

# Preliminary Guidelines for the Rotorcraft Certification by Simulation Process<sup>1</sup> Update No 1, March 2023

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

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

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

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

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



**The RoCS Team**



<sup>1</sup> The RoCS project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 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.

## 30 **Table of contents**

31	Executive Summary .....	5
32	1 Introduction.....	9
33	1.1 Purpose and Scope .....	9
34	1.2 Background.....	9
35	1.3 Document Structure .....	10
36	1.4 References.....	12
37	1.5 Abbreviations.....	14
38	1.6 Definitions .....	17
39	1.7 List of Symbols.....	21
40	2 Structure of the Rotorcraft Certification by Simulation (RCbS) process .....	23
41	3 Requirements-Capture and Build (Phase 1) .....	25
42	3.1 Introduction.....	25
43	3.2 Influence, Predictability and Credibility Levels.....	26
44	3.2.1 Credibility and the Assessment of Confidence.....	28
45	3.2.2 CR in the I-P Matrix.....	33
46	3.3 Flight Simulation Requirements .....	33
47	3.3.1 Components and features .....	34
48	3.3.2 Domains of physical reality and validation.....	35
49	3.3.3 Examples of tabulating FSM Requirements.....	35
50	3.4 Summary: Phase 1 .....	41
51	4 Rotorcraft Flight Modelling & Simulation.....	42
52	4.1 Introduction.....	42
53	4.2 Simulation Type.....	42
54	4.3 Strengths of M&S .....	43
55	5 Flight Simulation Model Development (Phase 2a).....	45
56	5.1 Introduction.....	45
57	5.2 Flight Simulation Model Build .....	45
58	5.2.1 Component-based adaptable fidelity modelling.....	45
59	5.2.2 Required fidelity; sufficiency .....	47
60	5.2.3 Trim, Stability and Response .....	48
61	5.2.4 Flight control and automatic flight control system .....	50
62	5.2.5 Engine, rotorspeed and transmission dynamics.....	51
63	5.2.6 Environment modelling .....	51

64	5.2.7	Coupling with the Flight Simulator (Phase 2b) .....	52
65	5.3	Verification & Validation .....	52
66	5.3.1	Introduction .....	52
67	5.3.2	Component-based building-block approach .....	54
68	5.3.3	The application domains re-visited .....	55
69	5.3.4	Verification .....	56
70	5.3.5	Validation and fidelity assessment .....	57
71	5.3.6	Validation error and uncertainty .....	58
72	5.3.7	Validation in parallel with development .....	59
73	5.3.8	Validation flight testing .....	60
74	5.3.9	Fidelity metrics .....	60
75	5.3.10	Investigating FSM error .....	61
76	5.3.11	Model tuning and updating .....	62
77	5.4	Summary: Phase 2a .....	63
78	6	Flight Simulator Development (Phase 2b) .....	64
79	6.1	Introduction .....	64
80	6.2	Flight Simulator Build .....	66
81	6.2.1	Operator Station .....	67
82	6.2.2	Environment System .....	67
83	6.2.3	Ground Reaction and Handling System .....	67
84	6.2.4	Crew Station Layout and Structure .....	68
85	6.2.5	Flight Controls and Forces .....	68
86	6.2.6	Visual Motion Cueing System .....	69
87	6.2.7	Sound Cueing System .....	70
88	6.2.8	Vestibular Motion Cueing System .....	70
89	6.2.9	Vibration Cueing Systems .....	71
90	6.3	Flight Simulator Verification .....	71
91	6.3.1	Codes .....	71
92	6.3.2	Solutions .....	72
93	6.3.3	Hardware .....	72
94	6.4	Flight Simulator Validation .....	73
95	6.4.1	FS Test .....	73
96	6.4.2	Flight/Ground Test .....	74
97	6.4.3	Fidelity Assessment .....	74
98	6.4.4	FS Tuning/Updating .....	75
99	6.5	Summary: Phase 2b .....	75

100	7	Flight test measurements for FSM/FS development (Phase 2c) .....	76
101	7.1	Introduction.....	76
102	7.2	FTMS Design .....	77
103	7.3	FTMS Build .....	77
104	7.4	Calibration .....	78
105	7.5	Installation .....	78
106	7.6	Usage, including flight testing .....	78
107	7.6.1	Pre-certification Flight Test Guide .....	79
108	7.7	Summary: Phase 2c .....	80
109	8	Credibility assessment and Certification (Phase 3) .....	81
110	8.1	Introduction.....	81
111	8.2	Simulation credibility and uncertainty .....	82
112	8.2.1	Simulation credibility assessment .....	82
113	8.2.2	Uncertainty analysis and quantification.....	83
114	8.2.3	Confidence ratio .....	85
115	8.3	Exploring DoV fidelity assessments extrapolated into the DoE .....	88
116	8.3.1	<i>Example scenario, CS-29 requirements for dynamic stability.</i> .....	88
117	8.3.2	<i>Typical sources of FSM uncertainties.</i> .....	90
118	8.4	Concluding remarks.....	91
119	8.5	Summary: Phase 3 .....	91
120	9	Process documentation; the project management plan, controlled development and configuration & data	
121		management .....	92
122	9.1	Introduction.....	92
123	9.2	Resourcing the RCbS Process.....	93
124	10	Guidance for specific ACRs within the Certification Specifications.....	95
125	10.1	Introduction.....	95
126	10.2	Controllability and manoeuvrability: low-speed .....	95
127	10.3	VFR/IFR dynamic stability .....	95
128	10.4	Category A take-off and landing .....	95
129	10.5	SAS failures .....	95
130	10.6	Power-off landing .....	95
131	11	What Next? Routes to the adoption of RCbS .....	95
132	11.1	Introduction.....	95
133	11.2	What Next for Early Applications? .....	96
134			
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## 137 EXECUTIVE SUMMARY

