworthiness regulations related to helicopters and tiltrotors. The paper presents the main objectives of the project and then introduces to some of the approaches that will be employed to achieve these goals.

1. INTRODUCTION

Certification is the process of demonstration that an aircraft type, or one component of it, is fit for purpose. In practice is the process where the aircraft is proven to meet requirements defined by relevant standard. This in turns will mean that the aircraft can be considered safe. The reduction in the scope of the test activities made possible by the exploitation of advanced analysis methods such as flight simulation, offers an immediate benefit in terms of the overall certification cost, schedule, and safety.

RoCS project is exploring in which conditions flight simulation could be used as a replacement for, or to complement, flight testing as a Means of Compliance (MoC) for rotorcraft certification. Rotorcraft certification relies heavily on flight testing for the substantiation of compliance with the regulatory requirements laid down in current certification standards (CS-29 for Large Rotorcraft [1], and CS-27 for Small Rotorcraft [2]) With the advent of increasingly high-fidelity flight simulation capabilities, the industry and certification authority have agreed on the application of simulation to complement or replace flight testing on a limited case-by-case basis [3, 4]. In addition, NLR has previously used (off-line) flight simulation for the national supplemental qualification of the NH90, for Category A (OEI One-Engine-Inoperative) operations [5]. These applications have shown the feasibility of rotorcraft certification by flight simulation. However, the requirements for 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 in a coordinated effort at a European level.

The capabilities of synthetic devices are nowadays considered suitable, and extensively used, as a tool for training and professional development of pilots, design of aircraft, and air accident investigation. Their usage for training is so well established that CS exist [6] for flight simulation training devices that define criteria for qualification. The potential of simulation to support flight testing has, for a long time, been recognised and sometimes exploited [7]. In fact, the certification guidance in AC25-7D [8] addresses the acceptable use of simulation in lieu of flight testing for the certification of flight aspects for fixed-wing aircraft. In this guidance the conditions under which simulation may be considered an acceptable means of compliance are defined as:

- Flight demonstration is too risky.

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

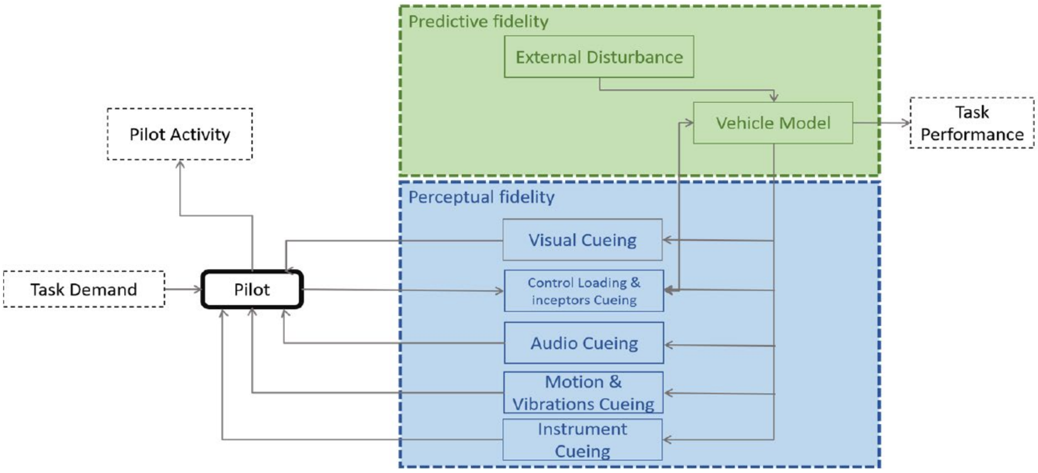

Figure 1 The flight model and simulator cueing systems as elements of the integrated flight simulation.

- Required environmental or aircraft conditions are too difficult to attain.
- Simulation is used to augment a reasonably broad flight test program.
- The objective is to demonstrate repeatability, or performance for a range of pilots.

More recently on the 23rd of July 2021, EASA within the process of development a Special Condition, i.e., a set of dedicated specifications, for the type certification basis for the Vertical Take-Off and Landing (VTOL) aircraft, published the proposed means of compliance with the Special Condition VTOL [9]. In this document "MOC 4 VTOL.2500(b) Certification credit for simulation and rig tests", is specifically dedicated to the description of the usage of "simulation bench" as pilot-in-the-loop simulator to demonstrate compliance.

It is reasonable to say that, even with the most sophisticate flight simulators available nowadays, it is not possible to account for the infinite combination of variables that may be experienced in operational flight. However, the same can be considered true for flight testing. In fact, flight testing is another form of 'simulation', whereby the compliance testing attempts to replicate scenarios which may be encountered in-service. It cannot be expected that flight simulation completely replaces flight testing for all rotorcraft certification regulations. However, there is a great possibility for flight simulators to become an efficient and powerful method to evaluate scenarios that are difficult or impossible to test without compromising safety. Of course, in addition to this the extension of simulated flight testing has the potential to significantly reduce the number of flight test hours required for the future certification of rotorcraft in Europe, i.e., a reduction of costs and time required for certification of new rotorcraft reducing the time-to-market of new vehicles binging a benefit to the society at large, with the faster introduction of greener, technologically advanced vehicles that will substitute the aging fleets of rotorcraft.

1.1. Main goals of RoCS project

The project started from the identification of a list of certification paragraphs from the appropriate regulations, suitable for compliance demonstration by flight simulation. For these topics, a set of guidelines that standardise the related simulation fidelity requirements will be finally generated. The continuous involvement of the certification authority in the definition of the guidelines will help acceptance by the authority, thereby facilitating the future practical application of the guidelines. Past experience [7] and certification guidance for fixed-wing aircraft [8] indicates that the elements that must be considered in terms of feasibility include: a) the availability of models able to adequately reflect the physics of the pilot-aircraft system in the specific condition under investigation; b) the availability of a sufficient set of test data (not necessarily including the exact conditions of interest) for validation and verification of the models; c) the availability of a flight simulator that can provide sufficient cues for test pilots to perform and evaluate the task under investigation.

