CASE STUDIES TO ILLUSTRATE THE ROTORCRAFT CERTIFICATION BY SIMULATION PROCESS; CS 29/27 CATEGORY A REJECTED TAKE-OFF, CONFINED AREA

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Abstract

This paper is one of a set presented at the 49th European Rotorcraft Forum discussing results from the EU Clean Sky 2 project, Rotorcraft Certification by Simulation (RoCS). The process developed by the RoCS team provides guidance on the use of flight simulation in certification and features four case studies that illustrate aspects of the process applied using flight simulation models and flight test data provided by Leonardo Helicopters. This paper presents the case study for Rejected Take-Off (RTO): Category A in a Confined Area, for the relevant certification paragraphs in the EASA Certification Specifications CS-27 and CS-29. The relevant paragraphs from the Specifications are described and results from simulation model fidelity assessment, and updating compared with test data, are presented for a reference flight condition. Results from piloted simulation trials, with a 'new' Flight Test Manoeuvre (FTM), are included to illustrate flight simulator fidelity assessment methods and to illustrate how the Rotorcraft Certification by Simulation process can be achieved.[1]

1 NOTATION

Symbols:

N_R	Main rotor speed
W	Aircraft weight
Y	Longitudinal touchdown position
$k_{x,y,z}$	Surge, sway, heave high pass motion filter gain
$k_{\phi,\theta,\psi}$	Roll, pitch, yaw high pass motion filter gain
$\ddot{\theta}$	Simulation model pitch acceleration
$\ddot{\theta}_s$	Motion platform acceleration
σ_ρ	Relative air density
$\omega_{hpx,y,z}$	2nd order high-pass, surge, sway and heave motion filter break-frequency
$\omega_{hp\ \phi,\theta,\psi}$	2nd order high-pass, roll, pitch and yaw motion filter break-frequency

Acronyms:

AC	Advisory Circular
ACP	Aerodynamic Computational Point
ACR	Applicable certification requirement
ADS-33	Aeronautical Design Standard-33
CAT A	Category A
CS	Certification Specification
DoE	Domain of Extrapolation
DoP	Domain of Prediction

DoR	Domain of Reality
DoV	Domain of Validation
EASA	European Union Aviation Safety Agency
EP	Evaluation Pilot
ERF	European Rotorcraft Forum
FAA	Federal Aviation Administration
F-AW109	FLIGHTLAB model of AW109 Trekker
FoV	Field of View
FS	Flight Simulator
FSM	Flight Simulation Model
FTM	Flight Test Manoeuvre
FTMS	Flight Test Measurement System
HQ(R)	Handling Qualities (Rating)
ICQ	In-cockpit Questionnaire
IFR	Instrument Flight Rules
I-P	Influence-Predictability
IPC	Influence, Predictability and Credibility
LHD	Leonardo Helicopter Division
MDA	Motion Drive Algorithm
MTE	Mission Task Element
OEI	One Engine Inoperative
OGE	Out of Ground Effect
PID	Proportional, Integral, Derivative
RCbS	Rotorcraft Certification by Simulation
RFM	Rotorcraft Flight Manual
RoC	Rate of Climb
RoCS	Rotorcraft Certification by Simulation
RoD	Rate of Descent
RTO	Rejected Take-off
SFR	Simulation Fidelity Rating
TD	Touch Down
TDP	Take-off Decision Point
TDP_E	Extended TDP
UoL	University of Liverpool
V&V	Verification and Validation
VeMCS	Vestibular Motion Cueing System
VzMCS	Visual Motion Cueing System

2 INTRODUCTION

A newly developed aircraft must be certified before entering service by demonstrating compliance with the safety requirements set by certification authorities. Both the structure of the certification process and the means to demonstrate compliance with the regulations must be agreed between the manufacturer, or more generally the applicant, and the authority. The compliance demonstration is usually performed through flight and ground tests that are typically the lengthiest and most expensive part of the development process. Compliance flight tests could pose safety issues, such as those related to flight control system or engine failures. To optimise the scope of flight test activities through reducing the cost and time required for the tests, whilst lowering the potential risk, advanced analysis-based methods of compliance, such as flight simulation, are being explored. As an exemplar, Leonardo Helicopters used simulation in the certification of the engine-off landings for the AW189 (Ref. 1), and tail rotor loss of effectiveness for the AW169 (Ref. 2). Both European Union Aviation Safety Agency's (EASA's) CS-27 and CS-29 Subpart B define the term "*analysis-based*" methods of compliance as "*calculations*" in the clause of "*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*" (Refs. 3, 4). Federal Aviation Administration (FAA) Advisory Circular AC-29.21(a) states "*calculation*" includes flight simulation (Ref. 5). 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 (Ref. 6). Similarly, with the burgeoning eVTOL market, EASA are developing Proposed Means of Compliance (MOC) with the Special Condition VTOL (MOC SC-VTOL) which has started to provide guidance on the use of "*'simulation bench'*" which "*refers to a simulator with pilot in the loop capability*" and how it may be used as part of the certification process (Ref. 7).

With the increase in fidelity of physics-based rotorcraft flight simulation models, it is foreseeable that the usage of flight simulation to replace flight testing through a virtual-engineering process will become more dominant, as the industry pursues efficiency, low cost, increased safety, and low energy consumption (Ref. 8). The team of the European CleanSky2 funded project, Rotorcraft Certification by Simulation (RoCS), has the aim to explore the possibilities, limitations, and guidelines for best practices for the application of flight simulation to demonstrate compliance with the airworthiness regulations related to helicopters and tiltrotors (Ref. 9).

Under the framework of the RoCS project, preliminary Guidance for the application of (rotorcraft) flight modelling and simulation has been developed in support of certification for compliance with standards CS-27/29, PART B (Flight) and other flight-related aspects (e.g. CS-29, Appendix B, Airworthiness Criteria for Helicopter Instrument Flight) (Refs. 10, 11, 12). The Guidance follows a requirements-based approach and is presented in the form of a structured process for Rotorcraft Certification by Simulation (RCbS)[2]. The process starts with the selection of 'applicable certification requirements' (ACRs) for the application of RCbS, with judgements on a matrix of factors of Influence (how the RCbS process will be applied), Predictability (the extent of interpolation/extrapolation), and Credibility (the level of confidence in results), in line with a comprehensive description of the assembly of flight simulation requirements. Case studies drawn from selected ACRs have been conducted to demonstrate the efficacy of aspects of the process and include example fidelity metrics and tolerances for fidelity sufficiency and credibility analysis.

This paper presents the results from the case study related to CS-29 paragraph 62 (Rejected take-off (RTO): Category A) (CAT A)) and CS-27 Appendix C (Criteria for Category A), to illustrate the application of the Guidance. Section 3 summarises the RCbS process whilst Section 4 describes the ACR requirements and motivation for examining the CAT A RTO. The Flight Simulation Model (FSM) evaluation and updating activities are presented in Section 5. Section 6 presents a new flight-test-manoeuvre (FTM), in the style of an ADS-33E mission-task-element (MTE) (Ref. 13), that can be used for fidelity and certification assessments, together with a description of the Flight Simulator (FS) build process. Results from exploratory piloted simulation trials are presented in Section 7 and Section 8 then summarises the main conclusions and associated recommendations derived from this RoCS case study.

3 OVERVIEW OF THE RCBS PROCESS

The Guidance for the RCbS process is organised into three, serial but iterative, phases, as shown in Figure 1 and expanded on in Refs. 10 and 11.

1) Phase 1; requirements-capture and build,
2) Phase 2; developments of flight simulation model (FSM, 2a), flight simulator (FS, 2b) and Flight Test Measurement System (FTMS, 2c),
3) Phase 3; Credibility assessment and Certification.

The activities in these three phases are undertaken within a governance-framework defined in the Project Management Plan and created in Phase 0 of the RCbS process.

Phase 1 contains subtasks for a selected ACR – selecting the appropriate Influence and Predictability (I-P) levels, defining the simulation types and critical features, and assembling their detailed requirements. The RCbS Guidelines (Ref. 12) uses the concepts of Influence, Predictability and Credibility (IPC) Levels to convey meaning to the underlying consequences of the application of RCbS, in terms of safety and efficiency in the certification campaign. The IPC Levels inform the FSM and FS requirements/capture and build phases of the RCbS process,

[2] *To distinguish between the two acronyms, RCbS refers to the process developed by the RoCS 'project' team.*

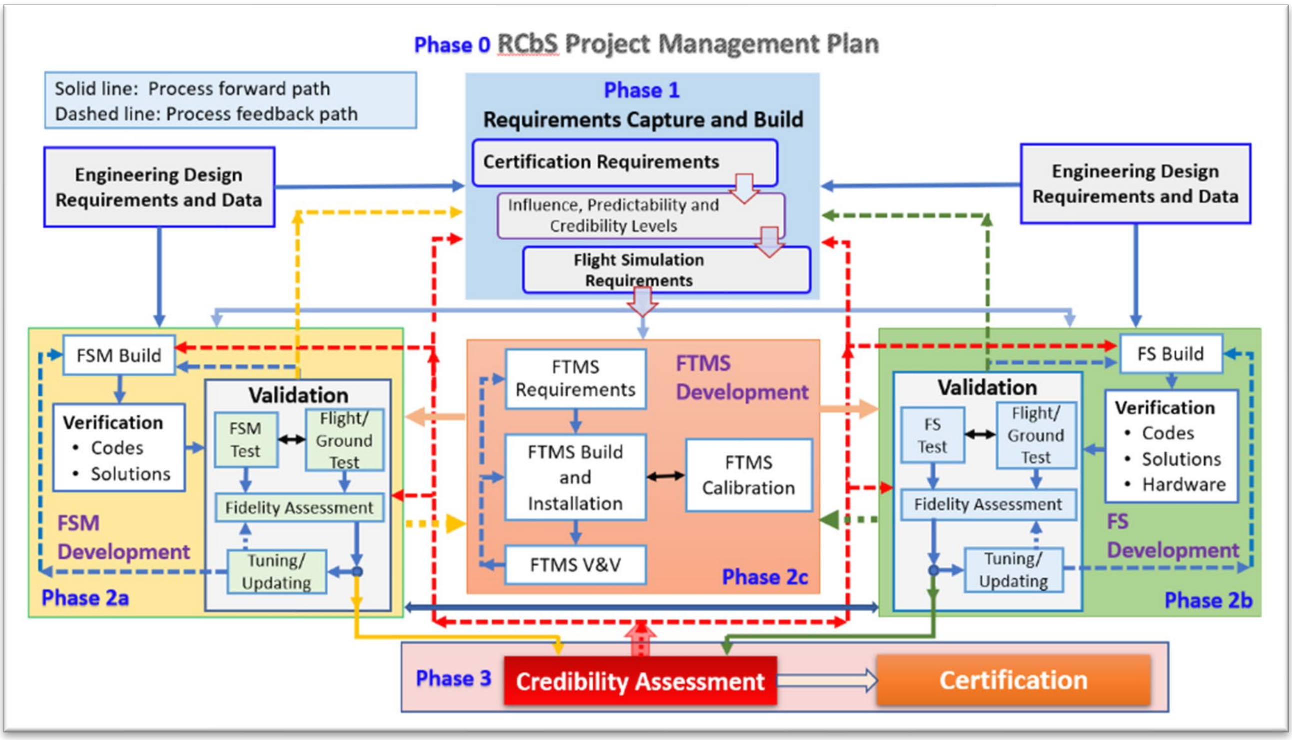


Figure 1: The RCbS process summarised as a flow diagram (Refs. 10, 11, 12)

The application of RCbS is contained within different domains as illustrated in Figure 2.

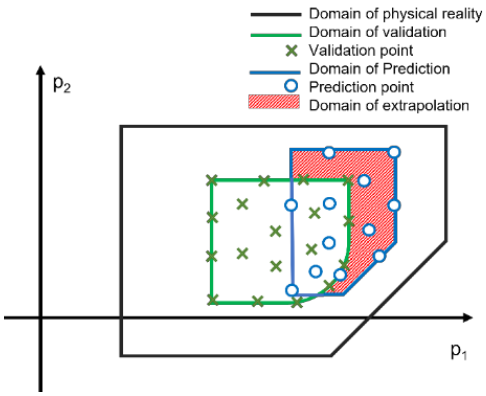


Figure 2: The domains in the RCbS process

In summary,

a) The domain of physical reality (DoR) is the domain within which the laws of physics being used are considered to be adequately represented in the flight model and flight simulator.

b) The domain of prediction (DoP) is the domain within which it is the intention to predict the behaviour of the aircraft and its components and to use these predictions to support certification at the defined I-P Levels.

c) The domain of validation (DoV) is the domain within which test data are used to validate the flight simulation. Interpolation is used in the DoV to predict behaviour between validation points.

d) The domain of extrapolation (DoE) is the domain within which extrapolations of predictions are made to achieve certification at defined Influence Levels for an ACR.

Figure 3 illustrates an example of how the I-P Matrix might be configured, showing the four forms of influence and predictability (i.e., 16 possible combinations).

RCbS ACR	Influence Levels	Predictability Levels			
		Full Interpolation in DoV (P1)	Extensive interpolation in DoV Limited extrapolation in DoE (P2)	Interpolation in DoV Extensive extrapolation in DoE (P3)	Full extrapolation in DoE (P4)
CS 29.62 Rejected take-off (RTO): Category A, Confined Area procedure	De-risking (I1)				
	Critical Point Analysis (I2)				
	Partial credit (I3)				
	Full credit (I4)				

Figure 3: Selection of the I4-P3 Level in the RCbS I-P process

4 ACR AND RCbS MOTIVATION

The example ACR for this case study is: "CS 29.51 Take-off data: General" which states: "*that take-off data must be determined at each weight, altitude and temperature selected by the applicant*" and for a CAT A Take-off (CS 29.53), "*the performance must be determined so that if one engine fails at any time after the start of take-off, the rotorcraft can: …return to and stop safely on the take-off area*". For CAT A operations, the aircraft take-off weight is limited to a value such that if an engine failure occurs at or before the Take-off Decision Point (TDP) (Figure 4) the pilot will have to abort the take-off as the rotorcraft "*has not yet achieved sufficient energy to assure continued flight*" (Ref. 5).