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

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

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

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

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

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

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

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

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

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

205 In extended summary form, the Phases are as follows:

- 206 a) Phase 0; RCbS Project Management Plan, addressing,  
207 i. resources and timescales,  
208 ii. dependencies and constraints,  
209 iii. risks and mitigations,  
210 iv. process control, documentation, configuration and data management,  
211 v. structure for documenting the RCbS certification case,  
212 vi. **Output – the RCbS PMP used to provide governance for all activities in Phases 1–3 (Section 9).**  
213
- 214 b) Phase 1; assembly of the (preliminary) RCbS Requirements Specification including,  
215 i. ACR(s) from the Certification Specifications are identified for RCbS,  
216 ii. the four domains within which the RCbS will be carried out are defined (DoV, DoP, DoE, DoR),  
217 iii. the Influence and Predictability Level matrices are defined for the selected ACRs,  
218 iv. the relevant aircraft design data are collected together with related uncertainties,  
219 v. preliminary description of expected complexity content for the FSM, FS and FTMS needed to  
220 achieve ‘sufficient fidelity’ for each of the selected ACRs,  
221 vi. analysis and metrics for DoV fidelity assessment, together with tolerances for sufficiency, are  
222 defined, in preparation for meetings with certification authorities,

- 223           vii.    definition of test data requirements to characterise the domain of validation including  
224                    programme for pre-certification flight trials and ground tests,  
225           viii.   analysis and metrics for uncertainty characterisation and credibility assessment are defined,  
226           ix.     **Output; the (preliminary) RCbS Requirements Specification assembled based on the above,**  
227                    **using a comprehensive descriptive framework (see Section 3).**  
228
- 229    c)   Phase 2; development of the FSM, FS and FTMS based on the (preliminary) Requirements Specification  
230            i.     FSM build, verification and validation and fidelity assessment, including updating/tuning,  
231            ii.    prototype FSM supplied to the FS and FTMS developers to support parallel activities,  
232            iii.   FS build, verification and validation and fidelity assessment, noting that legacy facilities could be  
233                    used which may, or may not, require modification,  
234            iv.    FTMS build, verification and validation and fidelity assessment, noting that legacy facilities and  
235                    approaches could be used which may, or may not, require modification,  
236            v.     conduct pre-certification ground and flight test programme to support validation of FSM and FS,  
237            vi.    multiple iterative pathways managed and exercised as required throughout Phase 2,  
238            vii.   updates to Requirements Specification based on Phase 2 activities,  
239            viii.   **Outputs; FSM and FS verified and validated for intended purpose, included in fidelity**  
240                    **assessment reports (Sections 5, 6, 7).**  
241
- 242    d)   Phase 3; credibility assessment and certification  
243            i.     RCbS certification tests performed for relevant ACRs  
244            ii.    uncertainty characterisation undertaken throughout the domain of prediction,  
245            iii.   credibility assessments undertaken based on the results from fidelity and uncertainty analyses,  
246            iv.    results assembled and presented to certification authorities to make the ‘means of compliance’  
247                    case in the certification,  
248            v.     based on the feedback from Phases 2 and 3, the Requirements Specification is updated to  
249                    constitute a formal element of the case for RCbS for the selected ACRs.  
250            vi.    **Outputs; updated RCbS Requirements Specification and Type/Supplemental-Type Certificate**  
251                    **documentation (Section 8).**

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

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

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

267    Finally, this Guidance makes use, in places, of the grammar modals should, shall, can, may, etc. Unlike in formal  
268    requirements specifications or rules, there is no intention to be prescriptive here or to differentiate between

269 levels of modal importance. However, the RoCS team envisage this Guidance as a starting point in achieving a  
270 grander objective of defining a formal Acceptable Means of Compliance with certification specifications using  
271 modelling and simulation.

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# 272 1 INTRODUCTION

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## 273 1.1 PURPOSE AND SCOPE

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

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

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

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

## 296 1.2 BACKGROUND

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

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

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

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

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

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

### 339 1.3 DOCUMENT STRUCTURE

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

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

# RCbS Guidance in Brief

## Executive Summary: A Guidance taster, not just for executives

**Section 1:** The Introduction describing purpose and scope with overview of document structure, references, acronyms etc

**Section 2:** Overview of the RCbS process showing master process diagram and the flow from Phase 0 through Phase 3

**Section 3:** Phase 1; emphasising the requirements-based framework and how to build requirements starting from the Certification Specifications, flowing through influence and predictability analysis

**Section 4:** Overview of Flight Modelling and Simulation, simulation types, describe and predict perspective and the virtual pilot

**Section 5:** Phase 2a; Flight Simulation Model Development, flight behaviour in terms of trim, stability and response, including V&V and fidelity assessment

**Section 6:** Phase 2b; Flight Simulator Development, including V&V and fidelity assessment with pilot-in-the-loop and features designed to enhance illusion of reality

**Section 7:** Phase 2c; Flight Test Measurement System Development, driven by FSM/FS requirements for pre-certification flight testing, fidelity assessment

**Section 8:** Phase 3; How to conduct the Credibility Assessment and progress to Certification

**Section 9:** Back to Phase 0 for the all-important administration, writing the project management plan, configuration management and process documentation

**Section 10:** RCbS in practice with case studies from the RoCS project

**Section 11:** Next Steps and Routes Forward for early adopters of the RCbS process

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

353

354

The second category is contained in Sections 10 and 11. Section 10 features guidance for specific sections of the Certification Specifications, drawn from the results of assessments with state-of-the art FSMs and FSs. The

355 opportunity is taken to illustrate particular aspects of the RCbS process that were exercised in these ‘case  
356 studies’. The initial content will be populated with examples from the Cleansky2 RoCS project [8] in the second  
357 update to this Guidance, but it is anticipated that the content of Section 10 will continue to evolve with further  
358 material drawn from different RCbS applications. Section 11 suggests possible next steps along the routes  
359 forward for the early adopters of the RCbS process outlined in this Guidance.