For these reasons, the project is currently focusing on the main two branches of flight simulation, shown in Figure 1, a) the predictive fidelity, which defines the accuracy of the simulation model, composed by the vehicle model and the model of the external disturbances caused by the flight environment; b) the perceptual fidelity, which defines the realism of the integrated simulation experience composed by the different simulator subsystems dedicated to

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

providing cues to pilots. The methodologies defined will include the selection of the metrics to be used for model and cueing systems fidelity, defining an agreed set of metrics.

In parallel with the work that will be done on simulation models and metrics a new class of flight simulators will be developed. Flight simulators are traditionally defined for training, with a focus on the positive transfer generated on the trainee. The development of a flight simulator for certification purposes requires a change from this point of view, because for certification the models must be both high fidelity and physically representative of the aircraft, to ensure that the correct response of the actual aircraft will be simulated. This may also be outside of the Operative Flight Envelope (OFE), or the envelope tested during flight tests. In this situation, pilot cueing is important as far as it can trigger the correct behaviour of the pilots who are testing the capabilities of the vehicle to be certified. Consequently, a new product must be developed, that must be competitive in terms of acquisition and maintenance costs in comparison to flight tests, and affordable also by small companies, to be a driver for the development of new certified aircraft.

The guidelines and flight simulators developed within RoCS will be subsequently verified on the NextGen Tiltrotor that is under development within the Fast Rotorcraft Work Package of the Clean Sky 2 programme.

2. METHODOLOGY TO IDENTIFY POTENTIAL CANDIDATES FOR CERTIFICATION BY SIMULATION

Flight simulation fidelity assessment has been the topic of much research in recent years. Typically, this research has been in the context of flight simulation for training purposes. The application of flight simulation in lieu of flight testing for certification has historically been limited, with authorities limiting the application to cases where it can be accurately validated. To allow for an increased use of flight simulation for certification, a process has been determined to evaluate if and how simulation could potentially be used effectively and safely as a means of compliance for airworthiness specification requirements related to rotorcraft flight aspects. This includes a scoring process to identify the most promising candidate Certification by Simulation for Rotorcraft Flight Aspects (CSRFA) topics.

To select a candidate requirement for Certification by Simulation, the following three criteria have been considered:

- **Simulation Feasibility (SF)**: based on the needed simulation tool characteristics, identified simulation challenges (if any) and the type of (validation) data needed or desired. This considers the current state-of-the-art simulation methods that are used by research institutes.
- **Flight Test Risk Reduction (FTRR)**: based on the reduction in flight test risk that is obtained if, for that specific Demonstration Parameter, the simulation approach as proposed is adopted. The score definition is related to the risk classification of the original flight testing required for demonstration of compliance compared to the residual flight testing that is either required for compliance demonstration and/or validation.
- **Demonstration Cost Reduction (DCR)**: based on the cost reduction obtained when compared to the original situation where the simulation as proposed for that specific Demonstration Parameter is not used. Both the costs of setting up the simulation as well as the costs of any validation flight tests should be taken into account.

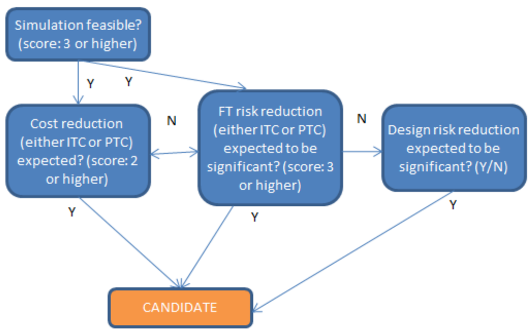

Figure 2 CS Candidate selection process.

These three criteria are independent. The SF criterion captures the ability to achieve the goal at the time the evaluation is performed The FTRR and DCR criteria capture the primary reasons behind stimulating the use of simulation tools for the reduction of compliance flight testing. It is noted that the scoring of these criteria necessarily requires assumptions to be made regarding the flight test approach, as well as the availability of flight test data and simulation tools at the applicant.

A fourth criterion was identified as well: **Design Risk Reduction (DRR)**. This criterion has not been considered in the scoring system, as it is not part of the compliance demonstration phase,

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

Table 1Score definition per criterion

Score	SF	FTRR	DCR
0			Simulation potentially and significantly more costly.
1	Key physical phenomena not captured in State-of-the-Art (SoA) simulation methods.	No reduction: flight test risk does not change	No (significant) change in sim / flight test costs
2	Simulation fidelity not expected to be sufficient with current SoA.	Risk reduction from Low to No Test, Medium to Low	Limited reduction: a subset of flight tests are still needed, high sim effort
3	Achieving the required simulation fidelity is technically challenging.	Risk reduction from High to Medium or Medium to No Test	Considerable reduction: a subset of flight tests are still needed, low sim effort
4	No major technical challenges foreseen to achieve adequate simulation fidelity.	Risk reduction from High to Low	High reduction: No flight test needed anymore, high sim effort
5	Capability already available and has been demonstrated before.	Risk reduction from High to no flight test	Maximum reduction: No flight test needed anymore, low sim effort

which is the scope of this research project. Moreover, design organizations already use simulation tools for design risk and cost reduction (impact of design choices to be made, sensitivity analyses, flight test preparation). The criterion is nevertheless evaluated for requirements that have a good score on SF but low scores on FTRR and DCR. This ensures that requirements that may not be so interesting from the point of view of cost or flight test risk reduction, might still be interesting from the point of view of reducing design risks, and, by extension, costly and/or lengthy design and certification iterations. For each criteria a score is defined according to the values and definitions reported in Table 1. Then the selection follows the process described in Figure 2. The process for the selection of candidates could be adapted to score DRR along with SF, FTRR and DCR, so that it has an additional role in determining interesting simulation candidates.