An extended TDP, TDP_E can be used if there are obstacles in the take-off flight path.

Testing to determine the TDP follows a similar approach to the testing conducted for determining the Height-Velocity diagram with the aircraft tested in a lightweight configuration which is then 'built-up' to determine the maximum take-off weight and c.g. configurations possible for the environmental conditions under consideration (Ref. 5). The flight trials require significant time and expense and also pose a safety risk; the RCbS process can be used to reduce these factors. What is required is guidance on the FSM and FS fidelity requirements to enable an applicant to demonstrate the Credibility of their RCbS approach.

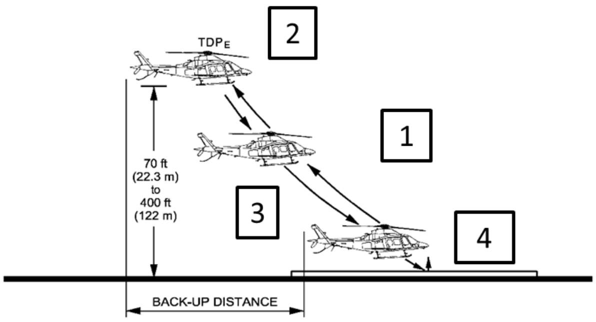


Figure 4: CAT A RTO (Confined Area) profile

In this paper, it is assumed that the applicant is seeking to use simulation in support of full credit for the CAT A RTO ACR for an AW109 Trekker using low altitude DoV flight test data and extrapolating to a high-altitude case. For this ACR the applicant is seeking I4-P3 approval (Figure 3).

In addition to the CS-29 requirements mentioned above , the FAA's AC 29.59 b) Procedures 2 ii B, require that 'abuse case' testing be conducted to show that operational variations in the take-off procedure, e.g., a change in flight path during climb out or misjudgement of TDP height, that may be experienced whilst the aircraft is in service does not result "*in a hazardous condition from which a safe landing cannot be accomplished*". This 'abuse case' testing is potentially hazardous and time consuming and further highlights the benefits of replacing some of this testing with simulation. A well-defined Flight Test Manoeuvre (FTM) is required to ensure repeatability of results for flight test and for FS fidelity assessment purposes.

A key element of the RCbS process is the appropriate use of FTMs for assessment of ACRs in simulation. FTMs have been developed as ADS-33-style MTEs with a rigorous task definition subject to defined performance standards, and assessed through various pilot rating scales, including the Cooper-Harper handling qualities (HQR) rating scale (Ref. 14). An RTO FTM was developed for the purposes of RoCS in accordance with the procedures provided in the AW109 Trekker Rotorcraft Flight Manual (RFM) CAT A supplement (Ref. 15). The profile of the manoeuvre is shown in Figure 4. The manoeuvre begins with the evaluation pilot (EP) starting in a 5ft hover above a helipad and then initiating a rearwards and upwards climb (position 1 in Figure 4) towards the TDP. Following an engine failure (position 2), the aircraft is flown in a controlled descent (position 3) and cushioned onto the helipad (position 4). Full details of the FTM are provided in Appendix A. The FTM ground speed performance requirements were informed through discussions with an EASA EP and a flight test engineer, based on a helicopter with skids.

Note that, in this case, it was decided to include the landing flare and touchdown to assess the ability of the FSM and FS to reproduce the relevant dynamics and provide the EP with sufficient 'motion' cues. In Ref. 1, an alternative approach was favoured in which safe entry criteria were defined in terms of rotor speed, pitch attitude, ground speed and vertical ensuring a landing without damage from 10ft above ground level.

5 FSM BUILD AND DEVELOPMENT

The RoCS project was provided with flight test data and a FLIGHTLAB FSM of the AW109 Trekker by Leonardo Helicopter Division (LHD) with which to exercise aspects of the RCbS process. Flight data for trims, stability and response assessment were provided to the RoCS team for a range of test conditions, prior to any FSM analysis. Note that in the formal RCbS process, the flight test data would be gathered in Phase 2, in conjunction with the development of the FSM and FS and following the development (incl. V&V) of the FTMS.

5.1 FSM Build

Following the RCbS process, the FSM development phase should follow a structured approach with V&V building up from component to aircraft level. The modelling complexity required depends on the application, but for CAT A RTO simulations of conventional rotorcraft configurations where performance is a major driver, it was initially considered that sufficient fidelity can be achieved using contemporary state of the art methods. The baseline FSM that formed the starting point for the RoCS activities was developed by LHD and was validated for up-and-away conditions, but not for low-speed conditions in proximity to the ground.

The baseline FSM features a rigid articulated blade-element main rotor with nonlinear aerodynamics. The tail rotor is modelled as a disk-type, collective-only, rotor (Bailey model), with aerodynamic properties originally tuned to level-flight pedal-to-yaw frequency response characteristics. The main rotor induced velocities are computed with a Peters-He three-state inflow model along with a source image ground effect model. The rotor aerofoil data are available in the form of table lookups of the aerodynamic coefficients C_l, C_d and C_m as functions of the angle of attack and Mach number. The blade airloads are computed in a quasi-unsteady fashion including unsteady circulatory effects from thin aerofoil theory. The fuselage aerodynamic loads are computed at, and applied to, a single computational point. The fuselage and tail surface force and moment coefficients are available as functions of angles of attack and sideslip, derived from model-scale wind tunnel test data.

The thermodynamic engine model included in the baseline model was modified from an existing engine model but does not represent the actual Trekker engine in all respects. The primary aim for the CAT A RTO ACR is to obtain realistic engine torque response and limits in available power (depending on atmospheric conditions). The power limits have been, in practice, imposed based on available flight test data instead of a dedicated engine deck. Information on the engine control logic was not available, so the rotor speed governor logic was emulated using a PID controller. The controller gains were originally tuned to up-and-away frequency response data but were modified for the One Engine Inoperative (OEI) scenario.

The control laws of the Stability Augmentation System and Attitude Hold modes were similarly not available. Although not in line with the RCbS recommended practice, the control logic was therefore replicated to the extent possible using a conventional PID control architecture with the gains tuned to available control response and frequency domain data (at 0kts, 90kts and 120kts).

The skid landing gear was modelled as a set of four spring-damper struts with default (ground contact) friction parameters. As the intent of the simulation was not to determine loads or acceleration profiles during touchdown, but only the entry conditions at the moment of ground contact, the simplification is considered justified.

To facilitate the offline simulation of the RTO trajectory, a virtual pilot model was used, modified from Ref. 16. The model enables the flexible definition of the piloting strategy to support both simulated Abuse Case Testing and validation against flight test data. The parameters that define the core of the RTO manoeuvre logic are:

- Hover:
  - Height above take-off surface
- Climb to TDP:
  - Vertical speed
  - Climb gradient
  - Engine failure height
- OEI descent to helipad:
  - Pilot intervention delay
  - Target OEI main rotor speed N_R or delta-collective
- Landing flare:
  - Collective flare lead time
  - Target touchdown rate of descent
  - Target touchdown ground speed

During the OEI descent the collective can be used to control main rotor speed in a closed-loop manner, or be help constant at a certain offset below the climb-out value in accordance with AW109 RFM procedure. The control logic itself features nested PID controllers on each of the four aircraft axes. The roll and yaw axes are controlled to maintain track and heading. Triggered and driven by the parameters listed above, the heave/collective axis is controlled based on vertical speed or OEI rotor speed, whereas the pitch/cyclic axes is governed by ground speed through the target climb/descent gradient.

5.2 FSM Validation

Beyond the basic model development, a dedicated validation effort is needed for the application of the FSM to CAT A RTO simulation. Elements of such validation may include:

- Performance in trim:
  - Hover IGE
  - Low-speed backward climb
  - Steady OEI descent (at target N_R)
- Control response:
  Hover & low-speed doublets on all axes
  - Hover & low-speed frequency response data (e.g., from control sweeps and system identification)
- Engine & RPM response characterization:
  - Torque recovery after single engine failure (ground or flight test)
  - Flare effectiveness flight tests
- CAT A RTO flight tests

In the context of the RoCS project, the amount of useful validation test data available was very limited, consisting mostly of data obtained for purposes other than FSM validation. Data available included low-speed level flight trims, doublet control responses in Out of Ground Effect (OGE) hover, frequency response data for a single OGE hover conditions, and time histories of CAT A RTO testing at both low and high-altitude sites. The next section will go into more details on the validation comparison against the FSM and related model updating.

A dedicated validation (and prediction) uncertainty quantification effort was beyond the scope of what could be achieved given the resources of the RoCS project but would generally be considered an integral part of the FSM validation process. That is, even if the FSM error is demonstrated to be conservative relative to the flight test data, it must be shown that the error and uncertainty at the prediction conditions ensure an 'adequate' performance margin. A more detailed treatise on this topic is provided in the RoCS European Rotorcraft Forum companion papers for low-speed controllability and manoeuvrability and dynamic stability ACRs (Refs. 17 and 18).

A fundamental question, of course, is what validation error or simulation fidelity can be accepted for a given parameter in a certain condition. In RoCS, the standards in flight simulator certification specification, CS-FSTD(H) (Ref. 19), were taken as a baseline under the justification that the standards are suitable from a piloting perspective. However, from a performance perspective, it must be remembered that the validation error carries over to the DoE In other words, the accepted DoV error (and associated uncertainty) in parameters related to key performance requirements must be accounted for (in some way) in the comparison against those requirements at the prediction conditions. In practice, this typically implies that the performance margin is sacrificed to accommodate the error and uncertainty in the predictions.

5.3 FSM Updating

The baseline FSM displayed several fidelity deficiencies in hover and low-speed flight. The most notable of these was a consistent underprediction of the OGE power required in hover and low-speed trim conditions. The prediction of attitudes in trim, and hover doublet control response also did not meet typical standards, e.g., those of CS-FSTD(H). The discrepancies necessitated a closer look at some of the features of the simulation model; the inflow model, tail rotor modelling, fuselage interference, wake decay properties and blade aerodynamic properties. Aspects of these will be discussed in the following.

In the absence of dedicated full or model scale test data of the isolated rotor and with insufficient resources for, e.g., a first principles CFD analysis, it was not possible to definitively identify the source of the discrepancy in the required power prediction. An attempt was made to determine a zero-lift drag correction in profile power by comparisons against flat pitch on ground test data. This correction improved the correlation of low-speed power required to a degree. The residual discrepancy was attributed, based on engineering judgement, to an underprediction of the fuselage download due to the main rotor wake. Considering the uncertainty associated with this effect, and in the absence of data sources for further quantification, the fuselage download was tuned to flight test hover torque data.

The aerodynamic interaction between the main rotor wake and the fuselage remains one of the more challenging phenomena to accurate modelling in low-speed forward and rearward flight conditions. Although a model excluding such interference modelling can be tuned in several ways to achieve somewhat equivalent effects in terms of power and thrust required, the RCbS framework strives for a more physics-based modelling which captures also, e.g., the effect on trim attitudes. The typical fuselage interference modelling in FLIGHTLAB (Ref. 20) uses a lookup table that provides the aerodynamic force coefficients as functions of the angles of attack and sideslip. In the baseline FSM, a single Aerodynamic Computational Point (ACP) was used, disregarding the distribution of interference velocities and cross-sectional area of the fuselage. In an attempt to account for these effects empirically, multiple ACPs have been defined by a set of locations along the length of the fuselage with a weighting defined by the local fuselage volume or projected area. The interference velocity vector used for table look-up is obtained through weighted averaging across the ACPs. The best results in terms of trim power, attitudes and control positions were obtained using 16 equally distributed ACPs with a weighting based on segmented fuselage volumes as shown in Figure 5.

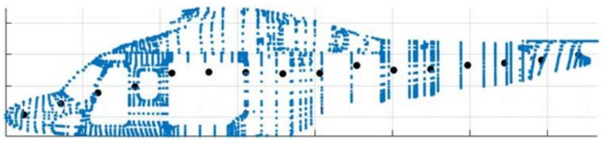


Figure 5: ACP distribution (black markers) used for rotor-fuselage interference computations

Figure 6 shows the impact of the aforementioned model updates for low-speed OGE level flight trim conditions. The error bars around the flight test data markers represent the standard deviation of the variation observed over a 10 second trim time history. The improved correlation of the updated FSM can be largely attributed to the inclusion of rotor-fuselage aerodynamic interference. A possible cause for the residual offset in the collective trim lies in the control rigging, for which no flight-specific information was available. Other factors such as the effect of blade and pitch control system flexibility were investigated, but these did not produce significant improvements.

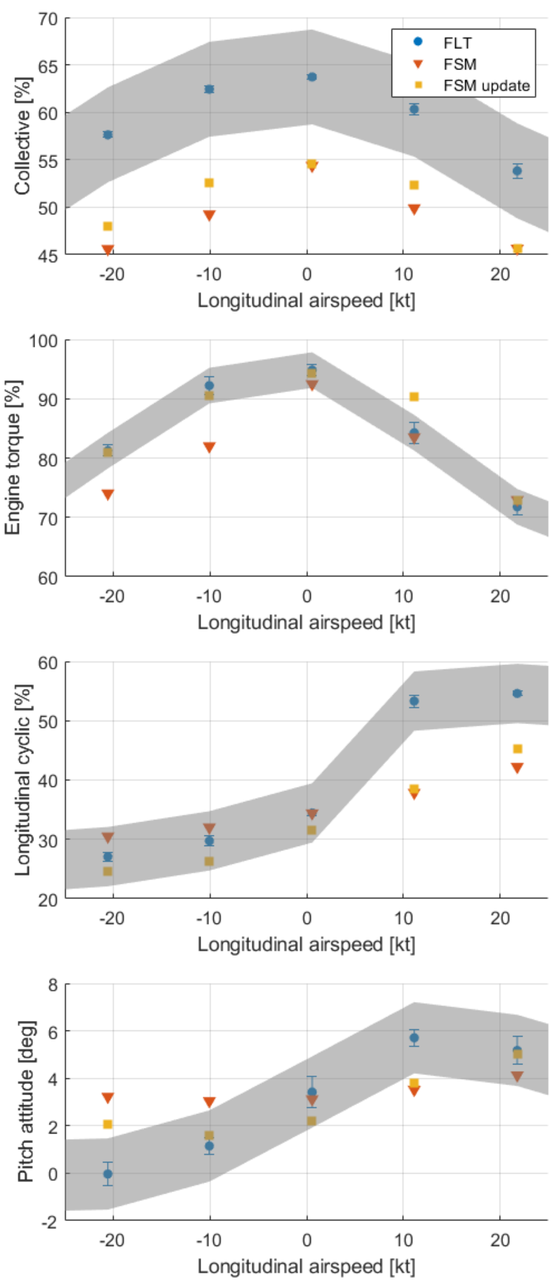


Figure 6: Impact of FSM updates on correlation against flight test for low-speed OGE level flight trim (shaded areas indicate CS-FSTD(H) tolerances for low-speed handling qualities)

5.4 FSM Predictive Fidelity

5.4.1 Domain of Validation

Ultimately, the ability of the FSM to be used in a piloted simulation of the CAT A RTO procedure with an acceptable performance prediction accuracy must be judged against flight test data of the procedure itself. The comparison against simulation can be achieved in multiple ways. In the first case, the pilot controls and engine torque response can be directly fed into the simulation. The disadvantage of this approach is that if discrepancies arise in, e.g., rotor speed and vertical speed, it becomes difficult to distinguish cause and effect. The alternative approach, the result of which will be presented in the following, was to set up the virtual pilot to fly the trajectory in much the same way as the pilot has. This approach allows for more control of the simulation, which in turn aids in building an understanding of the interrelations between the various parameters.