## 360 1.4 REFERENCES

361

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## 364 1.5 ABBREVIATIONS

365	ac	aerodynamic centre
366	cg	centre of gravity
367	tc	torsion centre
368	AC	Advisory Circular (FAA)
369	A/C	aircraft
370	ACR	Applicable Certification Requirement
371	ADS-33	Aeronautical Design Standard-33
372	AFCS	Automatic flight control system
373	AIU	Aleatory uncertainty

374	AMC	Acceptable Means of Compliance
375	AR	Augmented Reality
376	ATC	Air Traffic Control
377	CFD	Computation Fluid Dynamics
378	CPA	Critical Point Analysis
379	CR	Confidence Ratio
380	CS	Certification Specification (EASA)
381	CSRFA	Certification by Simulation for Rotorcraft Flight Aspects
382	DoE	Domain of Extrapolation
383	DoFs	Degrees of Freedom
384	DoP	Domain of Prediction
385	DoR	Domain of Physical Reality
386	DoV	Domain of Validation
387	DS	Dynamic Stability
388	EASA	European Union Aviation Safety Agency
389	EP	Evaluation Pilot
390	ES	Environment System
391	EpU	Epistemic uncertainty
392	FAA	Federal Aviation Administration
393	FAR	Federal Aviation Regulations
394	FCS	Flight Control System
395	FoR	Field of Regard
396	FoV	Field of View
397	FS	Flight Simulator
398	FSM	Flight Simulation Model
399	FT	Flight Test
400	FTG	Flight Test Guide
401	FTMS	Flight Test Measurement System
402	HITL	Hardware-in-the-Loop
403	HQs	Handling Qualities
404	HT	Horizontal Tail

405	IGE	In Ground Effect
406	IMC	Instrument Meteorological Conditions
407	I-P	Influence-Predictability
408	LDO	Lateral-directional-oscillation
409	M&S	Modelling and Simulation
410	MBDS	Multi-Body Dynamic System
411	MDA	Motion Drive Algorithm
412	ML	Machine Learning
413	MOC	Means of Compliance
414	MR	Mixed Reality
415	MUAD	Maximum Unnoticeable Added Dynamics
416	NPA	Notice of Proposed Amendment
417	OEM	Original Equipment Manufacturer
418	OMCT	Objective Motion Cueing Test
419	OS	Operator Station
420	OTW	Out-The-Window
421	p-model	Phenomenological model
422	PAO	Pilot Assisted Oscillations
423	PMP	Project Management Plan
424	QTG	Qualification Test Guide
425	RoCS	Rotorcraft Certification by Simulation (project name)
426	RCbS	Rotorcraft Certification by Simulation (process name)
427	RPCs	Rotorcraft-Pilot Couplings
428	SAS	Stability Augmentation System
429	SCAS	Stability and Control Augmentation System
430	SME	Subject Matter Expert
431	STC	Supplementary Type Certificate
432	TC	Type Certificate
433	UAQ	Uncertainty Analysis and Quantification
434	UQ	Uncertainty Quantification
435	V&V	Verification and Validation

436	VeMCS	Vestibular Motion Cueing System
437	VzMCS	Visual Motion Cueing System
438	VR	Virtual Reality

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## 440 1.6 DEFINITIONS

441	<u>Accuracy</u>	The closeness of a parameter or a variable with the assumed true reference. It usually requires a metric to be quantified.
442		
443	<u>Aleatory uncertainty</u>	The inherent variation associated with the physical system or the environment under consideration, e.g. the variation of geometric and or material properties due to manufacturing process It is stochastic and irreducible below a certain threshold.
444		
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447	<u>Applicable Certification Requirement</u>	A requirement, normally specified by a paragraph in a Certification Specification, that is considered a candidate (applicable) for compliance demonstration using modelling and simulation.
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450	<u>Average pilot</u>	A pilot able to apply a normal level of skills required in the context of civil rotorcraft operations. An average pilot would not require exceptional skills in the course of their flying duties.
451		
452		
453	<u>Comparison Error</u>	The difference between the result of an experiment, or any other referent, and the corresponding simulation result. It is indicated with the symbol $\delta_c$ .
454		
455		
456	<u>Compliance demonstration</u>	The process of demonstrating that a system is compliant with defined requirements or standards.
457		
458	<u>Conceptual Model</u>	The collection of assumptions and abstractions applied to develop a physical model of the system of interest.
459		
460	<u>Credibility</u>	The quality of a simulation for being convincing or believable in its representation of flight behaviour.
461		
462	<u>Damping ratio</u>	A characteristic measure describing how an oscillation in a system decays after a disturbance; for low damping, it is approximately proportional to how much the oscillation decays/grows in a cycle, as described in the logarithmic decrement method
463		
464		
465		
466	<u>Data Pedigree</u>	A record of traceability of the data used to build the FSM. It should cover all aspects of data source, transmission, storage and processing to its final form used to build or validate the FSM.
467		
468		
469	<u>Degrees of Freedom</u>	The set of independent variables that completely define the state of the flight simulation model.
470		
471	<u>Domain of Extrapolation</u>	The domain within which extrapolation of predictions are made to achieve certification at defined Influence Levels for an ACR.
472		