Following this approach, it has been decided to tackle these five most promising sections of the CS-27/29 [2] [1]:

1. Category A Rejected Take-Off (RTO)
2. Controllability & manoeuvrability: power-off landing
3. Controllability & manoeuvrability: 17 kts wind from all azimuths
4. AFCS/SAS failure recovery
5. IFR – Dynamic stability

3. PREDICTIVE FIDELITY

The comparison of results from predictive and perceptual assessments forms a key component of the overall fidelity assessment process. This is required to establish that the predicted and perceptual results are consistent; for the same reasons in the simulator as they are in flight and to understand better any differences. A flow diagram representing the process for the assessment of predicted and perceptual simulator fidelity is shown in Figure 4.

The process begins with a definition of the required purpose of the flight simulator, and hence the tasks that will be trained (Blocks 1-3 in Figure 4), which will set the required level of fidelity. Once the purpose of the simulator has been defined, testing using the simulator and the simulated aircraft can be conducted (Block 4). This leads to the assessment of the predicted fidelity (Block 5), using the chosen set of metrics. The results for each simulator component in the predicted fidelity stage can then be analysed to arrive at an overall level of predicted fidelity for a particular task. The results from these tests feed into the first decision point. The question is; *do the individual predictive fidelity metrics show a sufficiently good match between flight and simulation?* (Block 6). This stage highlights the quality of individual components of the simulation. Subject to a satisfactory result at this stage, further flight and simulator testing can be conducted to examine the perceptual fidelity of the simulation (Block 7). As with the predictive fidelity,

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

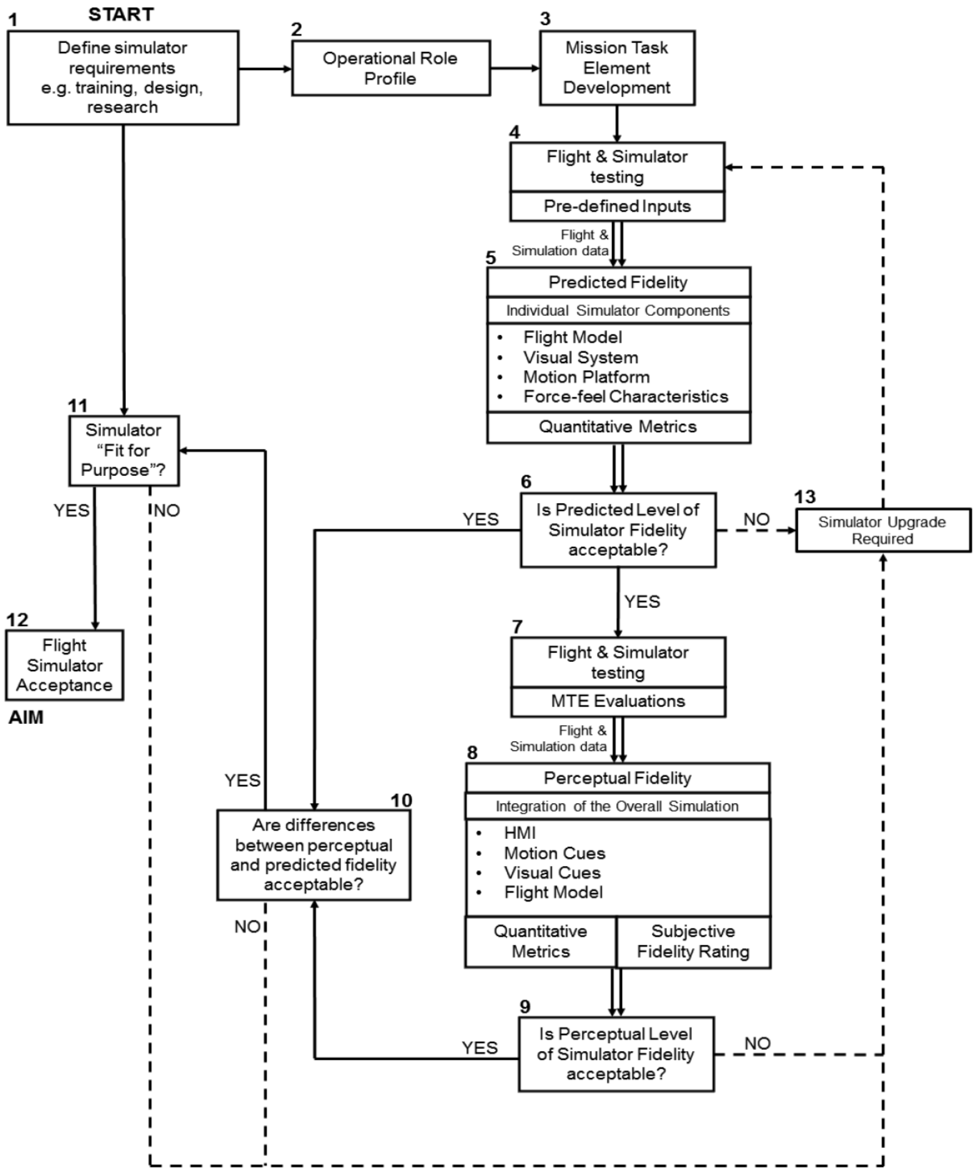

Figure 3 Methodology for integrated predicted and perceptual simulator fidelity assessment.

metrics are computed for each test point, in this case relying predominantly on subjective fidelity ratings, (Block 8), and a decision made as to the suitability of the resultant Level of perceptual fidelity for the intended purpose (Block 9). A third decision point addresses the acceptability of the comparison between predictive and perceptual fidelity (Block 10). This stage is analogous to the comparison between predictive and assigned HQs, as an assessment of the validity of the testing. If the test results are valid, it would be expected that the predictive level of fidelity for the simulator would agree with that from the perceptual assessment processes. In addition, the analysis at this point provides a further indicator as to the source of discrepancies between flight and simulation. For example, if the predictive metrics for the flight model show a good match, while the perceptual metrics do not, then the indication is that the fidelity issues lie within the generation of the task-dependent cues and not the flight model. If all questions (Blocks 6, 9 and 10) can be answered positively then a decision can be made that the simulator is fit for its designed purpose and can be accepted for service (Blocks 11 and 12). If, however, one of the fidelity requirements is not met, this would be an indicator that the simulator is not fit for purpose, and an upgrade, either to the cueing or the flight model or both, is required (Block 13). It should be recognised that a simulator may be fit for some purposes but not others and thus have limited fidelity.