Figure 7 through Figure 9 show the correlation against flight test data for one of the low-altitude flights available (within the notional DoV). For reference, the shaded areas indicate the tolerances defined in CS-FSTD(H). In this example, the simulated trajectory is initiated at the start of the stabilised climb. The engine failure is timed to coincide with flight test (represented by a blue circle in the figures) and the pilot reacts to the failure after a specified intervention delay by slightly lowering the collective, if needed, to achieve an OEI N_R of 101% in accordance with the RFM procedure. The engine speed governor reacts by demanding full power of the operative engine (aiming to achieve 102% N_R). At a defined lead time prior to projected touchdown, the skids are levelled, and the rate of descent is arrested and the rotor speed decays. The simulation is halted at the moment weight on skids is detected, prior to the rotor speed recovery observed in the flight test data. Note that the touchdown (at the front edge of the helipad) is performed with residual forward ground speed and with the skids approximately level.

Several observations can be made about the correlation achieved. Firstly, although within CS-FSTD(H) tolerance, there is a notable offset in the collective trace, in line with the trim results presented in Figure 6. Given that the collective control limits are not a driving factor for this ACR, the discrepancy can be accepted.

There are also notable differences in the pitch attitude between the flight test and simulation, starting from trim. The correlation is highly sensitive to the centre of gravity position which has not been corrected for fuel expenditure in the simulation. The pitch attitude does not significantly affect aircraft performance but does influence the visibility of the take-off and landing surface through the chin window, which is a crucial factor in determining the ability of the pilot to perform the RTO procedure. Piloted assessment is desired to confirm that the attitude prediction is satisfactorily equivalent to the real aircraft.

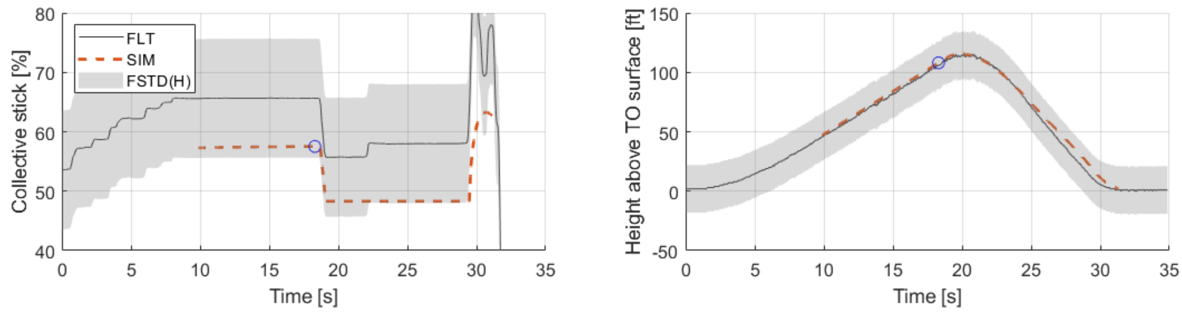


Figure 7: Correlation between simulation and flight test for CAT A RTO trajectory at low-altitude test site: collective channel

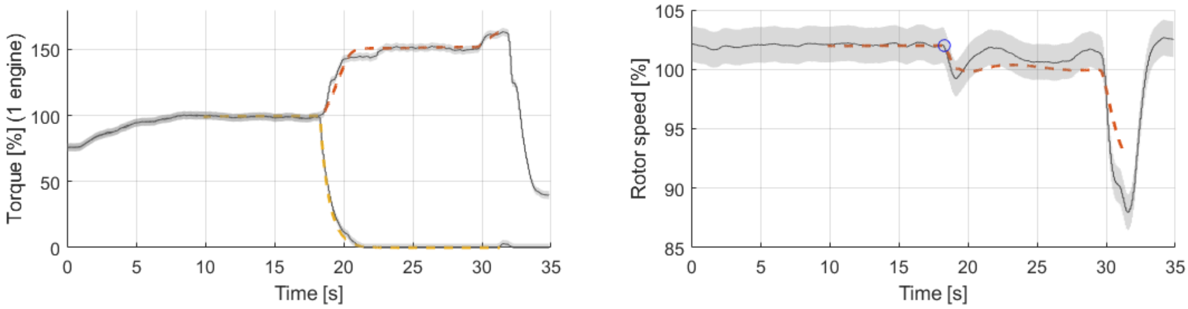


Figure 8: Correlation between simulation and flight test for CAT A RTO trajectory at low-altitude test site: engine torque and rotor speed

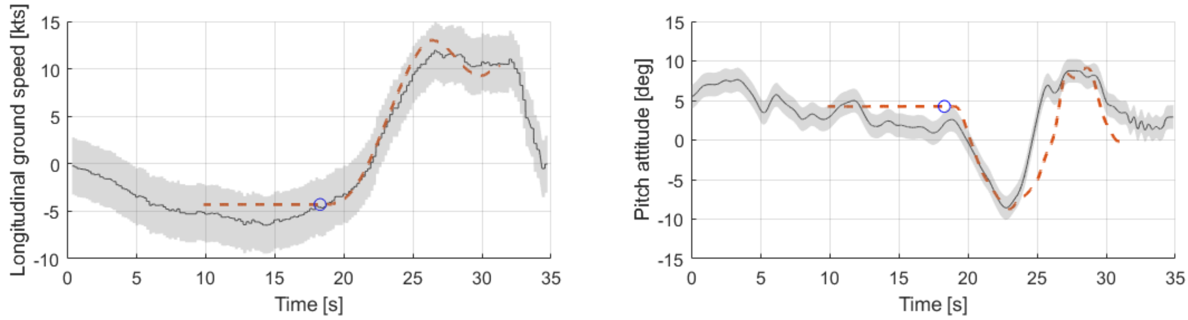


Figure 9: Correlation between simulation and flight test for CAT A RTO trajectory at low-altitude test site: pitch channel

A further observation can be made about the OEI rotor speed response. The prediction remains within CS-FSTD(H) tolerance and is conservative with respect to flight test. Notably, the flight test shows a marked transient increase between 25-30 seconds as a result of a cyclic flare leading to a peak nose-up attitude of around 9 degrees. The FSM generally shows a weaker rotor speed response to the change in attitude and tip-path-plane tilt. Such behaviour can be accepted because it is conservative, although a more detailed investigation involving, e.g., comparison against in-flight flare effectiveness test data would be desirable. Finally, it is worth reiterating that the CAT A RTO data available in RoCS were not historically gathered for the purpose of FSM assessment and validation. Missing information that would have been useful for validation purposes includes control rigging measurements, accurate position data to compare 3-D trajectories, wind mast measurements to confirm the requisite calm winds, rotor flapping for tip-path-plane correlation, and measurement of electrical generator load to name a few.

5.4.2 Domain of Extrapolation

In Phase 3 of the RCbS process, following extensive V&V, the FSM is to be exercised in the DoE. In the scenario considered in RoCS, the DoE concerns extrapolation in density altitude (beyond the limits of extrapolation defined in AC 27). In an initial RCbS application, flight test data are not available in the DoE and statements on the credibility of the prediction will need to be supported, e.g., by quantification of the prediction uncertainty. In the current demonstration case, flight test data are in fact available, such that the prediction error can be quantified directly. Although not exemplifying the RCbS guidelines and rather more anecdotal in nature, this approach does serve to increase the confidence in the underlying tools and methods of the FSM. For this exercise, in the DoE, the aircraft configuration and ambient conditions are defined based on existing flight test data, but no other changes are made to tune the model towards flight test data. Due to density effects on power available and thrust capability, the maximum gross weight (*W*) as well as the referred gross weight (W/σ_ρ where σ_ρ is the relative air density) at the altitude test condition are significantly reduced. Therefore, the extrapolation is, in fact, multidimensional.

Figure 10 through Figure 12 present the correlation achieved for one of the high-altitude test conditions (9280ft, 8.7°C) at maximum take-off weight for which test data are available. The trends are comparable to that observed in the DoV, with similar discrepancies in collective stick position (not corrected for flight-specific control rigging) and pitch attitude. Given accurate information on the available power limits of the installed engine, the prediction fidelity for aircraft performance does not suffer notably from the extrapolation to high altitude conditions.

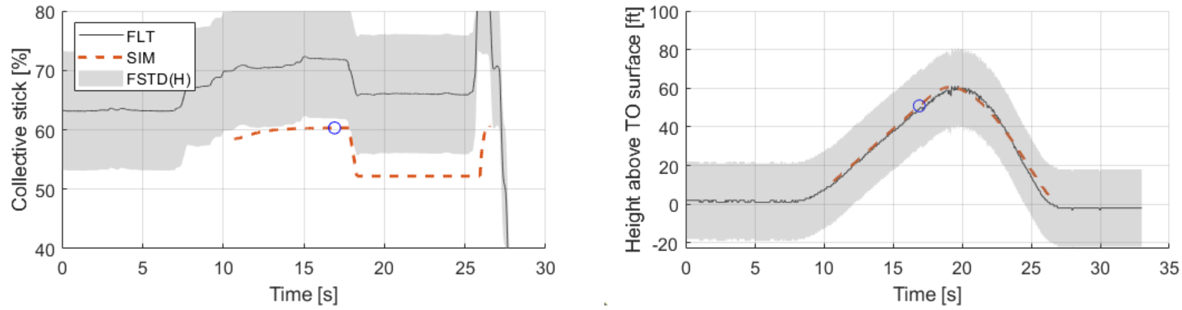


Figure 10: Correlation between simulation and flight test for CAT A RTO trajectory at high-altitude test site: collective channel

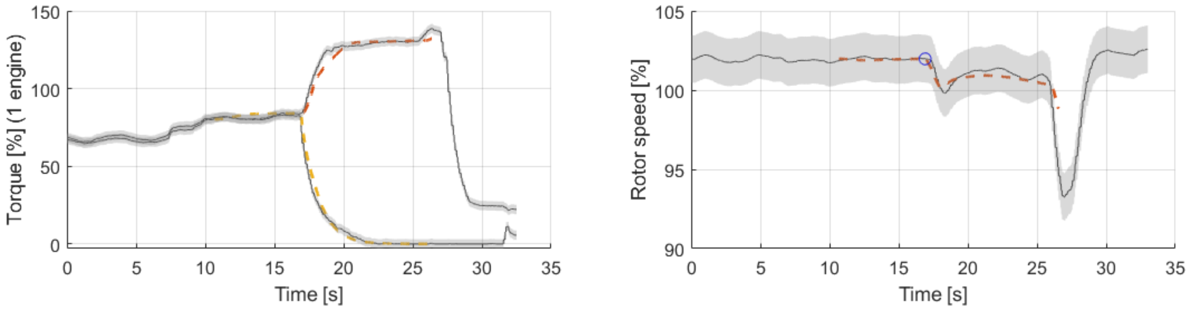


Figure 11: Correlation between simulation and flight test for CAT A RTO trajectory at high-altitude test site: engine torque and rotor speed

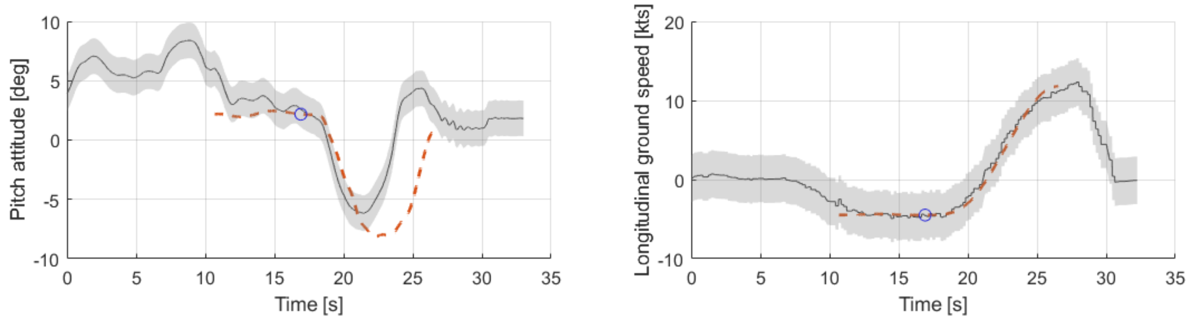


Figure 12: Correlation between simulation and flight test for CAT A RTO trajectory at low-altitude test site: pitch channel

In the context of the RoCS project, what remains to be established through piloted simulation is the pilot perception of the predictive of the predictive fidelity of the rotor speed dynamics and handling qualities, which may be noticeably affected by the change in air density. In a true RCbS application where there is no test data nor pilot experience in the DoE, a more comprehensive set of offline analyses would be required to establish the credibility of the simulation and the proximity to noncompliance. In the case of the CAT A RTO procedure, the primary compliance limits that are readily tracked in offline simulation include the OEI rotor speed and the landing gear limits (touchdown sink rate, ground speed and attitude). The ability of the pilot to maintain visual sight of the take-off/landing surface is ultimately best evaluated in the simulator.