473	<u>Domain of Physical Reality</u>	The domain within which the laws of physics being used are adequately represented in the flight model and flight simulator. Since all models and simulations used in the RCbS process will include approximations to physical reality, this domain is strictly the region where the approximations are valid, reflecting the description 'adequately represented'.
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479	<u>Domain of Prediction</u>	The domain within which it is the intention to predict the behaviour of the aircraft or component and to use these predictions to achieve certification at the defined Influence Levels for an ACR.
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482	<u>Domain of Validation</u>	The domain within which test data will be used to validate the flight model or simulator and their components/features. Validation means a positive outcome has been achieved for the relevant metrics in the fidelity assessment. Within the DoV, interpolation is used to predict behaviour between validation points.
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487	<u>Domain of Verification</u>	The region of all conditions for which FSM/FS codes and implementations are deemed to be correct (i.e. function as intended) and solutions have been determined to possess the required accuracy.
488		
489		
490	<u>Epistemic uncertainty</u>	The potential inaccuracy in any phase or activity of the modelling process that is due to a lack of knowledge or to intentional approximations applied by the analyst. It is potentially reducible by model improvements or by a better measuring technique employed to assess model parameters.
491		
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494	<u>Experimental Error</u>	The difference between the experimental value, or the value of any other referent, and the true (unknown) value. It is indicated with the symbol $\delta_r$ . To this error, it is possible to associate a numeric uncertainty $u_r$ .
495		
496		
497	<u>Input Error</u>	The error in a parameter used as input for the simulation model. It is indicated with the symbol $\delta_{inp}$ . To this error, it is possible to associate a numeric uncertainty $u_{inp}$ .
498		
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500	<u>Flight Simulation</u>	Flight simulation refers to either offline desktop simulation, or real-time pilot-in-the-loop simulation in a suitable FS.
501		
502	<u>Flight Simulation Model</u>	A computational model that can be created and analysed through the employment of software, to generate data useful to support the design, development and certification processes.
503		
504		
505	<u>FSM fidelity</u>	Fidelity of the FSM as reflected in the accuracy with which flight behaviour is modelled compared with the real aircraft or, more generally, the referent. It is assessed through the definition of one or more metrics to identify the model accuracy. The same model can have different fidelities, depending on the usage of the model and on the prediction domain chosen. So, the concept of fidelity must be always associated with the FS and the prediction domain.
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512	<u>FSM Uncertainty</u>	Estimated variation in the results of simulation of the FSM due to factors inherent to the model and not to the referent used for validation.
513		

514	<u>Flight Simulator</u>	A device for enabling a pilot to fly tasks associated with an ACR in a virtual environment.
515		
516	<u>FS fidelity</u>	How well the outputs of the flight simulator agree with the corresponding values in the referent (parameters that quantify the fidelity). The FS fidelity is composed by two parts: the predictive fidelity and the perceptual fidelity.
517		
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520	<u>Handling Qualities</u>	As defined by Cooper-Harper in Ref [32], <i>“Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.”</i>
521		
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523	<u>Influence level</u>	The extent to which the use of RCbS influences the Certification process classified in four levels - full credit, partial credit, critical point analysis, de-risking
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526	<u>Mathematical Model</u>	Mathematical formulation of the relationships between cause and effect
527	<u>Metrics</u>	Normally a mathematical function to measure a distance between two elements: two points or results, or two sets of points or results.
528		
529	<u>Model calibration</u>	The process of adjusting physical modelling parameters in the model to improve agreement with a referent (commonly used in other fields of application).
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532	<u>Model component</u>	The subsystems or individual elements that make up the Flight Simulation Model. A model component to be defined as such must be a system for whom it is possible to perform a specific validation. Typically, each FSM is composed by several components interconnected together.
533		
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536	<u>Model Error</u>	The error caused by the modelling assumptions. It is indicated with the symbol $\delta_{model}$ .
537		
538	<u>Model tuning</u>	The process of adjusting model parameters to improve agreement with a referent. Can also be used in cases where the physics-based structure of the model is not considered critical.
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541	<u>Model updating</u>	The process of updating model structure and content to improve agreement with a referent (term more commonly used than model calibration in flight mechanics applications).
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544	<u>Modelling &amp; Simulation</u>	Modelling and Simulation (M&S) is the use of a (conceptual, mathematical or numerical) model as a description or representation of a real system or phenomena for simulation by computational means. Modelling is the act of constructing a model; simulation is the execution of a model to obtain results.
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549	<u>Numerical Error</u>	The error due to the numerical algorithms employed to solve the problem. It is indicated with the symbol $\delta_{num}$ . To this error, it is possible to associate a numeric uncertainty $u_{num}$ .
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551		
552	<u>Phenomenological model</u>	A mathematical relationship between cause and effect that is created from measurements. This term is used in the RCbS process with reference to, e.g. linear models derived from system identification, usually with a
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555		structure defined at the outset based on simpler, linear forms of the FSM.
556		Other examples include models, such as wind tunnel aerodynamic data,
557		or models obtained by using Artificial Intelligence or Machine Learning
558		algorithms. The latter algorithms present specific risks and challenges,
559		particularly with regards to extrapolation, which are not addressed within
560		this Guidance [9].
561	<u>Physics-based</u>	A physics-based model is one where all relationships between cause and
562		effect, inputs and outputs, are governed by the laws of physics. This is in
563		contrast with phenomenological models, where relationships are
564		generally constructed from measurements of cause and effect, inputs
565		and outputs, often without regard for the underlying physical laws.
566	<u>Physical laws</u>	A scientific generalisation based on empirical observations of physical
567		behaviour. Empirical observations are typically conclusions based on
568		repeated scientific experiments over many years, and which have become
569		accepted universally within the scientific community.
570	<u>Perceptual fidelity</u>	Perceptual fidelity refers to the fidelity of the cues that are transferred
571		from the simulator hardware to the pilot to allow the pilot to put in place
572		reactions that are as close as possible to those that will be implemented
573		in flight. It is composed by many aspects and reflects the variety of
574		sensorial inputs that can be acquired through the human body (visual,
575		auditory, tactile and also movement perception).
576	<u>Predictive fidelity</u>	Predictive fidelity is the fidelity of the FSM, i.e. the fidelity of the
577		numerical model associated with the vehicle and to the environment to
578		be represented.
579	<u>Referent</u>	Data, information, knowledge, or experimental results against which a
580		FSM or simulation can be compared. It can be real word data, or results
581		obtained using analogous systems or, in some cases, higher fidelity
582		models.
583	<u>Requirements</u>	The source description for how an entity (e.g. FSM, model component)
584		should function, operate (including constraints) and interact with other
585		entities through inputs and outputs. The associated requirements
586		specification should be complete and traceable and testable within the
587		V&V processes.
588	<u>Risk</u>	The risk is the combination of the predicted severity of consequences and
589		the likelihood – i.e., probability – of an event. A risk can be reduced by
590		addressing either of these two elements.
591	<u>Sensitivity analysis</u>	The study of how the variation of an output of the FSM can be appointed
592		to different sources of variation in the model input and parameters.
593	<u>States</u>	Variables required to completely define the condition of a degrees of
594		freedom. For example, a single degree of freedom mechanical system,
595		whose dynamics is represented by a second order differential equation,
596		requires two states to be modelled (often the position and the velocity of
597		the degree of freedom).