3.1. Verification, validation and credibility of

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

models

When developing a numerical model to be used to take decision it is important to establish the credibility of the model used, i.e., how trustworthy are the simulation results. In this sense an essential phase of the model developed is that of Verification and Validation V&V.

Verification is the confirmation through objective evidence that a computational model accurately represents the underlying mathematical model and its solution. This means verify that the correct physical modelling is used, that the code reliability has been assessed together with its numerical accuracy.

The Validation is instead the confirmation through objective evidence that the model developed is an accurate representation of the real world at least for the intended uses of the model. In practice the validation always involves the comparison with experimental data and so it requires:

- The availability of flight data for whom the reliability has been assessed.
- The definition of objective metrics to obtain a quantifiable measure of the quality of the model

A detailed discussion of all the phases necessary to perform a complete V&V are beyond the scope of this paper but good information could be found in [10] [11] [12].

AC25-7D [8] states that the simulation should be suitably validated for the conditions of interest, where the level of substantiation of the simulator to flight correlation should be commensurate with the level of compliance. In other words, the closer the case is to be non-compliant, the higher the required fidelity of the simulation. Metrics to measure the fidelity are not defined. However, the selected metrics shall represent the distinguishing flight characteristics of the aircraft across the trim conditions and/or amplitude and frequency range of pilot control relevant for the simulation task. The legitimacy of the metrics and tolerances are to be substantiated by evidence, i.e., test data, and suitably documented.

In the approach followed by NASA in [10] the effort to be taken in the V&V phase depends on one side on the consequences of the decisions taken using the simulation data (in particular in terms of human safety), and on the other side on the influence of the data acquired from the simulation on the decision.

In the case of certification, the validation flight test data may not be available, or the data set may be incomplete. For instance, the available test data potentially does not cover the full certification flight envelope, is not available for a particular aircraft configuration, or is missing entirely because the conditions or manoeuvres have not been flight tested, e.g., for practical or flight safety reasons. Nevertheless, the selected fidelity metrics shall enable quantification of the credibility of the simulation based on dedicated or available flight test validation data to demonstrate that the simulation model is fit for purpose. This means that it is necessary to rely on physics-based simulation approaches in order to justify the application of the simulation outside of the validated envelope.

In this way it will be possible to establish the limits of validity of the computational model, knowing what has been physically modelled and what has been neglected, to ensure the model is applied within these limits defined by the assumptions, conditions and underlying data used to develop the model.

3.2. Metrics to assess the fidelity level for certification

Several flight simulation fidelity metrics that have been proposed in the past do enable the quantification of simulation accuracy relative to flight, but without providing a clear foundation, useful to define rationale tolerances. It is proposed herein that, in addition to generally applicable fidelity metrics such as those defined in ADS-33E [13], specific fidelity metrics are defined in direct relation to requirements in the paragraph of the certification standard that is being addressed. The acceptable tolerance on simulation error can then be directly related to the demonstration requirement. For instance, when considering controllability as per CS 29.143, the prediction tolerance on pilot control position may be defined as a function of the distance between the predicted control position and the minimum accepted control margin. In this way, the requirement on simulation fidelity is linked to the proximity to noncompliance. On the other hand, whereas for training simulator applications the aim is to achieve the highest level of fidelity, the application of simulation for certification compliance demonstration potentially allows for a lower level of fidelity to be accepted as long as conservativeness can be demonstrated.

Different predictive fidelity metrics have been considered in RoCS. The simulation to flight test error tolerances that form the basis of the Acceptable Means of Compliance of CS-FSTD(H) [6] have been considered. The context of flight simulation for training purposes is distinctly different from the application to certification but it may be of interest. The metric is based on tolerances applied to errors between simulation and flight for aircraft parameters that are of primary interest for a given scenario. tolerance-based flight simulation fidelity assessment adopted in CS-FSTD(H) has merits in terms of the intuitive implementation and the fact that the tolerances are tailored to specific flight conditions and manoeuvres. However, the rationale behind the different values is not always clear. The handling qualities section generally only considers small amplitudes and is based on trims, step control responses (w/o clear definition of the control input) and short-period stability tests in various conditions.

GARTEUR Action Group (AG) HC/AG-12 showed that the relationship between fidelity and the CS-FSTD(H) tolerances is sensitive to the nature of the manoeuvre being flown and, more significantly, that matching tolerances does not always lead to matching handling qualities [14]. They recommended the use of HQ metrics for fidelity assessment, see

The stability and agility criteria adopted in the predicted HQs section of ADS-33E-PRF to assess each region are:

1. Small amplitude, high frequency – bandwidth and phase delay.
2. Small amplitude, low to medium frequency – open-loop stability.
3. Moderate amplitudes – quickness.
4. Large amplitudes – maximum response.

A further set of HQ metrics is required that specify the required level of handling for the cross-coupled, off-axis responses, e.g. pitch response to roll control inputs (and vice versa) and the yaw response to collective control inputs. Additionally, for forward flight the magnitude of the pitch response to a collective input is assessed:

The comparison of these HQ metrics between flight and simulation provides an indication of the fidelity of the model as shown in [15] and [16]. An open question at this point in time is how closely the HQ metrics of the aircraft need to be matched in simulation in order for the simulation to be considered adequately representative for application in a certification context.