Beyond the issue of FSM credibility, a necessary aspect of the compliance demonstration for CAT A operations is that the prescribed procedure can be safely executed by the average pilot. In practice, this implies that the aircraft performance and the piloting procedure must be robust against deviations from the RFM piloting strategy that can be expected in a normal operational environment. In fact, analyses of this sort may be considered part of an established uncertainty quantification practice, although it is not commonly referred to as such.

Figure 13 presents an example abuse case analysis in which the rate of climb to the TDP is varied from 200 ft/min to 600 ft/min, relative to a nominal value prescribed in the RFM of 400 ft/min. The engine failure is triggered at a given height above ground.

For consistency, the virtual pilot is set up to control collective to achieve and maintain a target rotor speed of 101% during the OEI descent. The higher climb rate leads to only a slightly larger drop in rotor speed following engine failure and prior to pilot intervention. The virtual pilot can achieve the same stable descent conditions without excessive pitch attitude excursions, which would make it impossible to maintain sight of the helipad, and touchdown within rate of descent, ground speed and rotor speed limits.

The shallowest gradient shown in Figure 14 is dominated by excessive ground speed, necessitating a large pitch attitude to arrest, posing problems both in terms of touchdown pitch attitude limits and maintaining visual line of sight to the target landing spot. This result suggests that a reduction in take-off gross weight may be necessary to provide margin for piloting variations, as has since been confirmed through the piloted simulations discussed in the following section.

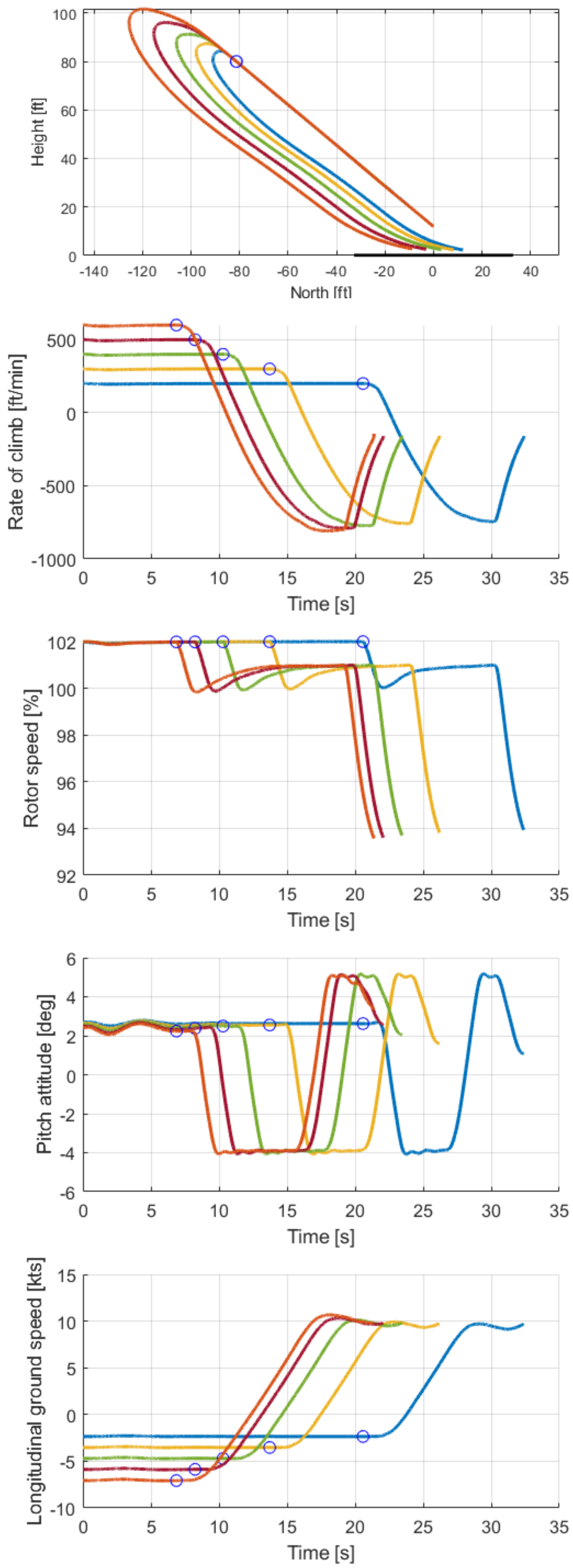


Figure 13: Example CAT A RTO abuse case: variation in rate of climb towards TDP

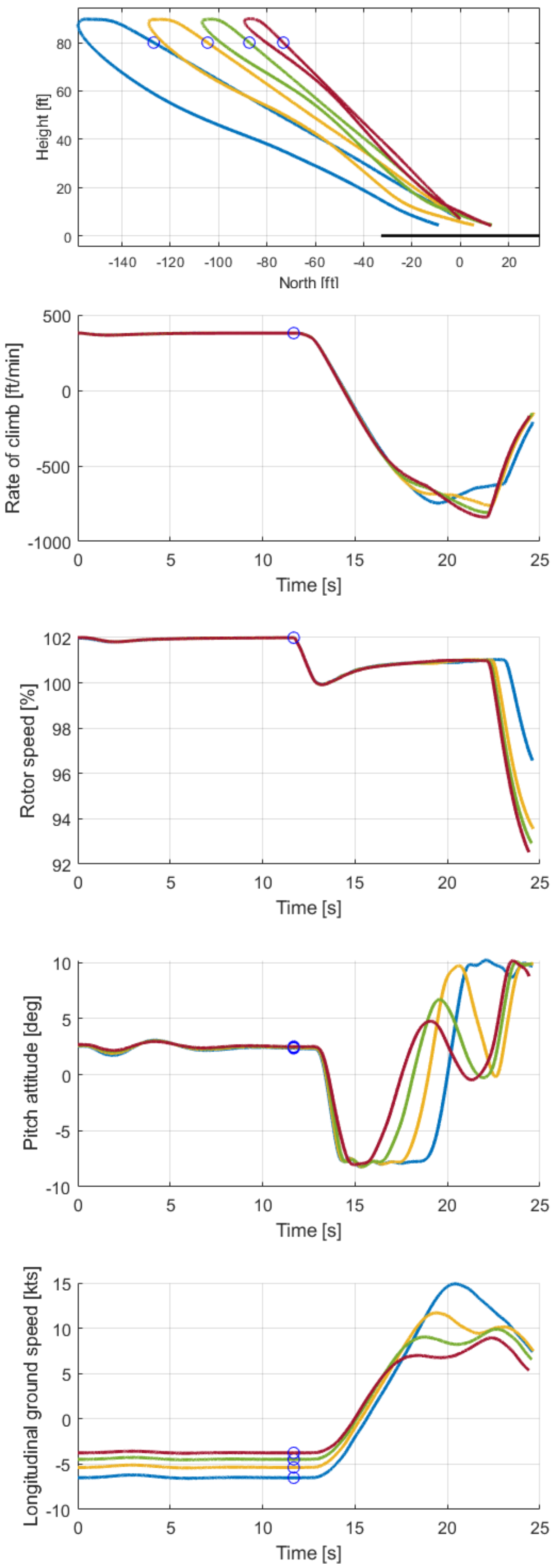


Figure 14: Example CAT A RTO abuse case: variation in climb gradient towards TDP

Figure 14 shows another abuse case, this time with variation in the climb gradient towards the TDP between 30 and 45 degrees (equivalent to the range accounted for in the RFM procedure for this aircraft). Even steeper climb gradients would present problems in terms of visibility of the take-off/landing surface which is better evaluated in a piloted simulation.

6 FS BUILD AND DEVELOPMENT

A pilot-centred approach is adopted in the RCbS process wherein the EP is provided with 'sufficient' cues, from the FS features (see Appendix B), to complete the task. This should enable the EP to achieve the same level of task performance as in flight with minimal control strategy adaptation. This approach draws upon the Simulation Fidelity Rating (SFR) scale methodology that was developed in Ref. 23, and shown in RCbS-revised form in Appendix C.

The FS build in Phase 2b requires inputs from Phase 1 in terms of the ACR and IPC level and includes 'Engineering Design Data' in the form of, but not limited to:

- Flight Control Mechanical Characteristics
- instrument panel displays,
- warning lights/sounds and aural cues.

Input is also required from the FTMS and DoV flight test activity to ensure that procedures used, and data gathered in flight are also replicated in the simulator for validation or compliance testing.

6.1 FS Development

The RTO simulation trial was conducted on UoL's HELIFLIGHT-R facility (Appendix D). Previous testing of the RTO FTM (Refs. 22, 23), in conjunction with workup testing in HELIFLIGHT-R, highlighted the following FS features of importance to cue the EP:

- the Visual Motion Cueing System (VzMCS) i.e., the outside world visual scene content,
- the Vestibular Motion Cueing System (VeMCS) – note that both the VzMCS and VeMCS provide the EP with 'motion cues',
- the crew station layout and structure, including the instrument panel,
- the sound cueing system e.g., main rotor noise, annunciation of failures,
- the flight control inceptors and related forces.

Another consideration in the RCbS FS Credibility assessment is the role and experience of the EPs who aided in the RTO FTM and FS development. As acknowledged in the SFR assessment, the EPs need to have real-word experience with the FTM, ideally on the test aircraft, to provide confidence in the FS development and assessment process. Five pilots participated in the work-up and formal RCbS simulation trials, all with experience flying the CAT A RTO manoeuvre.

6.1.1 VzMCS Development

The VzMCS feature provides the EP with visual motion cues. Definition of the VzMCS feature sufficiency requirements can be considered under several categories e.g., Field of View (FoV), micro- macro-textures, pixels per arc/s, and image generation transport delay (Ref. 19), In terms of an ACR, CS-29 paragraph 773, "*Pilot compartment view*" states:

"*Each pilot compartment must be arranged to give the pilots a sufficiently extensive, clear, and undistorted view for safe operation.*"

Some further guidance on the "*Pilot compartment view*" requirement is provided in AC-29 paragraph 773 which states:

"v) For steep rejected take-offs and steep approaches such as used for oil rigs or confined heliports, the visibility should be such that the pilot can see the touchdown pad and sufficient additional area to the side and forward to provide both an accurate approach to the touchdown point as well as a satisfactory degree of depth perception".

Two aspects of the VzMCS were examined for this requirement: FoV and the degree of depth perception, acknowledging that for the latter, there is no objective requirement defined.

In previous testing at the DLR simulation facility (Ref. 23), the 'Level C' FoV requirement of 150° x 40° horizontal/vertical FoV (Ref. 19) did not provide sufficient vertical FoV for maintaining sight of the helipad during the manoeuvre. Also, limiting the horizontal FoV to less than 180° has the consequence of restricted peripheral cues for the EP. In testing at the DLR and UoL simulators, with FoV's 240° x 93° and 230° x 70°respectively, the inclusion of chin windows provided the additional vertical FoV that the EP required to maintain full sight of the helipad following the engine failure. The ability of the EP to maintain the helipad in the FoV was assessed at UoL using eye tracking that allowed real-time and post-sortie analysis of the EPs' scanning pattern during the test. Figure 15 shows a still image from a video recording of an EP's scan following the engine failure and descent to the helipad. The green dot shows the pilot's gaze point, indicating that he was able to maintain the helipad in view during the descent.

Figure 15: Post engine failure eye tracking during the phase 3 of the FTM

Regarding micro- and macro-texture VzMCS fidelity, two EPs flew assessment tests at UoL, without the VeMCS feature active. Pilot C commented that the ground texture on the helipad and in the near and far field (Figure 16a) did not provide sufficient detail to aid precise flightpath control in the final phases of the MTE, the flare and landing. Following their assessment, the helipad texture detail was enhanced (Figure 16b) with additional texture layers to increase the scene content and additional medium and far field features e.g., vehicles, trees on distant hills to add depth cues.

(a)

(b)

Figure 16: Original (a) and enhanced (b) VzMCS for the start of the RTO FTM.

6.1.2 VeMCS Development

A key element of the VeMCS feature is the design of the Motion Drive Algorithms (MDA), or motion filters. Previous research at UoL has shown that careful selection of the MDA parameters, gains (k) and high pass break frequencies (ω_{hp}), is essential to provide both sufficient and 'correct', i.e. not adverse VeMCS cues (Refs. 24-26). The research has shown that sufficient vestibular motion cues could be achieved by careful harmonisation of the motion filter gains for a yaw-sway (Ref. 24), roll-sway (Ref. 25) and pitch-surge task (Ref. 26). Reference 27 proposes a framework that should be adopted for the systematic tuning of motion filter parameters for a simulator flying task. A similar 'tuning' approach was adopted in the current study considering both the primary and secondary axes of the FTM. The pitch-surge motion filters were initially tuned from a default set (Intermediate T45) before further tuning was conducted to provide additional yaw and heave cueing following the engine failure and in the final flare (Tuned RTO). The parameters of both sets are given in Table C2, Appendix C.

Subjective assessment of the VeMCS feature was undertaken using the Motion Fidelity Rating (MFR) scale (Ref. 24) in advance of the RoCS testing. A 'default' MDA tuning set which had been tuned for general rotorcraft flying i.e., not for this FTM, and an MDA set tuned for the RTO FTM were assessed using two EPs against a case with the VeMCS disabled.