598	<u>Simulation Error</u>	The difference between the simulation value and the true (unknown) value. It is indicated with the symbol $\delta_s$ .
599		
600	<u>Subject Matter Expert</u>	An individual having education, training and/or experience in a particular discipline, system and process.
601		
602	<u>Validation</u>	The part of the V&V process for determining the degree to which a model, or a simulation, is an accurate representation of the real world from the perspective of the intended uses of the model. It is conducted by comparing the model or simulation with a referent, extracted from the real world. The validation process aims to ensure that the model or simulation meets the associated fidelity requirements.
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608	<u>Validation Standard Uncertainty</u>	An estimate of the standard deviation of the combination of the effects of input, numeric and experimental uncertainties. It can be estimated both in the domain of validation or in the domain of prediction. Indicated with the symbol $u_{val}$ , or more generically with U.
609		
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612	<u>Verification</u>	The part of the V&V process for determining that a computational model accurately represents the underlying conceptual and mathematical models and their solutions. It is usually composed of two elements: code verification and solution verification. The verification process aims to ensure that the model meets the code structure and solution requirements, so functioning as intended.
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618	<u>Variables (Global)</u>	Variables associated with the flight simulation model as a whole, at aircraft-level.
619		
620	<u>Variables (Local)</u>	Variables associated with model components.
621	<u>Virtual pilot</u>	A computer-pilot operating through defined algorithms to fly manoeuvres and tasks.
622		

## 624 1.7 LIST OF SYMBOLS

625	$u_{inp}$	Input uncertainty
626	$u_{model}$	Model structure or form uncertainty
627	$u_{num}$	Numerical uncertainty
628	$u_p$	Prediction uncertainty
629	$u_r$	Experimental (referent measurement) uncertainty
630	$u_{val}$	Validation uncertainty
631	$u_{x_i}$	uncertainty associated with input $X_i$
632	$x_i$	input in the context of input uncertainty analysis
633	$M$	Performance margin

634	$N_r$	yaw damping derivative (1/sec)
635	$R$	Referent data, from experimental data (in the DoV), used to compute validation error
636	$S$	result from Simulation prediction, used to compute validation error
637	$U$	Uncertainty (combined from variety of sources)
638	$V$	Aircraft velocity
639	$V_{NE}$	Never exceed velocity
640	$V_Y$	Best rate of climb velocity
641	$\alpha$	Incidence
642	$\beta$	Sideslip
643	$\delta_c$	Comparison error
644	$\delta_{inp}$	FSM input parameter error
645	$\delta_{model}$	FSM model (structure/form) error
646	$\delta_{num}$	Numerical error in FSM solutions
647	$\delta_p$	FSM prediction error
648	$\delta_r$	Experimental error in producing the referent data
649	$\delta_{val}$	validation error ( $S-R = \delta_p - \delta_r$ )
650	$\omega, \omega_n$	frequency and natural frequency of oscillation on the eigenchart
651	$\zeta, \zeta\omega_n$	relative damping and damping of oscillation on the eigenchart
652		

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

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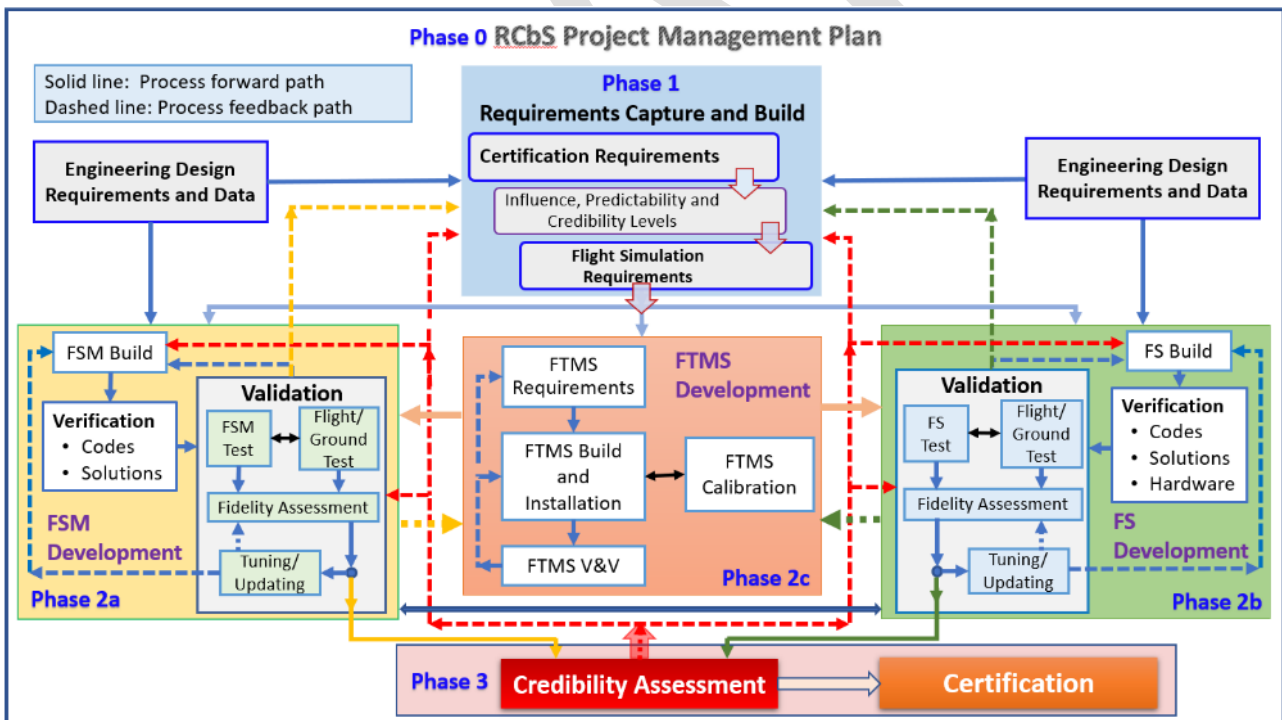
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The comprehensive and structured RCbS process is illustrated in Figure 2-1, with activities in each 'box' having dedicated Sections or sub-Sections. Following on from the creation of a RCbS Project Management Plan in Phase 0, the RCbS process is organised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