The frequency-domain envelopes defining Maximum Unnoticeable Added Dynamics (MUAD), first developed in the 1980s, define regions of acceptable levels of mismatch between a flight simulation and the real aircraft in terms of magnitude and phase of the simulation error response based on the pilot's ability to perceive the difference in the dynamics [17]. The MUAD envelopes were originally defined for fixed-wing but have since found application in the field of rotorcraft and tiltrotor simulation, typically in the realm of flight dynamics simulation [18]. In most cases, the envelopes are adopted without rigorous verification of their suitability for the intended application. However, research by Mitchell et al [19], in which the method was applied to a helicopter in hover, revealed that the envelopes were too stringent for this application due to the higher bandwidth of the baseline aircraft, while the envelopes were not stringent enough at lower frequencies. In the context of certification by simulation, there are three main deficiencies to the concept of unnoticeable dynamics; 1) there are no universal unnoticeable dynamics envelopes that are proven to be applicable to all rotorcraft, piloting tasks and simulation facilities, 2) similar to other metrics discussed herein the concept only reflects the simulation fidelity in terms of aircraft dynamics, providing no validation of other physical parameters, and 3) system identification validation flight test data that is required for evaluation may not be easy to obtain in critical parts of the flight envelope (e.g. at VNE).

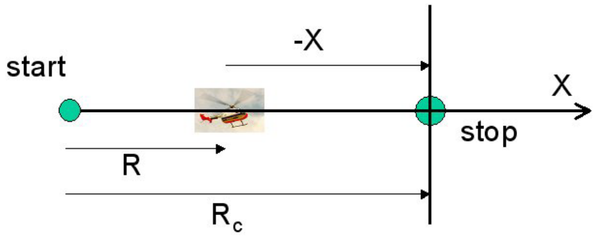

Figure 4 Illustration of accel-decel manoeuvre logic.

The Adaptive Pilot Model (APM) methodology has been developed in the context of training flight simulators to quantify overall simulation fidelity based on an analysis of pilot visual guidance strategy [20]. The general hypothesis behind the APM approach follows from earlier representations [21], whereby, in flying a manoeuvre, the pilot acts to transform the coupled aircraft-pilot system to a simple relationship between command and output. In the acceleration-deceleration manoeuvre, for example, the pilot initiates the manoeuvre from a hover in response to the command Rc and finishes in a new hover when the error (Rc-R) is reduced to zero (Figure 4). The distance to stop is defined as -X. Figure 5 shows the corresponding closed-loop control scheme, where θc is the commanded pitch attitude and θ is the current pitch attitude. By applying several simplifying assumptions, the vehicle-pilot model can be reduced to extract, e.g., pilot gains, and the frequencies and damping of the closed-loop dynamics. The comparison of the identified parameters between flight test and simulation

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

provides a means to quantify and assess the

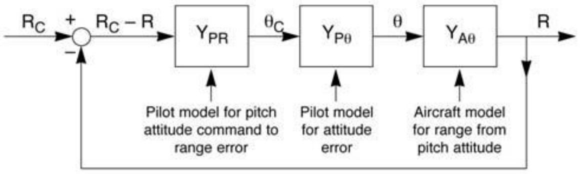

Figure 5 Closed-loop control of aircraft range.

fidelity of the simulation, with the identified parameters acting as fidelity metrics.

Flight simulation using a physics-based approach is a promising means to acquire the compliance data at reduced cost and/or risk. However, it is essential to demonstrate the credibility of the simulation in the (partial) absence of validation data. Figure 6 illustrates the problem at hand using the altitude-extrapolation of trim control margin as an example. The non-hashed area indicates the demonstrated worst-case simulation error bandwidth within the tested envelope, taking into account the scatter in the measurement data. The hashed area reflects the unknown evolution in the prediction error over the extrapolation ‘distance’. Finally, the blue error bar indicates the allowable prediction error at the corner of the envelope in relation to the distance to the compliance limit (in this case the minimum control margin required for adequate gust control). Questions that arise are:

- What is an acceptable error tolerance in the validated part of the envelope given the allowable error at the extrapolated conditions?
- What is the minimum number of validation data points that is needed to gain confidence in the simulation and accept extrapolation using a physics-based model?
- Can we define limits for the allowable extrapolation distance for a given parameter (e.g., altitude, weight, airspeed) and flight condition?

In terms of extrapolation, AC 29-2C contains guidance that limits straightforward extrapolation for altitude to ±4,000 ft for performance in hover, take-off and landing, whereas a ±2,000 ft extrapolation limit is specified for IGE handling qualities, h-V testing, and engine operating characteristics. In contrast, controllability and stability shall be flight demonstrated at least at the lowest practical altitude and the highest cruise altitude (with interpolation between). Weight may be extrapolated for certain aspects, but only along an established W/σ line within the allowable altitude extrapolation range up to the maximum gross weight of the rotorcraft. The proposed application of physics-based simulation in lieu of

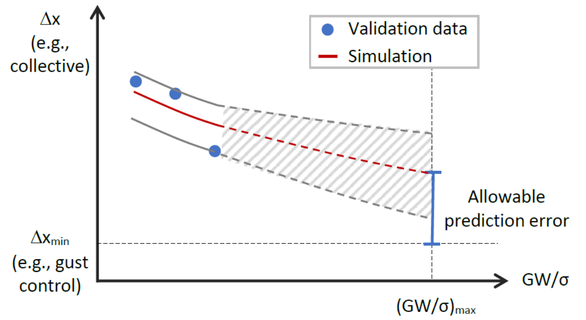

Figure 6 Illustration of trim control margin simulation prediction error in an altitude extrapolation scenario.

flight testing will require these limits to be re-evaluated.