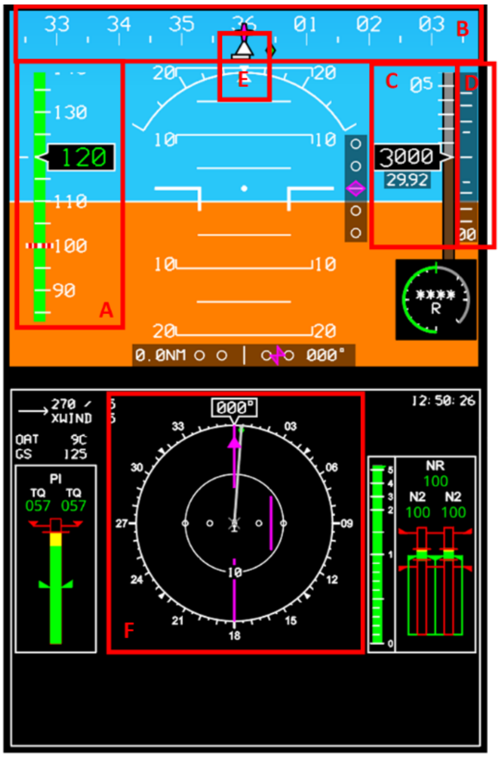
Both pilots found reported that enabling the VeMCS improved task performance in the RTO FTM, allowing for improved control of ground speed and rate of descent when approaching touchdown. However, the Intermediate T45 tuning set gave adverse cues to the pilot in the bow and flare phases of the manoeuvre where large pitch changes were required. Both pilots also cited a lack of yaw and heave cues after the engine failure as deficiencies with the default MDA tuning.

These issues were addressed in the RTO-tuned set by increasing heave gain and break frequency, increasing yaw gain, and reducing pitch break frequency. Other minor changes were made to harmonise with the changes that addressed the primary deficiencies. The tuned MDA gains allowed for marginally improved task performance, but significantly improved perceived fidelity of the VeMCS for both pilots.

Both EPs did comment on poor heave cueing in the final phase of the FTM, attributed partly to disengaging the motion platform during the final flare to prevent any undue structural loading to the projectors of the visual system; a point that was revisited in the formal June 2023 trial.

6.1.3 Additional FS Development

The AW109 Trekker uses the Genesys Aerosystems IDU-680 instrument panel (Ref. 28). A replica of this panel was developed and implemented in the HELIFLIGHT-R simulator (Figure 17) using Presagis' VAPS XT software. Ideally, adopting the RCbS process, full details of the specific aircraft's panel functionality would have been provided in Phase 1. However, as this was not available an initial implementation was developed based on information from the publicly available IDU-680 (H) user manual (Ref. 28) which describes a generic version of the IDU-680, not one specific to the Trekker. The panel was updated during workup testing based on EP feedback e.g., removal of 'clutter' around the attitude indicator to provide clearer indication of pitch information.



A – Airspeed Display

B – Heading Display

C – Barometric Altitude Display

D – Climb Rate Display

E – Sideslip Indicator

F – Heading Display with Lateral Track Indicated in Purple

Figure 17: Genesys Instrument Panel

An important element of the RTO testing was to ensure that a representative test point was evaluated. This is based on the flightpath profile i.e., a climb rate of approximately 350ft/min and a rearwards ground speed of 4-5kts prior to the engine failure (see Appendix A). Profiles outside this range can be considered as test points for 'abuse case' testing, but the aim of this testing was to examine certification for a 'standard' flightpath profile. To assist with the assessment of this 'standard' profile, a performance display was added to the Genesys multi-function display. The FS operator could use the performance display during flight to provide real-time flightpath correction information e.g., above/below desired flightpath (lower right indication in Figure 18). The current value of a performance variable is indicated by a blue cross in each of the displays. During flight, the EP could not see this panel, but could access it after a test point to assess their performance at touch down (TD), shown by a white 'X' on the display.

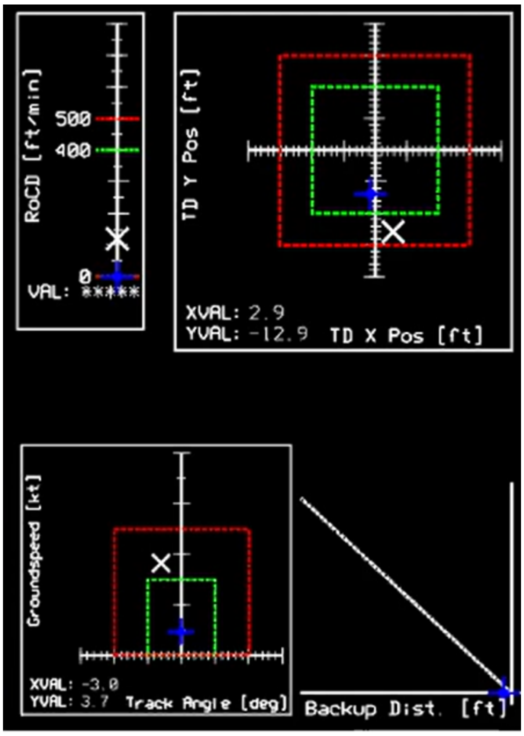


Figure 18: RTO Performance Parameter display.

Another element that was developed during the workup trials was an automatic engine failure engagement which could be triggered at a defined height above the ground. This was developed to provide consistency in the engine failure point during testing. It is acknowledged that in real-world testing there would be variations in the failure height, and this could be included in future 'abuse case' testing.

Based on EP feedback in previous RoCS testing it was identified that variations in N_R of +/- 1-2% could be detected through aural cueing. Hence HELIFLIGHT-R's Audio Cueing System feature, SimAudio, was improved to modulate the audio file of the rotor noise (over a small frequency and amplitude range) to better cue N_R variations. SimAudio was also upgraded to enable failure aural cues to be provided directly to the EP via their headset to reduce any potential delay in recognising and responding to an engine failure.

7 PILOTED SIMULATION ASSESSMENT

The aim of the simulator testing presented in this paper was to illustrate how an applicant might achieve the I4-P3 approval for a CAT A RTO. As part of the Phase 2b V&V, a fidelity evaluation of the FS was undertaken using the Simulation Fidelity Rating (SFR) scale (Ref. 21). The SFR scale[3] allows the EP to assess the FS fidelity based on a comparison of the task performance achieved in flight and in the FS, together with an assessment of any adaptation of strategy. Clearly, experience with the real aircraft in flight is a pre-requisite here. To aid in the FS fidelity assessment, HQRs and SFRs were awarded by the EP, supported by comments obtained using an in-cockpit questionnaire (ICQ) (Appendix E); it should be noted that 'equivalent' HQRs had not been awarded in flight, but the EP was familiar with the RTO on the 109 Trekker. The ICQ has been designed to elicit structured feedback on:

- FS feature fidelity e.g., visual and vestibular cues,
- HQR metrics e.g., task performance and pilot compensation,
- the phase of the FTM 'driving' the HQR,
- the award of other ratings, e.g., Pilot Induced Oscillation ratings and MFRs.

The EP's assessment of the task performance achieved was supported by feedback from the operator using the display shown in Figure 18 and also by a non-handling pilot in the FS left-hand seat. The role of the non-handling pilot was defined prior to testing as:

- Any duties as directed by the EP.

[3] The SFR scale documented in Ref. 21 was originally aimed at application to flight training but was modified, as shown in the Appendix C, for application in the RCbS process.

- Note task performance and be prepared to provide additional feedback to the EP if required.
- Monitor control inputs for frequency and amplitude and provide feedback if required.
- Monitor cockpit motion, visual and aircraft flightpath anomalies and feedback if necessary.
- Ensure a copy of the FTM description and all relevant questionnaires are in the cockpit.
- Provide feedback, if required, during the relevant item in the ICQ and not before.

7.1 DoV Testing

Testing was conducted at an aircraft mass of 3115kg at a pressure altitude of 748ft. A comparison of the flight and FS data is presented in Figure 19 and Figure 20. The dashed vertical line indicates when the engine failure occurs, and the grey shaded area represents the CS-STD(H) fidelity boundaries for the flight test data.

In the RCbS process, comparisons between flight test and FS data would be made during the Phase 2b V&V assessment activity. As shown in section 5.4.1, the FSM predictive fidelity showed an acceptable match, between flight test and offline FSM predictions. Hence any differences observed between flight test and FS data, e.g. shown in Figure 19 to Figure 21, could indicate an FS fidelity issue. It should be noted here that the EP who conducted the simulator testing was not the same as the EP in flight test. Furthermore, the flight test point was not conducted using the new FTM; it was conducted solely using the RTO procedures described in the RFM. The FTM used in simulator testing is also based on the RFM procedures, but additionally applies performance standards to enable HQR evaluation, which may alter pilot strategy.

Differences between flight and simulation are evident in the control strategies used following the engine failure. In both cases, the pilot makes a forward longitudinal stick input and lowers collective following the engine failure, shown in Figure 19 (a) and Figure 20 (b), but the orders are reversed in flight and in simulation. This difference in control strategy then affects the aircraft response shown in the pitch attitude, ground speed and RoCD plots.

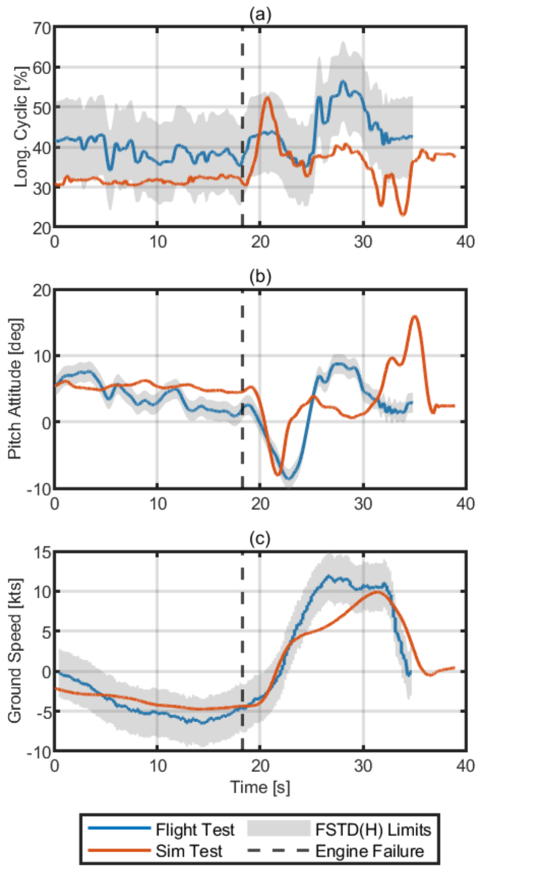


Figure 19 Comparison of flight and simulator test data for longitudinal cyclic (a), pitch attitude (b) and ground speed

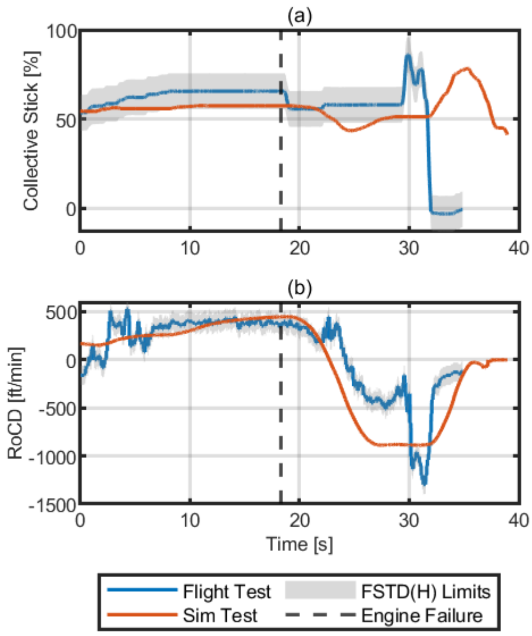


Figure 20 Comparison of flight and simulator test data for collective (a), rate of climb/descent (RoCD) (b)

The results show that rates of descent prior to TD exceed 800ft/min in both flight and simulator. The F-AW109 FSM 'raises a flag' when the conditions for vortex-ring-state are entered, although the consequent loss of vertical control is not modelled correctly. The RoCS team consider that the risk of entering VRS in this FTM needs to be given more attention and the modelling improved to more accurately represent behaviour following entry.

Figure 21 (a) shows that engine torque response in flight and simulation is similar during until the final phase of the manoeuvre, and that in flight and simulation, the EP is able to achieve the requirement of 101% main rotor speed following the failure, as required in the manoeuvre description. The differences between flight and simulation N_R time-histories reflect the control strategies mentioned above.

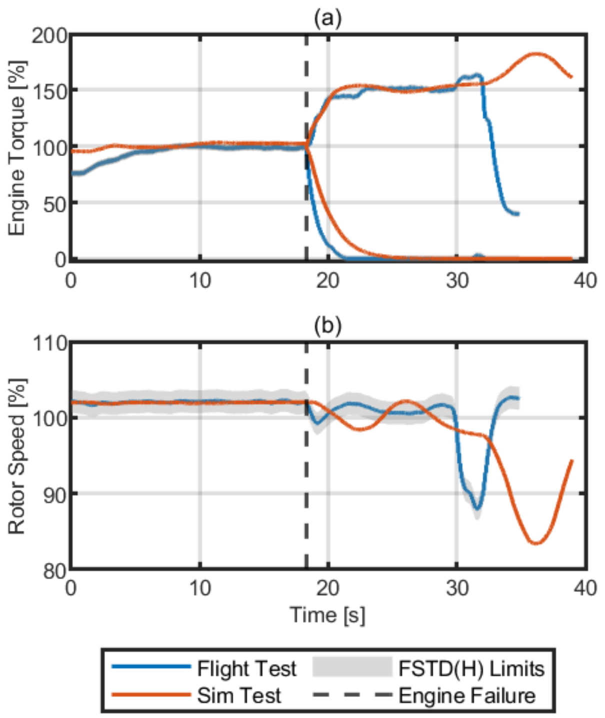


Figure 21 Comparison of flight and simulator test data for engine torque (a), main rotor speed, N_R (b)

A subjective fidelity assessment of the FS, with motion-on, was conducted using the SFR scale (Ref. 21) at a reduced aircraft mass of 3040kg. The EP awarded an SFR 5, indicating that "*similar performance*" was attainable with a "*moderate adaptation of task strategy*". The EP achieved similar task performance in terms of plan-position, vertical and ground speed at TD compared with flight. In terms of task strategy adaptation, the EP reported that he was conducting the FTM in a "*similar manner*" to that used in flight (positions 1-3 in Figure 4). However, during the final flare phase (position 4 in Figure 4) there was a lack of "*ground rush*" motion cueing which led to a moderate adaptation with the EP "*looking for other cues*" to aid in this phase of the FTM. As noted above, in the HELIFLIGHT-R testing, it has been standard practice to disengage the motion base during the final moments of the FTM to prevent any potential projector misalignment issues following 'hard' contact with the ground. The EP was asked to rate the FS fidelity, ignoring the final flight phase (position 4 in Figure 4), and awarded an SFR 2. This indicates that the cueing fidelity was 'sufficient' for this FTM for the proposed certification IP level.