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

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

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It is recommended that, in the early adoption of this RCbS process, progress from one phase of the process to the next could be managed by reaching consensus between the applicant and the authority. This is particularly

679 important for the requirements capture phase and the planning of the simulation and flight test campaigns, but  
680 also for decision-making related to fidelity and credibility assessment.

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

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

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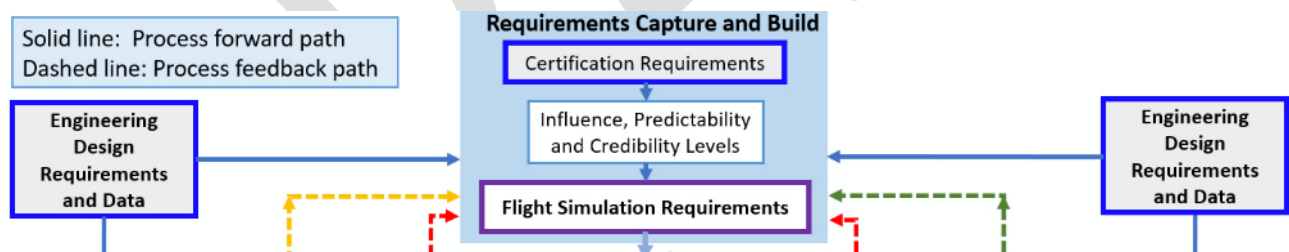
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## 690 3 REQUIREMENTS-CAPTURE AND BUILD (PHASE 1)

### 691 3.1 INTRODUCTION

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

711



712

713

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

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

- 718
- 719 a) Flight envelope, aircraft configurations, and environmental conditions to be tested,
  - 720 b) Flight test points and associated piloting techniques,
  - 721 c) Parameters and variables, and their associated accuracies, to be measured, and analysis to be performed
  - 722 d) Required qualitative information, such as pilot or test engineer commentary,
  - 723 e) Flight test monitoring parameters.

723 The RCbS process commences at the same ‘starting point’, but aims to address these elements through flight  
724 simulation. A crucial step in the simulation requirements development as proposed herein is the identification  
725 and description of the flight simulation Influence, Predictability and Credibility levels. These levels differentiate

726 how modelling and simulation are to be used,  
727 how good the predictive capability needs to be  
728 and how credible the predictions are,  
729 particularly outside the domain of validation  
730 where judgements are made based on  
731 extrapolation.

### 732 3.2 INFLUENCE, PREDICTABILITY AND 733 CREDIBILITY LEVELS

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

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

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

#### The Four Domains in RCbS

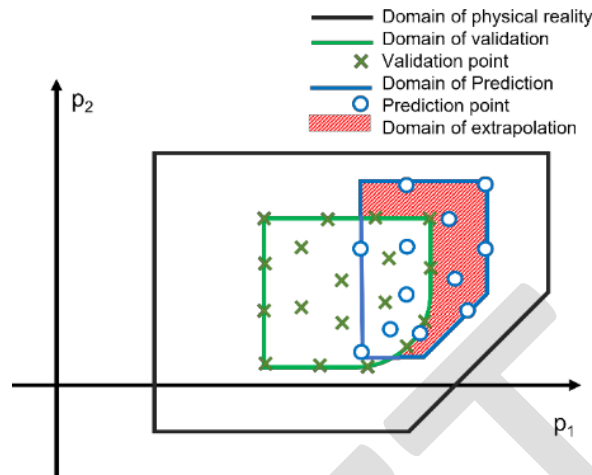
Using M&S to describe and predict flight behaviour, four domains are considered (Figure 3-2). In the case of a whole aircraft, the domain concept is intended to encompass both the region of the flight envelope and the range of aircraft configurations relevant to the ACR. In the case of a component, or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

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

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

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

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



772  
 773 Figure 3-2: Illustrating the Domains concept in RCbS

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

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

775  
 776 In theory, a higher influence level will translate into more activity required in the development of model(s) and  
 777 simulator(s), and in the validation and credibility assessment phases, providing increased evidence that the  
 778 models are a correct and properly implemented mathematical translation of physical phenomena and the  
 779 simulation is a credible representation of real-world behaviour of the aircraft. However, there is potential for the  
 780 Influence level to be revised during the certification process, upwards or downwards, following the credibility  
 781 assessment in Phase 3 of the RCbS process. It is, therefore, recommended that the full RCbS process is  
 782 undertaken, where possible and appropriate, regardless of the initially selected influence level.

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

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


- 793 P1 Full interpolation: predictions performed within the DoV, the (interpolation) errors for the quantities  
 794 of interest can be estimated with high confidence,
- 795 P2 Extensive interpolation in the DoV and limited extrapolation in the DoE: all cases of acceptable  
 796 extrapolation as per the current CS-29 and CS-27 AMCs are of predictability level P2.
- 797 P3 Interpolation in the DoV and extensive extrapolation in the DoE: including extrapolation beyond CS-  
 798 29 and CS-27 AMCs, as well as significant changes in design features.
- 799 P4 Full extrapolation: all points used in simulated tests are outside the DoV and so no direct  
 800 comparisons of the complete FSM with flight test data are available.