4. PERCEPTIVE FIDELITY

Perceptual fidelity, specifically the influence of cueing elements is the subject of RoCS WP4. The requirements for cueing fidelity for certification aspects are currently not understood and to date have not been subject to research. Within RoCS, the objective is to propose the first ‘classification’ of minimum cueing fidelity to perform certification aspects. The scope will be limited to the certification aspects identified in RoCS. A proposed methodology has been developed to achieve this, shown in the following section.

4.1. Proposed Methodology

Currently, no process exists to determine the ‘fitness for purpose’ of a simulation device to perform certification aspects. Although this is the case, simulators are already used to achieve ‘certification credit’ for aspects not covered during flight test programs (due to risk or operational restrictions). The suitability of the simulation facility is currently determined on a case-by-case basis, through cooperation between the applicant and the certification authority. This is in contrast to training simulators whereby well-defined standards are used during the commissioning of simulators. For helicopter simulators in Europe these standards are contained in [6]. Currently EASA is performing activities to update the standards for training simulators and the first outputs of this activity are shown in [22]. Activities are being conducted together with stakeholders within Rule Making Task (RMT) 196. Within this task, training standards will be updated for fixed-wing, rotorcraft and VTOL aircraft. In addition, the use of novel devices (e.g., virtual reality) is being considered.

There are two main aspects of fidelity which should be considered:

- Component fidelity level

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

- Overall perceptual fidelity

Both aspects should be addressed to determine a first ‘classification’ for certification simulation devices.

Although there are differences concerning the end-use of the simulation facilities, many of the techniques used to determine the fidelity of training simulators could be applied to the certification simulators. In addition, using training simulator standards as a basis for further development should lead to greater acceptance from the certification authority EASA and stakeholders. For this reason, in RoCS, a methodology and ‘classification’ similar to [22] is proposed. The focus is particularly concerning the determination of minimum requirements for component fidelity.

The following process (Figure 7) is proposed to determine the first minimum requirements for cueing fidelity for given certification tasks.

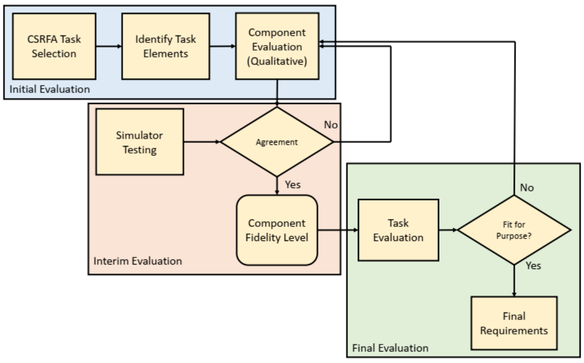

Figure 7: RoCS proposed process to determine requirements for cueing fidelity of a given certification task

In the initial evaluation phase, the CSRFA task selection is undertaken, and the key elements of the tasks are identified. Here, the task requirements should be assessed to determine the likely areas of interest in terms of the cueing requirements. From these elements, an initial evaluation of the required fidelity at the component level should be undertaken. The intention is to discuss this in detail with subject experts and those with experience in certification.

In the interim evaluation stage, specific areas of interest will be explored in dedicated simulator tests, to confirm the required fidelity of each specific component. The output of the interim evaluation should be the component fidelity level requirements for each of the CSRFA tasks.

The final evaluation is to confirm that the perceived fidelity is sufficient to complete the CSRFA task. This final step is required to confirm that fidelity of all components have been adequately considered. Furthermore, it is important to ensure that the overall perceptual fidelity is “fit for purpose”. During the interim evaluation stage, it is likely that the fidelity is assessed only with respect to a single variable (e.g., visual cueing fidelity), due to time constraints.

The classification of component fidelity is performed using a similar method as proposed in [22]. Here, 12 FSTD ‘features’ are identified. One of these features concerns the flight model, not related to cueing. Some other features (e.g., Air Traffic Control, Navigation) are of limited relevance to certification simulation devices. However, most of the features are relevant. Within the NPA, simulator fidelity of individual elements is divided into four classifications:

N: None
G: Generic
R: Representative
S: Specific.

Each of these terms is given a definition based upon the feature. Fidelity is based upon general observations, software or hardware requirements. These definitions have generally been adopted from ICAO 9625.

For each feature, a minimum fidelity ‘level’ is defined for each type and level of FSTD device. This is based on experience and is not the output of targeted research efforts. For example, for an FFS device, Motion cues are required with a ‘Specific’ fidelity level whereby for FNPT devices (A-D) no motion cues are required (vestibular cueing, None).

A similar process to classify the component fidelity is proposed in RoCS, using four “fidelity levels”. However, the exact terminology for these has not yet been defined. This will be defined in the next steps of the project. To avoid confusion with [22] it is proposed to use different terminology in RoCS to describe the elements. The initial proposal is to use the terms; **None (N), Low (L), Medium (M), High (H).**

Although these are yet to be defined in detail, Table 2 shows two initial examples relating to the requirements for the cockpit/ergonomics and sounds of the simulator.

From the FSTD features defined in [6], 8 are considered as relevant for the initial efforts to define standards for certification simulators. These are shown in Table 3. The objective is to

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

define a component fidelity level for each with respect to a given certification task and a proposed 'certification credit'.

Table 2: Examples of possible definitions of N/L/M/H for two SFFs

	Low (L)	Medium (M)	High (H)
Cockpit/ Ergonomics	Generic cockpit, not specific to the aircraft type	Similar to aircraft, however, differences in the configuration or position may exist	Replica of actual aircraft
Sounds	Generic sounds, not necessarily dynamic. Additional warnings or specific sounds not modelled	Cues deemed necessary are available (for example torque warning), however, sounds or warnings may differ from actual aircraft	Sounds represent the actual aircraft, all additional cues (warnings) feature realistic sounds

The exact definition of the certification credit will be defined in RoCS together with the input of the certification authority. Here it is envisaged that 100% certification 'credit' means that flight testing is not necessary and has been completely replaced by simulation. In the case of 50% credit, half of the

testing may be conducted in simulation, but flight testing is still required. The minimum required fidelity levels for each component is yet to be defined in the project. It is planned that this will be determined for all of the CSRFA topics identified in RoCS.