The flight and simulator results both demonstrate 'successful' RTOs, but comparison is difficult when different piloting strategies have clearly been applied, and the tasks have not been flown to consistent standards of performance. Furthermore, no HQR was available for the flight test case, as it was not flown to a defined FTM definition and evaluated in this way. These factors make objective assessment of FS fidelity difficult, but subjective metrics such as the SFR are still useful tools for the FS fidelity assessment. To enable more objective comparisons, it is critical to define and use a standardised FTM, with defined performance parameters, for both flight and simulator testing if the simulator is to be used for RCbS.

The utility of the VeMCS was investigated through a comparison of testing with motion-off and motion-on in the DoV, as shown in Figure 22 and Figure 23. The figures show results for multiple practice runs and the rated run. In the motion-off case (Figure 23 (a)) the EP required a larger number of runs prior to the award of an HQR compared with the motion-on case. A larger scatter of TD parameters is also noted (Figure 22 (b)), the increased range of which is illustrated by the upper and lower black bars in Figure 23 compared with the motion-on case testing.

Whilst an HQR 4 was awarded in both the motion-on and -off cases (rated runs denoted by circles in Figure 22), the EP reported that he was able to better control flightpath with the motion-on and the TD RoCD and groundspeed was well within desired performance, compared with the motion-off case, where borderline desired performance was achieved. The performance achieved was confirmed by the non-handling pilot. An MFR 5 was awarded for the motion-on case indicating that "*useful*" VeMCS cues were provided for the task. In both cases, the EP reported that 101% N_R could be achieved following the failure and that the driving phase of the FTM for the HQR was the flare to TD.

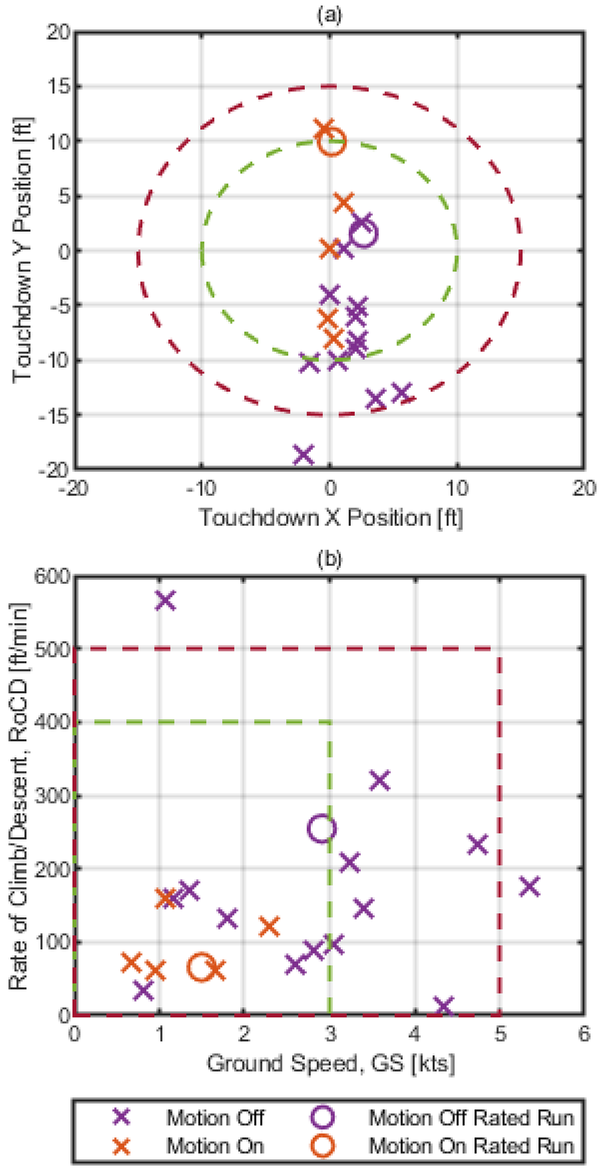


Figure 22: Effect of motion off/on for landing scatter (a) and TD parameters (b) during DoV testing

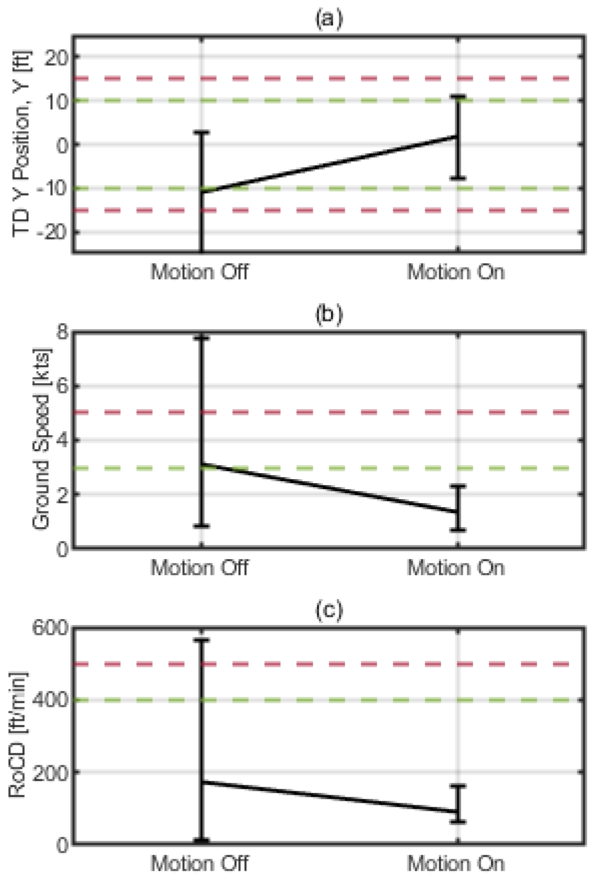


Figure 23: Range of Y position (a), ground speed (b) and RoCD (c) for motion off/on testing

In subsequent testing in the DoE, at an aircraft mass of 2455kg, the importance of including motion to the TD point was examined. Figure 24 shows the effect of maintaining motion-on to the TD point compared with deactivating it in the final phase.

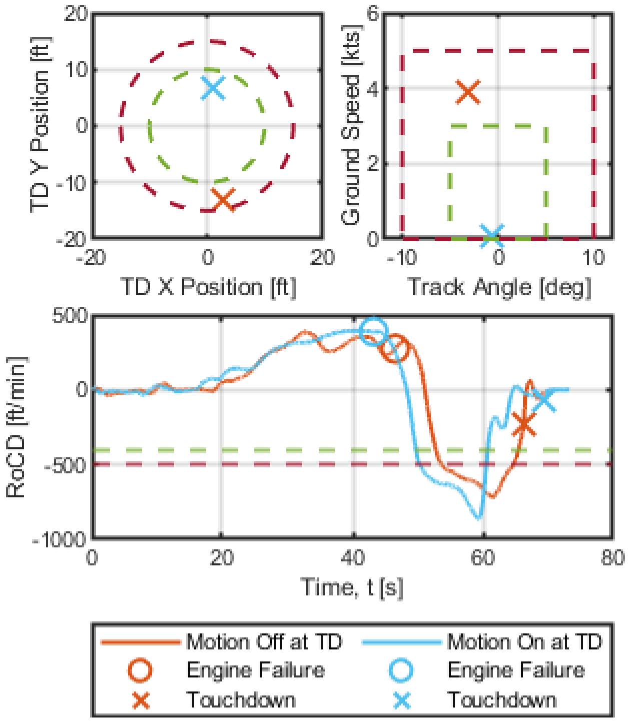


Figure 24: Comparison of performance for motion-off with motion-on

Using the ‘standard’ approach of disabling the motion in the final phase of the FTM resulted in ground speed being outside desired performance with the pilot awarding an HQR 5. With motion-on to the TD point, the EP was able to better control ground speed and could achieve desired performance, resulting in an HQR 4 being awarded. The non-handling pilot confirmed the EP’s assessment during the testing.

7.2 DoE Testing

The section above has focussed on the fidelity assessment of the FS which is a critical part of the RCbS process, but the ultimate goal is to demonstrate that the FSM and FS have sufficient credibility to achieve full credit in the DoE (I4-P3).

Whilst results of the testing in the DoV, (pressure altitude of 745ft with an aircraft mass of 3115kg), were considered representative of ‘real-world’ conditions, it should be noted that this is a preliminary result and that further testing would be required related to ‘abuse case’ assessment. Nonetheless, the results provided sufficient confidence to conduct testing in the DoE.

The DoE tests were conducted with the motion-on at TD. An incremental approach was used to determine the maximum take-off mass for CAT A operations in the DoE. Starting at a mass of 2430kg, a minimum of three tests were flown before an HQR was awarded. Following the award of an HQR, the mass was increased in 25kg increments in testing up to a maximum that could be achieved. Figure 26 and Figure 26 show the ranges of the TD parameters recorded and maximum engine torque used after the engine failure (given by the upper and lower limits of the black bars) for all tests, as the aircraft mass was increased.

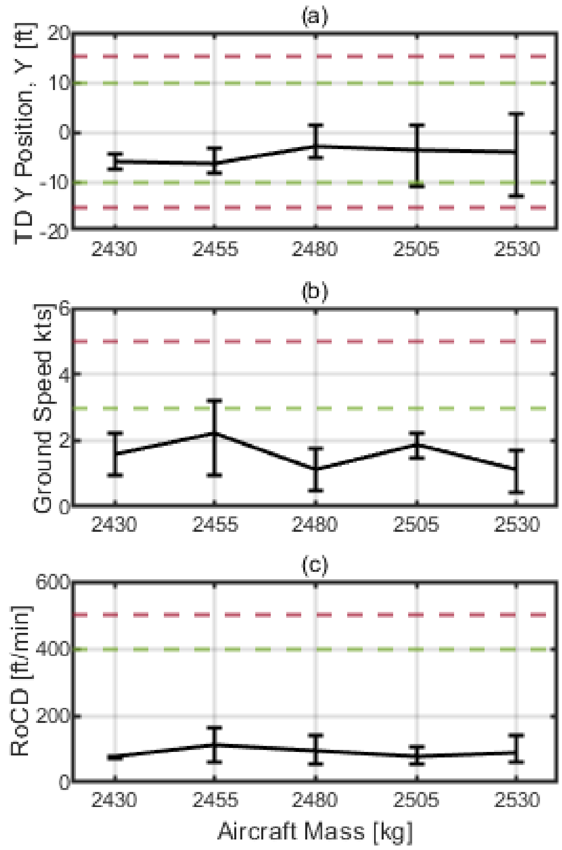


Figure 25: Range of Y position (a), ground speed (b) and RoCD (c) with increasing aircraft mass during DoE testing

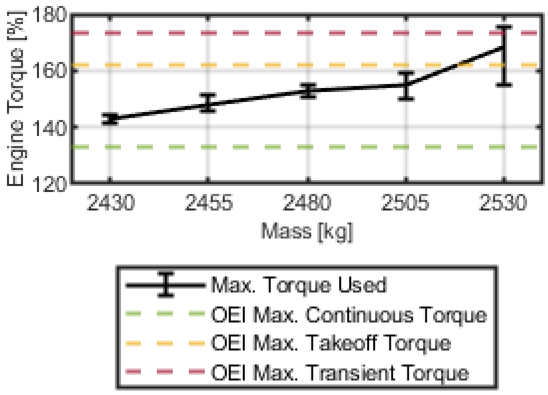


Figure 26: Ranges of the maximum (single-engine) torque used after the engine failure with increasing aircraft mass during DoE testing

At a mass of 2430kg, the EP awarded an HQR 4 noting he was within desired performance for all parameters, he was able to achieve 101% N_R following the failure, and there was moderate compensation in the longitudinal cyclic during the initial bow and final flare of the FTM. As the aircraft mass was increased to 2480kg, there is a small change in the range of the TD parameters, all still within desired performance values, and an increase in the maximum torque used is observed; the EP awarded an HQR 4 for all these configurations. Increasing the mass to 2505kg, the EP still awarded an HQR 4, but there is an increase in the range of longitudinal touchdown points, *Y*, for this test condition (Figure 25 (a)) and the maximum torque used increases (Figure 26) with the EP reporting a noticeable reduction in engine performance margin.

Increasing the mass to 2530kg, the EP awarded an HQR 5 noting that whilst longitudinal position performance was "*borderline*" desired, he was encountering issues with maintaining N_R (Figure 27 (c)) and reached pedal limits (Figure 27 (b)) whilst applying collective (Figure 27 (a)) in the flare at TD. The EP's assessment of task performance was confirmed by the non-handling pilot. In the EP's opinion, noting that further testing would be required including 'abuse' case testing, this aircraft mass would not be certified for this ACR.

The outcome of the testing was that the EP considered that "*full credit*" could be obtained for this ACR in the DoE at a mass of 2505kg at the extrapolated high-altitude condition with the FS environment developed in this case study.

It should be noted here that this is an initial result as abuse case testing would be required for 'clearing' this mass for certification based on, for example, variations in RoC in the climb out phase and engine failure height. Nonetheless, from communication with LHD, the mass identified as the limiting case for the DoE extrapolation is representative of that certified for the aircraft per the weight-altitude-temperature charts in the RFM. This is an encouraging result for the RCbS process proposed in the RoCS project.