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

805

806

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

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

807

### 808 3.2.1 Credibility and the Assessment of Confidence

809 Credibility assessments then consider the consequences to human safety and operational performance from  
 810 the reliance on simulation, considering the assigned Influence and Predictability Levels. Credibility is an  
 811 assessment of confidence, and is particularly important for, but not exclusive to, test conditions in the DoE. So,

812 for each ACR selected for RCbS, there needs to be such an assessment, to determine the extent of flight test  
813 data required and the technical content, the complexity, in terms of features and components, of both FMS and  
814 FS. An approach to credibility analysis is introduced later in this Section. Prior to this, the following examples are  
815 used to illustrate the integrated nature of influence and predictability assessment, and how this feeds through  
816 into the detailed FSM/FS requirements.

- 817 a) Appendix B of both CS-27 and CS-29 (Airworthiness Criteria for Helicopter Instrument Flight) quantifies  
818 the requirement for a helicopter's dynamic stability in terms of the damping as a function of oscillation  
819 period. The intention (Influence level) might be that partial credit is sought for this ACR by achieving  
820 credit for 50% of the speed-altitude envelope, for all weight and loading configurations. To achieve this  
821 RCbS level, it might be proposed that medium-high altitude tests are replaced by simulation, using the  
822 validation results and model-updating process successfully developed with data from low-medium  
823 altitude testing. A question that must be asked is what FSM characteristics are considered necessary to  
824 ensure sufficient Credibility in this 'extrapolation' process. Previous experience may have indicated that  
825 with the aerofoil sections used on the certification aircraft, dynamic stall is to be expected at high Mach  
826 numbers, with consequent impact on blade torsional response and the damping of the aircraft pitch-  
827 heave oscillations. Modelling correctly the loss of dynamic pressure at the vertical stabiliser, due to  
828 fuselage interference effects, might be considered critical to capturing the reduction in weathercock  
829 stability and the impact on the frequency of the lateral-directional-oscillation. The model-update  
830 process embodying this effect that was successful at low altitude could be replicated at the high-altitude  
831 conditions.
- 832 b) ACR 29.143 (Controllability and Manoeuvrability), requires that the "*wind velocities from zero to at least*  
833 *31 km/h (17 knots), from all azimuths, must be established in which the rotorcraft can be operated*  
834 *without loss of control on or near the ground in any manoeuvre appropriate to the type.*" To avoid the  
835 safety risk in flight test, a combination of off-line (CPA) and piloted simulation might be proposed to  
836 achieve partial or even full credit for defining the flight envelope within which loss of controllability in  
837 such low-speed manoeuvres might occur. The FSM characteristics considered to be important in this  
838 application involve the interaction of the main rotor wake with the ground, fuselage, empennage and  
839 particularly the tail rotor, when hovering in winds from different directions. It is recognised that, at least  
840 for conventional rotorcraft configurations, to achieve sufficient fidelity at critical azimuths, high fidelity  
841 CFD or vortex-wake solutions are likely to be necessary and converting the solutions into reduced-order  
842 models (e.g. data-maps) for real-time computations represents a significant, but not insurmountable,  
843 challenge. An FS characteristic considered important might be 'realistic' fine-textured ground surfaces  
844 that provide the pilot with the 'required' translational and attitude motion cues. It might also be  
845 proposed that the provision of vestibular motion cues is important, allowing the pilot to anticipate the  
846 visual motions. Likely characteristics required in the FTMS for the pre-certification flight testing to  
847 support validation are low airspeed pace-car trials with angles of incidence  $\alpha$  and sideslip  $\beta$  sensing, and  
848 tail rotor flapping data.
- 849 c) ACR 29.53(a) relates to Category A take-off requiring that a rotorcraft, following an engine failure, can  
850 return to and land safely in the (confined) take-off area. De-risking might be sought by using a piloted  
851 simulation to evaluate the robustness of the defined rejected take-off procedures through simulated  
852 'Abuse Case Testing', and to determine the maximum take-off weight from an energy management and  
853 controllability perspective for all foreseen helicopter configurations and within the applicable flight  
854 envelope. FSM characteristics considered important to the accurate prediction of power/torque limits,  
855 and transient one-engine-inoperative torque/rotorspeed response include the heave/yaw responses to  
856 collective control inputs, the importance of high-complexity rotor wake with strongly non-uniform radial  
857 inflow distribution, taking account of ground-effect, and the thermodynamic characteristics of the  
858 engines and the functions of the engine and rotorspeed control systems. In the FS, establishing

859 sufficiency for the fidelity of the visual and vestibular cueing will need attention, particularly in the final  
860 phase of the manoeuvre prior to touch down.

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

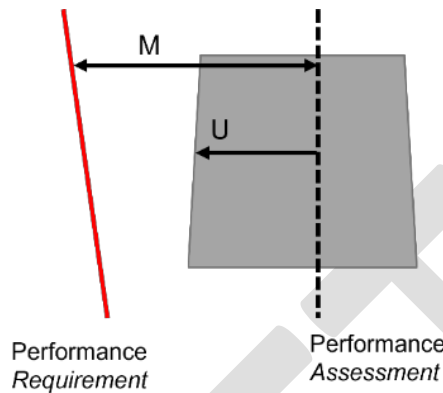
874 As part of the Influence-Predictability (I-P) Level assessment, an applicant needs to define, for each ACR for  
875 which RCbS is sought, how the activity is distributed throughout the DoP described above. This can be achieved  
876 in terms of the extent of interpolation (activity within the DoV)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

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

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

902 Confidence is an elusive concept, but for RCbS it must be reinforced by quantitative analysis of the uncertainties  
903 in predictions, and test data, in both the DoV and DoE. Figure 3-3 illustrates the Confidence Ratio (CR) concept  
904 used in this Guidance to quantify the credibility assessment relating to the prediction of a ‘margin’. M is the

905 margin, or the generalised ‘distance’, between the performance requirement (e.g. control limit, touch-down  
 906 velocity or the damping of an oscillation) and the FSM prediction, i.e. the performance assessment. Credibility  
 907 assessments are concerned with deriving, and ultimately ensuring, the sufficiency of, the variety of margins  
 908 related to an ACR.