Table 3 Features considered relevant for the certification simulator standard.

	Proposed Certification Credit	Cockpit Layout and Structure	Ground Handling	Helicopter Systems	Flight Controls and Forces	Sound Cues	Visual Cues	Motion Cues	Environment
CSR FA Task	100 %	?	?	?	?	?	?	?	?
	50 %	?	?	?	?	?	?	?	?

Initial component fidelity levels will be proposed through discussions with experienced pilots and together with EASA for the relevant certification topics. Following this initial proposal, results from further simulation tests will be used to update or confirm these proposals. During these tests, the use fidelity metrics is proposed to support general pilot comments and questionnaires.

Within WP4, an initial selection of metrics was undertaken following a review of previous efforts concerning simulation fidelity. The advantages and disadvantages of methods were considered and are shown in Table 4.

Table 4: Selected fidelity metrics for RoCS.

Topic	Metric	Advantages	Disadvantages
Overall Fidelity	**Simulation Fidelity Rating (SFR) [24]**	Directly assesses simulation fidelity	Designed to compare sim v. flight
Overall Fidelity (Objective)	**Perceptual Fidelity Metrics** (Attack no, Attack rate, Cut-off frequency and Time-Frequency Spectrograms.)	Measurable differences in results	May be difficult to apply /understand. Not suited to industry
Visual Cueing **(Subjective)**	**Useable Cue Environment (UCE) [13]**	Practical method applied during flight test Can assess specific cases	Can take significant time (i.e. with 3 pilots)
Motion Cueing **(Subjective)**	**Motion Rating Scales [25]**	Systematic approach to assessment of motion	Only applied in limited campaigns (not in industry) Improvements and potential noted in previous work

Motion Cueing (Objective)	Objective Motion Cueing Test [26]	Designed for industry application Accepted for fixed-wing training simulators	Rotorcraft guidance and boundaries not available.
Failures	**Integrated Failure Evaluation Scheme (IFES) [27]**	Applied in industry	Complicated scale

In addition, the following additional assessment methods are considered useful for piloted simulation tests.

- Cooper-Harper Rating – determine changes in handling qualities due to changes in cueing environment.
- Bedford Workload Rating, NASA Task Load Index (TLX) – determine change in workload due to changes in cueing environment.
- Situational Awareness Rating Technique (SART) – changes to situational awareness due to changes in cueing.
- Assessment methods specifically concerning the use of virtual reality.

4.2. Simulation Tests Planned

Table 5 Overview of Simulator Facilities available.

Simulator	AVES (DLR)	HFR (UOL)	HPS (NLR)
Visual FoV	*240° x 93°*	*230° x 70°*	Unlimited
Motion	Yes – full sized hexapod	Yes – short stroke hexapod	No
Cockpit	Replica EC135	Generic	Generic
Advantages	Large motion platform, large FoV, realistic cockpit	Large FoV, generic cockpit, FLIGHTLAB models	Very large FoV (through VR) FLIGHTLAB models
Dissadv.	Generic cockpit not available, not possible to use FLIGHTLAB models	Limited motion range, no specific cockpit	No motion platform, limited peripheral cueing

Within RoCS, simulation campaigns are planned both using partner facilities and at Leonardo Helicopters. The goal of tests at partner facilities is to develop and test proposed methodologies and fidelity metrics. The primary goal of activities at LH facilities is to use the developed methods and metrics to perform an evaluation of the upgraded simulation facilities. This demonstrates the application of RoCS results to an industry simulator.

The ROCS consortium has several simulation facilities at its disposal for tests. These facilities offer complementary characteristics to help understand the role of cueing fidelity when performing certification aspects. Some aspects of the three main facilities available at project partners are shown in Table 5.

Model Integration

To prepare for piloted tests at partner facilities, significant efforts were made to integrate the flight simulation model of the AW109. This model was supplied by Leonardo Helicopters for use in the project at partner facilities. The FLIGHTLAB model was provided to all partners for use. Both UoL and NLR use FLIGHTLAB software and were able to integrate the full nonlinear flight dynamics model to their respective facilities.

Since DLR uses in-house simulator software instead of FLIGHTLAB, the full nonlinear model could not be used in AVES. In this case, the solution was to integrate a stitched model of the AW109 for tests. The FLIGHTLAB model was linearized by UoL with results provided to DLR. This model was subsequently checked and stitched with respect to flight speed by DLR. The stitched model is based upon the initial FLIGHTLAB model of the AW109 prior to the completion of any updates in WP3. The stitched model uses MATLAB Simulink software.

The flight control system was provided by POLIMI within the FLIGHTLAB model. Within the stitched model, DLR implemented the control system directly using MATLAB Simulink.

Initial tests at both DLR and NLR have been conducted between March-June 2021. Tests at DLR were conducted using two internal experimental test pilots and tests at NLR were conducted with a helicopter PPL.

The focus of these initial tests was to obtain initial feedback regarding the simulation setup and on the importance of different simulator cueing elements for a number of RoCS certification topics. These results will be reported in future dissemination activities as part of the project.

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The use of flight simulation to support rotorcraft certification activities has potential benefit in terms of safety, economy, time, and effectiveness.

The following impacts are expected by the project RoCS:

- Decrease the risks associated with rotorcraft certification compliance demonstration. In particular this includes tests close to the boundaries of the OFE and cases where the effects of failures have to be demonstrated. During flight simulation it is possible to collect a large amount of test data that cannot be easily measured during a test flight. Additionally, it is possible to perform many repetitions to assess piloting variability without substantially increasing costs and with no additional risk. Similarly, a large number of different aircraft configurations (in terms of mass, position of the cg, environmental conditions, failure modes, etc.) can be tested with only a slight increase in the overall cost.
- Reduce cost of rotorcraft certification
- Reduce the time required to complete rotorcraft certification. Additionally, initial simulation testing can, in some instances, be performed during the aircraft development phases, shortening considerably the time required for certification. Certification of aircraft with innovative configurations (like tiltrotors, or eVTOL) may require a significant increase in the time required also due to the necessity to establish appropriate means of compliance for a new, and somehow uncertain due to lack of experience, vehicle. Simulation for certification could really represent a game-changer in this case.
- Define a new family of flight simulators. The outcomes of RoCS are expected to form the first steps in the classification of simulation devices for CSFRA topics.