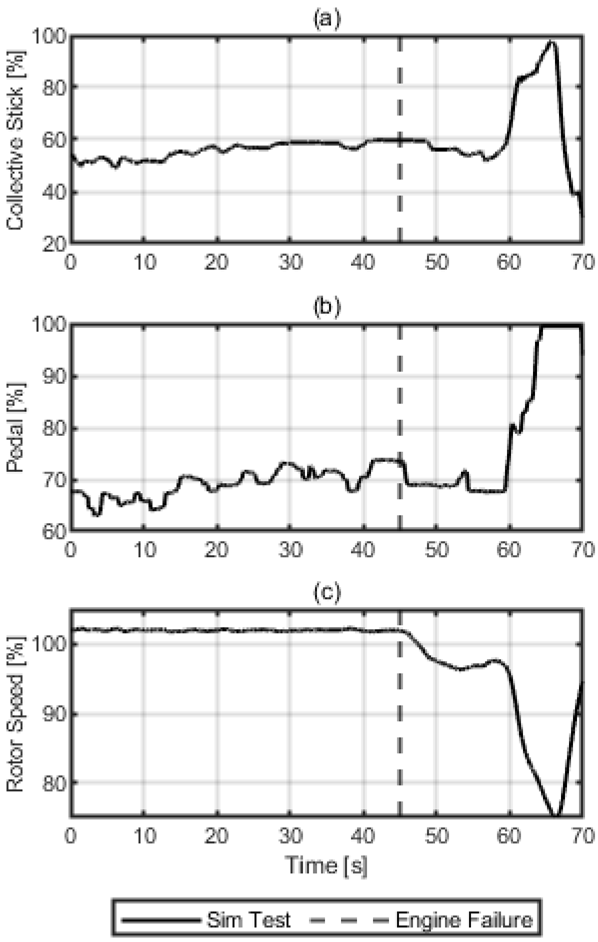


Figure 27 Time histories of collective position (a), pedal position (b) and main rotor speed, N_R, (c) for the 2530kg test condition

8 CONCLUDING REMARKS AND RECOMMENDATIONS

This paper has reported on an exercise of the RCbS process and presented results from the case study on the CAT A RTO ACR as expressed in CS-27 and 29.

A general conclusion is that an FS has been developed, including the FSM, to be of sufficient fidelity to allow full credit for testing in the defined DoV and DoE. Detailed conclusions from the case study are as follows:

(i). An FTM has been designed to enable Phase 2b FS fidelity and Phase 3 credibility assessment to be conducted.
(ii). The use of a virtual pilot model to aid in the tuning of the FSM is a viable step in the V&V process for this ACR.
(iii). The VeMCS feature, and the MDA configuration used, had a positive impact for this ACR in terms of control of touch-down speed and

plan position.

(iv). The SFR scale provides a useful tool for assessing the (perceived) fidelity of the FS for the chosen ACR.

(v). The non-handling pilot role is important for both the FS fidelity assessment and certification testing.

(vi). Extrapolation from the DoV to the DoE condition in terms of altitude increase) has been shown to be viable for this ACR, indicating the feasibility of the RCbS process.

The results in this paper, whilst promising, pose additional questions that provide 'fruitful' areas for exploration. For example, what would be an acceptable HQR for an ACR, if adopted in the certification process? Another example, would be; how should an MDA be designed to match with the dynamics of a particular ACR? These and other questions should be addressed in the continuing development of the Guidelines and application by users of the RCbS processes.

The paper is one of a collection of case studies presented at the 49th ERF, material from which will be included in the final issue of the RoCS project Guidelines for the application of modelling and simulation in rotorcraft certification, scheduled for publication in late 2023.

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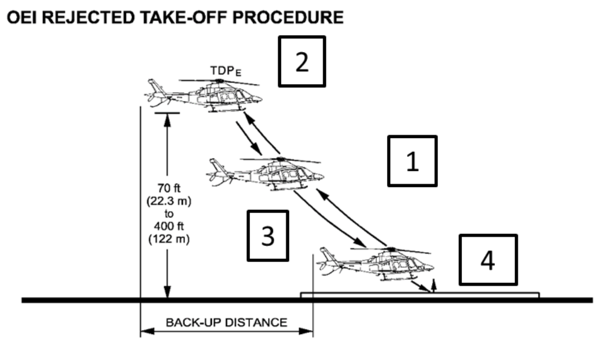
10 REFERENCES

1. Bianco-Mengotti, R., Ragazzi, A., Del Grande, F., Cito, G., and Brusa Zappellini, A., "AW189 Engine-Off-Landing Certification by Simulation," AHS 72nd Annual Forum, West Palm Beach, FL, May 17-19, 2016.
2. Ragazzi, A., Bianco-Mengotti, R., and Sabato, P., "AW169 Loss of Tail Rotor Effectiveness Simulation," 43rd European Rotorcraft Forum, Milano, Italy, September 12 – 15, 2017.
3. anon., "Certification Specifications and Acceptable Means of Compliance for Small Rotorcraft CS-27 / Amendment 6," EASA, 2018.
4. anon., "Certification Specifications and Acceptable Means of Compliance for Large Rotorcraft CS-29 / Amendment 5," EASA, 2018.
5. anon., "AC 29-2C - Certification of Transport Category Rotorcraft," FAA, Sept. 2008.
6. anon., "AC 25-7D Flight Test Guide for Certification of Transport Category Airplanes," FAA, 2018.
7. anon., "Third Publication of Proposed Means of Compliance with the Special Condition VTOL," EASA, 2022.
8. Padfield, G. D., "Rotorcraft Virtual Engineering; Supporting Life-Cycle Engineering through Design and Development, Test and Certification and Operations," *The Aeronautical Journal*, Vol. 122, (1255), 2018, pp. 1475–1495, DOI: 10.1017/aer.2018.47.
9. Quaranta, G., van 't Hoff, S., Jones, M., Lu, L., and White, M. D., "Challenges and Opportunities Offered by Flight Certification of Rotorcraft by Simulation," 47th European Rotorcraft Forum, Glasgow, Scotland, UK September 7-9, 2021.
10. van 't Hoff, S., Lu, L., Padfield, G. D., Podzus, P., White, M. D., and Quaranta, G., "Preliminary Guidelines for a Requirements-Based Approach to Certification by Simulation for Rotorcraft," 48th European Rotorcraft Forum, Winterthur, September 6-8, 2022.
11. Quaranta, G., van't Hoff, S., Lu, L., Padfield, G.D., Podzus, P., White, M. D., "Employment of Simulation for the Flight Certification of Rotorcraft", 79th Annual Forum of the Vertical

Flight Society, West Palm Beach, FL, USA, May 16-18, 2023.
12. https://www.rocs-project.org/guidelines/ accessed 28th July 2023.
13. anon., ADS-33E, "Aeronautical Design Standard Performance Specification: Handling Qualities Requirements for Military Rotorcraft," US Army Aviation Engineering Directorate, Redstone, Alabama, March 2000.
14. Cooper, G. E., and Harper, R. P., "The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153,1969.
15. anon., A109S Trekker – RFM Document 109G0040A034 – Supplement 4, CAT Operations General.
16. Serr, C., Hamm, J., Toulmay, F., Polz, G., Langer, H.J., Simoni, M., Bonetti, M., Russo, A., Vozella, A., Young, C., Stevens, J., Desopper, A. and Papillier, D., "Improved Methodology for Take-Off and Landing Operational Procedures: The Respect Programme", 25th European Rotorcraft Forum, Rome, Italy, September 14-16, 1999.
17. van 't Hoff, S., White, M. D., Dadswell, C. M., Lu, L., Padfield, G. D., Quaranta, G., Podzus, P., "Case Studies to Illustrate the Rotorcraft Certification by Simulation Process; CS 29/27 Low-Speed Controllability", 49th European Rotorcraft Forum, Bückeberg, Germany, 5–7th September 2023.
18. Lu, L., Padfield, G. D., White, M. D., Quaranta, G., van 't Hoff, S., Podzus, P., "Case Studies to Illustrate the Rotorcraft Certification by Simulation Process; CS 29/27 Dynamic Stability Requirements", 49th European Rotorcraft Forum, Bückeberg, Germany, 5–7th September 2023.
19. anon., "Certification Specifications for Helicopter Flight Simulation Training Devices CS-FSTD(H)", EASA, Initial issue, June 2012.
20. DuVal, R.W., and He, C., "Validation of the FLIGHTLAB Virtual Engineering Toolset", *The Aeronautical Journal*, Vol. 122, (1250), 2018, pp. 519-555.
21. Perfect, P., Timson, E., White, M. D., Padfield, G. D., Erdos, R., and Gubbels, A. W., "A Rating Scale for the Subjective Assessment of Simulation Fidelity", *The Aeronautical Journal*, Vol. 118, (1206), August, 2014, pp. 953 – 974.
22. White, M. D., Perfect, P., Padfield, G. D., Gubbels, A. W., and Berryman, A. C., "Acceptance testing and commissioning of a flight simulator for rotorcraft simulation fidelity research" *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 227 (4), April 2013, pp. 663 – 686.
23. Podzus, P., White, M. D., Dadswell, C. M., van 't Hoff, S., and Crijnen, J., "Evaluation of Simulator Cueing Fidelity for Rotorcraft Certification by Simulation", 78th VFS Annual Forum & Technology Display, Fort Worth, Texas, May 10-12, 2022.
24. Hodge, S. J., Perfect, P., Padfield, G. D., and White, M. D., "Optimising the Yaw Motion Cues Available from a Short Stroke Hexapod Motion Platform", *The Aeronautical Journal*, Vol. 119, (1211), January, 2015, pp. 1-21.
25. Hodge, S. J., Perfect, P., Padfield, G. D., and White, M. D., "Optimising the Roll-Sway Motion Cues Available from a Short Stroke Hexapod Motion Platform", *The Aeronautical Journal*, Vol. 119, (1211), January, 2015, pp. 23-44.
26. Roscoe, J., White, M. D., Hodge, S.J., and Padfield, G. D., "Rotorcraft Pitch-Surge Motion Cueing Requirements for a Simulated Offshore Approach Task", 78th VFS Annual Forum & Technology Display, Fort Worth, Texas, May 10-12, 2022.
27. Schroeder, J. A., "Helicopter Flight Simulation Motion Platform Requirements," NASA/TP-1999-208766, 1999.
28. anon., IDU-680 Version 8.0E, Pilot Operating Guide and Reference, Document 64-000098-080E, Genesys Aerosystems, November, 2016

APPENDIX A – CAT A RTO (Confined Area) FTM

<table>
<tr><td>Mission</td><td colspan="4">Civil Transport</td></tr>
<tr><td>Critical HQs</td><td colspan="4">Vertical velocity and N_R response to collective, pitch/roll response to cyclic; cross-couplings: pitch/roll, roll/pitch, collective/yaw, collective/pitch</td></tr>
<tr><td>Objectives</td><td colspan="4">• Check ability to perform steady climb to Take-off Decision Point.
• Check ability to return to a helipad after failure of one engine, while controlling vertical descent rate and forward speed with longitudinal cyclic and lateral track and roll angle with lateral cyclic and pedals, whilst monitoring N_R.</td></tr>
<tr><td>Manoeuvre Description</td><td colspan="4">The EP shall perform the confined area take-off procedure as described in the AW109S Trekker Rotorcraft Flight Manual (RFM). Starting from a stabilised hover 5ft above the ground, on a Northerly heading at the centre of the helipad, the EP will initiate a (nominal) 350 ft/min Rate of Climb (RoC) whilst maintaining sight of the helipad by translating backwards (position 1 in the figure below). The EP will continue the ascent towards the Extended Take-Off Decision Point (TDP_E) while keeping the helipad in view. The aircraft will experience a single engine failure during the climb (position 2) and the EP will initiate a One-Engine-Inoperative (OEI) return to the helipad. The EP will lower collective to stop climbing and apply forward cyclic to arrest the rearwards motion and capture a descending flightpath to return to the helipad, maintaining sight of the helipad during the descent (position 3). An N_R value of 101% should be re-captured following the failure. The collective should be adjusted to cushion the touchdown (TD) as required (position 4). Rate of Descent (RoD), ground speed and track angle at TD must be within performance requirements below.</td></tr>
<tr><td rowspan="3">Test Variations</td><td rowspan="2">Condition</td><td>Failure Height</td><td>Mass</td><td>Pressure Altitude</td></tr>
<tr><td>120ft
120ft</td><td>3,115 kg
Up to MTOWkg</td><td>745ft
9,280ft</td></tr>
<tr><td colspan="2">TDP_E</td><td colspan="2">400 ft</td></tr>
<tr><td>Test Course Description</td><td colspan="4">Helipad, with appropriate markings situated in a confined area and in Visual Meteorological Conditions (VMC)</td></tr>
<tr><td>Ratings Scales</td><td colspan="4">1. Simulation Fidelity Rating (SFR) Scale (Ref. 21)
2. Motion Fidelity Rating Scale (MFR) (Ref. 24)
3. Cooper-Harper Handling Qualities (HQR) Rating Scale (Ref. 23)</td></tr>
<tr><td rowspan="5">Performance Standards</td><td colspan="2"></td><td>Desired (d)</td><td>Adequate (a)</td></tr>
<tr><td colspan="2">Landing position from centre of helipad:</td><td>±10ft</td><td>±15ft</td></tr>
<tr><td colspan="2">TD Rate of Descent:</td><td>< 400 ft/min</td><td>< 500 ft/min</td></tr>
<tr><td colspan="2">Track angle at TD:</td><td>±5º</td><td>±10º</td></tr>
<tr><td colspan="2">Forward ground speed at TD:</td><td>3kts</td><td>5kts</td></tr>
</table>