ACKNOWLEDGEMENTS

RoCS Project received funding from the Clean Sky 2 Joint Undertaking (JU) Framework under the grant agreement N.831969. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

REFERENCES

[1] Anonymous, Certification Specifications and Acceptable Means of Compliance for Large Rotorcraft CS-29 / Amendment 5, EASA, 2018.

[2] Anonymous, Certification Specifications and Acceptable Means of Compliance for Small Rotorcraft CS-27 / Amendment 6, 2018.

[3] R. Bianco-Mengotti, F. Del Grande, A. La Barbera, G. Lo Coco and A. Ragazzi, "AW139 Ship Interface: Experimental Trials and Simulations," in *AHS 69th Annual Forum*, Phoenix, AZ, 2013.

[4] R. Bianco-Mengotti, A. Ragazzi, F. Del Grande, G. Cito and A. Brusa Zappellini, "AW189 Engine-Off-Landing Certification by Simulation," in *AHS 72nd Annual Forum*, West Palm Beach, FL, 2016.

[5] R. A. van Kralingen, "Operational Test and Evaluation of the NH90 NFH," in *SFTE European Chapter*, Lulea, Sweden, 2014.

[6] Anonymous, Certification Specifications for Helicopter Flight Simulation Training Devices CS-FSTD(H) / Initial Issue, EASA, 2012.

[7] D. O. Hines, Simulation in Support of Flight Testing RTO-AG-300 Vol. 19, RTO NATO, 2000.

[8] Flight Test Guide for Certification of Transport Category Airplanes, Federal Aviation, 2018.

[9] Anonymous, "Proposed Means of Compliance withthe Special Condition VTOL," EASA, 23 June 2021.

[10] Anonymous, "Standard for Models and Simulations," NASA, 2016.

[11] W. L. Oberkampf, M. Pilch and i. G. Trucano, "Predictive Capability Maturity Model for Computational Modeling and Simulation," SANDIA, 2007.

[12] Anonymous, "Notification of a Proposal to issue a Certification Memorandum "Modeling & Simulation" -- CS-25 Structursl Certification Specifications," -, 2020.

[13] Anon, "ADS33E-PRF, Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft," United States Army Aviation and Missile Command, Aviation Engineering Directorate, 2000.

[14] M. D. Pavel, M. White, G. D. Padfield, G. Roth, M. Hamers and A. Taghizad,

"Validation of mathematical models for helicopter flight simulators past, present and future Challenges," *The Aeronautical Journal,* vol. 117, no. 1190, pp. 343-388, 2013.

[15] G. D. Padfield, M. T. Charlton and A. T. McCallum, "The fidelity of Hi-Fi Lynx on the DERA Advanced Flight Simulator using ADS-33 handling qualities metrics," DRA/AS/FDS/TR96103/1, 1996.

[16] P. Perfect, M. D. White, G. D. Padfield and A. W. Gubbels, "Rotorcraft Simulation Fidelity: New Methods for Quantification and Assessment," *The Aeronautical Journal,* vol. 117, no. 119, pp. 235-282, 2013.

[17] R. Smith, J. Hodgkinson and R. Snyder, "Equivalent System Verification and Evaluation of Augmentation Effects on Fighter Approach and Landing Flying Qualities," Ohio, 1981.

[18] K. Strope, C. Borden and J. Harding, "Verification & Validation of a UH-60 FLIGHTLAB Model in Support of the UH-60M Limited User Test," in *American Helicopter Society 60th Annual Forum*, Maryland, 2004.

[19] D. Mitchell, C. He and K. Strope, "Determination of Maximum Unnoticeable Added Dynamics," in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Colorado, 2006.

[20] M. White and G. Padfield, "Measuring Simulation Fidelity Through an Adaptive Pilot Model," *Aerospace Science and Technology,* vol. 9, no. 5, pp. 400-408, 2005.

[21] D. McRuer and E. Krendel, "Mathematical Models of Human Pilot Behaviour," AGARD, 1974.

[22] Anonynmous, "Update of the Flight Simulation Training Device Requirements, Notice of Proposed Ammendment 2020-15," European Union Aviation Safety Agency EASA, 2020.

[23] M. White and G.D. Padfield, "Measuring Simulation Fidelity through an Adaptive Pilot Model," *Aerospace Science and Technology,* vol. 9, no. 5, pp. 400-408, 2005.

[24] P. Perfect, E. Timson, M. White, G. Padfield, R. Erdos, A.W. Gubbels, "A rating scale for the subjective assessment of simulation fidelity" *Aeronautical Journal*, vol. 118 no. 1206, pp. 953-974, 2016

[25] M. Jones, M. White, T. Fell, M. Barnett, "Analysis of motion parameter variations for rotorcraft flight simulators" 73rd American Helicopter Society International Annual Forum and Technology Display 2017, Fort Worth, 9 May 2017 - 11 May 2017

[26] Hosman, R., Advani, S., "Design and evaluation of the objective motion cueing test and criterion", *Aernautical Journal*, vol. 120, no. 1227 pp. 873-891, 2016

[27] M. Jones, M. Barnett, "Active inceptor failure as a trigger for pilot-induced oscillations", *J. American Helicopter Society*, vol. 65, no. 2 , April 2020

Presented at 47th European Rotorcraft Forum, Glasgow, Scotland, UK 7-9 September 2021