APPENDIX B

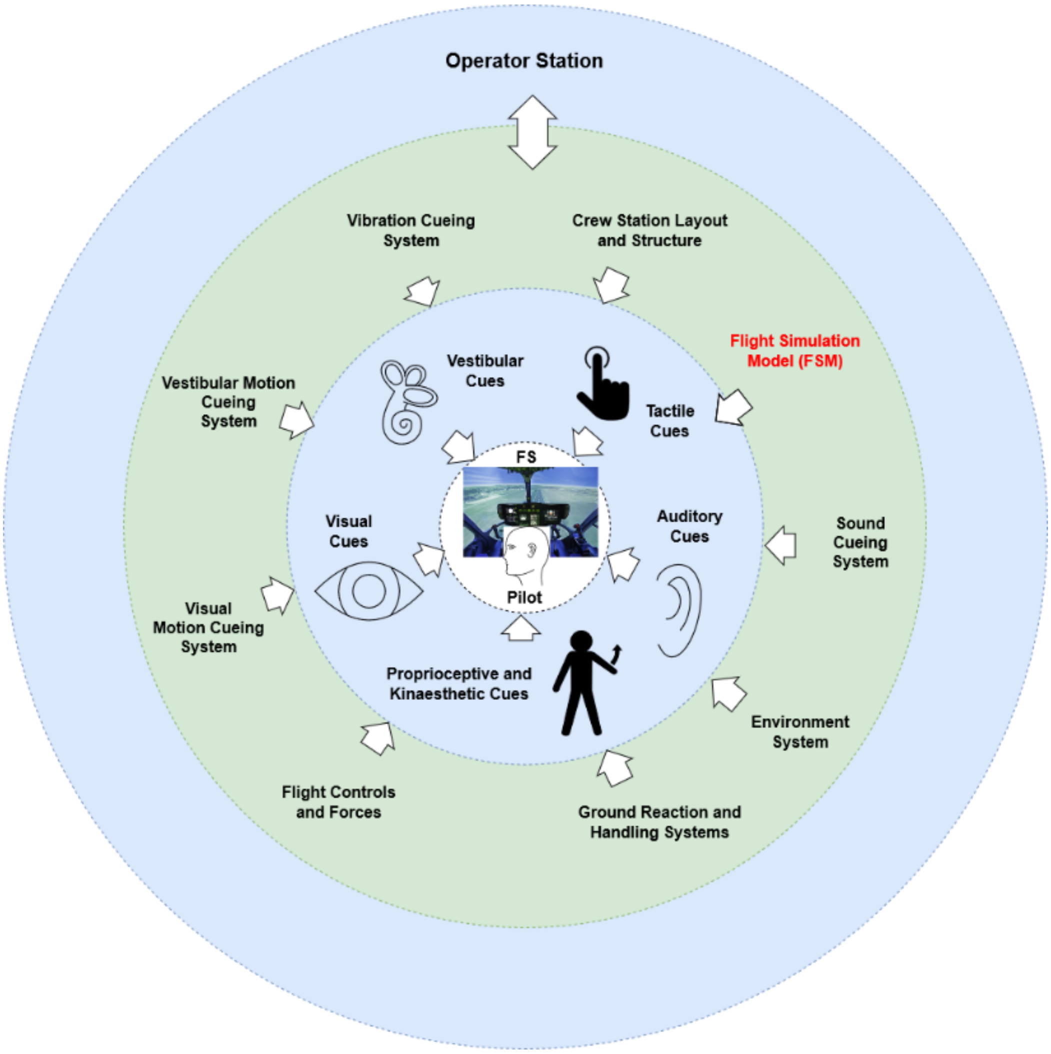
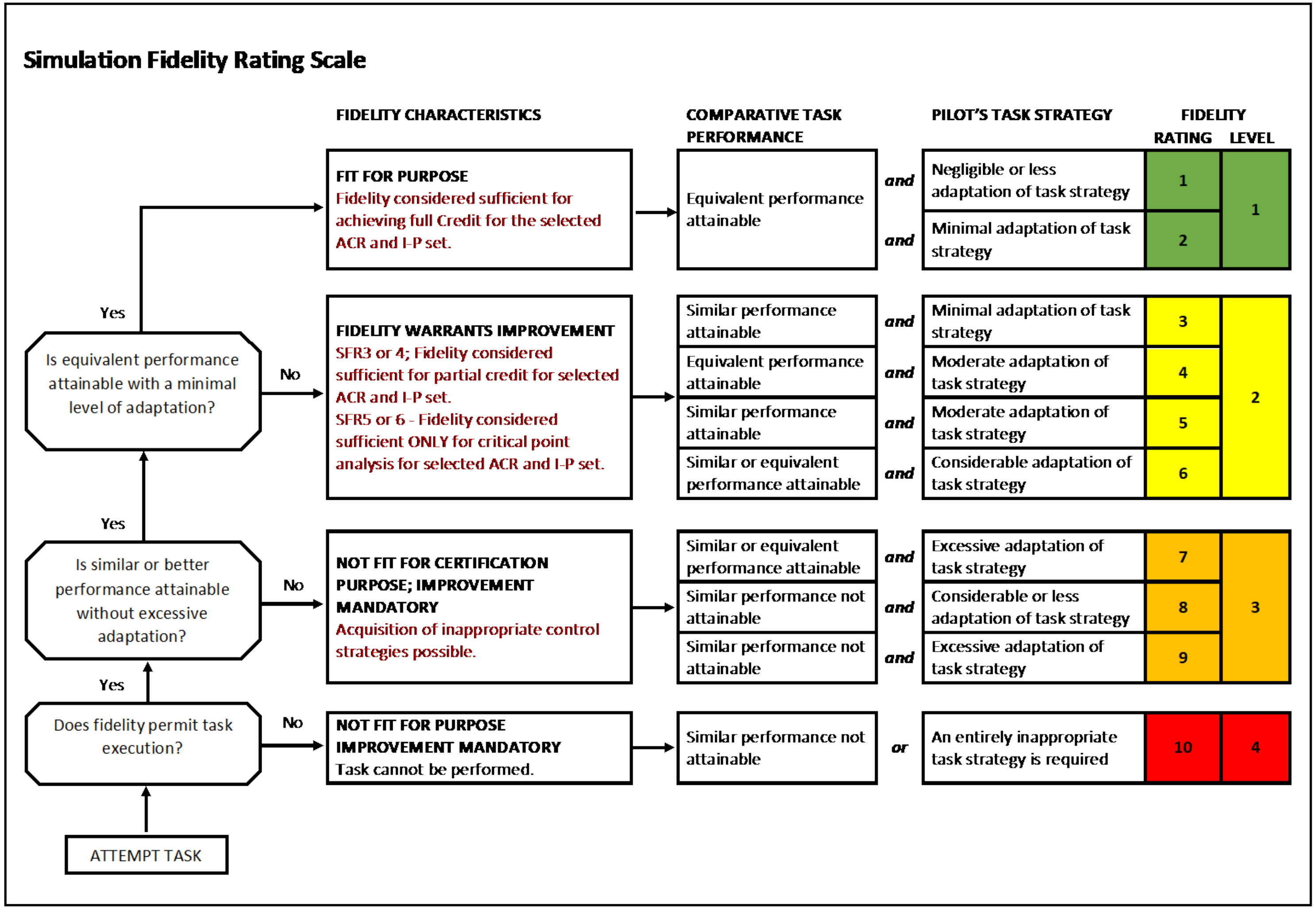


Figure B1: FS Features

Appendix C


Simulation Fidelity Rating Scale
FIDELITY CHARACTERISTICS
COMPARATIVE TASK PERFORMANCE
PILOT'S TASK STRATEGY
FIDELITY
RATING
LEVEL
FIT FOR PURPOSE
Fidelity considered sufficient for achieving full Credit for the selected ACR and I-P set.
Equivalent performance attainable
and
Negligible or less adaptation of task strategy
1
and
Minimal adaptation of task strategy
2
1
FIDELITY WARRANTS IMPROVEMENT
SFR3 or 4; Fidelity considered sufficient for partial credit for selected ACR and I-P set.
SFR5 or 6 - Fidelity considered sufficient ONLY for critical point analysis for selected ACR and I-P set.
Similar performance attainable
and
Minimal adaptation of task strategy
3
Equivalent performance attainable
and
Moderate adaptation of task strategy
4
Similar performance attainable
and
Moderate adaptation of task strategy
5
Similar or equivalent performance attainable
and
Considerable adaptation of task strategy
6
2
NOT FIT FOR CERTIFICATION PURPOSE; IMPROVEMENT MANDATORY
Acquisition of inappropriate control strategies possible.
Similar or equivalent performance attainable
and
Excessive adaptation of task strategy
7
Similar performance not attainable
and
Considerable or less adaptation of task strategy
8
Similar performance not attainable
and
Excessive adaptation of task strategy
9
3
NOT FIT FOR PURPOSE
IMPROVEMENT MANDATORY
Task cannot be performed.
Similar performance not attainable
or
An entirely inappropriate task strategy is required
10
4
Yes
Is equivalent performance attainable with a minimal level of adaptation?
No
Yes
Is similar or better performance attainable without excessive adaptation?
No
Yes
Does fidelity permit task execution?
No
ATTEMPT TASK

Simulation Fidelity Rating Scale Terminology

PERFORMANCE:

- **Equivalent Performance:** The same level of task performance (desired, adequate etc.) is achieved for all defined parameters in simulator and flight. Any variation in performance are small.

- **Similar Performance:** There are no large single variations in task performance, or, there are no combinations of multiple moderate variations across the defined parameters.

- **Not Similar Performance:** Any large single variation in task performance, or multiple moderate variations, will put the comparison of performance into this category.

ADAPTATION:

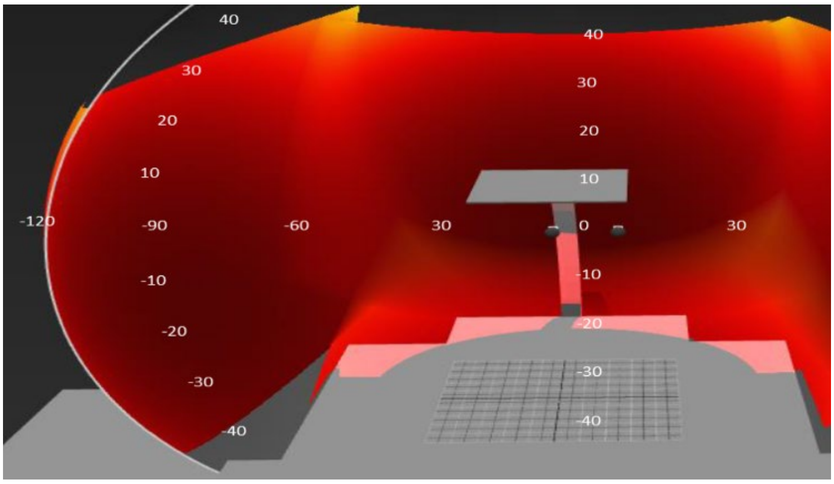
- **Control Strategy:** differences in the size, shape and frequency of the applied control inputs

- **Cueing:** differences in the way in which task cues are presented to the pilot

- **Workload:** including differences in the physical effort of moving the controls; scanning of the available task cues; and the mental work associated with interpreting cues and determining control inputs.

- **Vehicle Response:** differences in the perceived response of the vehicle

APPENDIX D



(a) (b)

Figure D1: Liverpool's HELIFLIGHT-R research simulator (a) (Ref. 23) and projector FoV (b), coloured areas indicating dome image brightness coverage (deeper red represents higher brightness)

Table D1 – HELIFLIGHT-R motion capability

	Displacement	Velocity	Acceleration
Pitch	-23.3°/+25.6°	±34°/s	>300°/s²
Roll	±23.2°	±35°/s	>300°/s²
Yaw	±24.3°	±36°/s	>500°/s²
Heave	±0.39m	±0.7m/s	±1.02 g
Surge	-0.46m/+0.57m	±0.7m/s	±0.71g
Sway	±0.47m	±0.5m/s	±0.71g

Simulator platform movements are determined by the MDA that scale, limit and filter the signals from the FSM to generate VeMCS commands. An example of a third-order filter used for the pitch axis MDA is given in Eqn. (D1) which scales and filters the FSM pitch acceleration, $\ddot{\theta}$, converting it into a commanded motion platform pitch acceleration, $\ddot{\theta}_s$. The parameters k_θ and $\omega_{hp\theta}$ are the pitch high pass (hp) filter gain and break-frequency coefficients, respectively which are 'tuned' for a given FTM. Similar filters are used in other rotational (ϕ, ψ) and the translational axes (x, y, z).

$$\frac{\ddot{\theta}_s}{\ddot{\theta}}(s) = k_\theta HP_\theta(s) = k_\theta \left(\frac{s^2}{s^2 + 2\zeta_{hp\theta}\omega_{hp\theta}s + \omega_{hp\theta}^2}\right)\left(\frac{s}{s + \omega_{b\theta}}\right) \quad \text{(D1)}$$

Table D2 – RTO FTM MDA parameters

	Surge		Sway		Heave		Roll		Pitch		Yaw	
MDA	k_x	ω_{hpx}	k_y	ω_{hpy}	k_z	ω_{hpz}	k_ϕ	$\omega_{hp\phi}$	k_θ	$\omega_{hp\theta}$	k_ψ	$\omega_{hp\psi}$
Intermediate T45	0.3	1.8	0.25	2.0	0.2	1.9	0.35	0.9	0.35	0.9	0.35	0.9
Tuned RTO	0.5	1.0	0.5	1.0	0.7	2.8	0.4	0.4	0.35	0.4	0.87	0.6

Appendix E

UNIVERSITY OF LIVERPOOL
FLIGHT SCIENCE & TECHNOLOGY
IN-COCKPIT QUESTIONNAIRE

A. TASK CUES • FIELD OF VIEW • SCENE CONTENT • VESTIBULAR MOTION • DISPLAYS • AUDIO	INADEQUATE FOR TASK	POOR	FAIR	GOOD	VERY GOOD
B: PERCEIVED LEVEL OF AGGRESSION • % OF AIRCRAFT PERFORMANCE	VERY HIGH	HIGH	MODERATE	LOW	VERY LOW
C: TASK PERFORMANCE • TIME • PRECISION • TASK TOLERANCES	ADEQUATE PERF. UNACHIEVABLE	ADEQUATE PERF. ACHIEVED MARGINALLY	ADEQUATE PERF. ACHIEVED COMFORTABLY	DESIRED PERF. ACHIEVED MARGINALLY	DESIRED PERF. ACHIEVED COMFORTABLY
D: COMPENSATION • SPARE CAPACITY • CONTROL ACTIVITY	EXTENSIVE	CONSIDERABLE	MODERATE	MINIMAL	NOT A FACTOR

AXES ORDER (1/2/3/4):	LAT.		LONG.		PEDAL.		COLL.		

HQR:		**INFLUENCING FACTORS**	**-/0/+**	**KEYWORDS**
DRIVING FTM PHASE:		PRIMARY RESPONSE		
PIO RATING:		COUPLING		
MFR:		FLIGHT CONTROLS		
MFR SUFFIXES:	**N** NOISE **L** LATENCY **M** MISMATCH **R** RETURN **S** SPURIOUS **A** ATTENUATION **C** COORDINATION **O** ONSET **B** BIODYNAMIC FEEDBACK	VEHICLE LIMITS		
		STABILITY		
		VISUAL MOTION		
		VESTIBULAR MOTION		