909  
 910 *Figure 3-3: Conceptualisation of the confidence ratio relating to a performance margin (M) and uncertainty (U)*

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

912 
$$CR = M/U \tag{1}$$

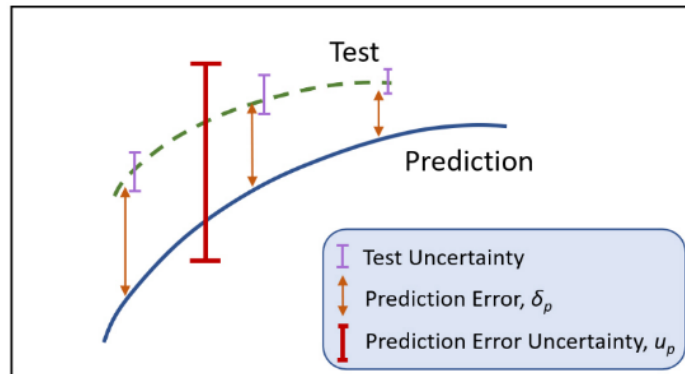
913 An intuitive result of this simple expression is that the smaller the margin to the performance limit, then the  
 914 lower should be the uncertainty. Credibility relates to the relative size of  $U$  and  $M$ , and from a safety perspective  
 915 it seems appropriate to define a minimum acceptable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

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

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

<sup>3</sup> In some references, the difference between the simulation and test is described as the ‘comparison’ error,  $\delta_c$ . In the DoV, this is equivalent to the validation error,  $\delta_{val}$ . Further discussion on this is deferred to Section 8.

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



945  
 946 *Figure 3-4: The concept of prediction uncertainty relating to prediction error*

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

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

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

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

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

961

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

967 **3.2.2 CR in the I-P Matrix**

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

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

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

976  
 977 For the time being, what is acceptable, in terms of the distribution of CRs within the table for an ACR, will likely  
 978 be a topic of negotiation between the applicant and certification authority. Following the above process will  
 979 ensure that applicants address credibility in Phase 1 of the RCbS process, setting the scene for the credibility  
 980 analysis in Phase 3. It is no exaggeration to note that developments in uncertainty and credibility analysis are  
 981 likely to feature large as RCbS is increasingly used. In this context, the community-wide sharing of good-practice  
 982 by early adopters is strongly encouraged.

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

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

993 **3.3 FLIGHT SIMULATION REQUIREMENTS**

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

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

- 1000 2. The requirements in terms of characteristics that the FSM(s) and FS(s) must feature, and the associated  
1001 predictive and perceptual fidelity they should satisfy.  
1002 3. The flight test data required to support validation, and consequent fidelity and credibility assessments.  
1003 4. Documentation detailing the proposed FS requirements as well as the associated rationale and/or  
1004 justifications.

1005 The requirements are composed of a detailed description of the characteristics and capabilities of the FSM(s)  
1006 and the FS(s) and their components and features, and associated flight test measurements that are relevant to  
1007 the RCbS process. It is recognised that applicant organisations are likely to have experience in developing  
1008 requirements specifications for their products. This Guidance is intended to aid applicants build on this  
1009 experience, and to propose an approach that forms a solid foundation for the FSM/FS/FTMS development  
1010 processes. The following properties are suggested for the framework and content of the requirements  
1011 specification:

- 1012 a. Measurable - numerically quantifiable through a parameter or metrics  
1013 b. Unambiguous - clear, straightforward to interpret  
1014 c. Predictable - location in the prediction domain  
1015 d. Substantiated - drawn from known evidence  
1016 e. Traceable - with a specified, direct, association with ACR or more general flight behaviour  
1017 f. Appropriate - sufficiently robust to discern quality in the intended application  
1018 g. Complete - covering all functions and operations included in the ACRs

### 1019 3.3.1 Components and features

1020 Individual elements that can be distinguished by their function within the FSM are referred to as components in  
1021 this Guidance. An FSM is then created as a collection of linked components. The FS also has components but in  
1022 this Guidance the term 'feature' is used to characterise the systems that provide the pilot experience (e.g. visual  
1023 system). The usage of this term is well known from ICAO Doc 9625 [11] and EASA's Notice of Proposed  
1024 Amendment (NPA) 2020-15 [12]. Components or features can be described in terms of the requirements they  
1025 are serving, addressing functions, modes of operation, data structures, inputs and outputs, constraints and  
1026 interfaces with other components. The prediction domain within which the component/feature should operate  
1027 also needs to be specified, along with the DoV. A textual example is intended to be illustrative of functional and  
1028 operational elements of an FSM component, but of course not prescriptive;

1029 Each rotorblade is divided into N blade sections, spanning the radius, each with its own inertial, geometric  
1030 and (optionally) elastic properties; each blade section is a component. The **function** of each blade section  
1031 component is to generate a lift, drag and pitching moment in response to inputs from neighbouring  
1032 rotorblade components and associated aerodynamic components, e.g. the atmospheric free-stream  
1033 component, the finite-state inflow component and unsteady dynamic stall component. Typically, 2-  
1034 dimensional aerodynamic data tables, derived from wind-tunnel or CFD experiments, provide the lift,  
1035 drag and pitching moment, in coefficient form, as functions of incidence and Mach number. Three-  
1036 dimensional effects could be included as a function of yawed flow angles. The DoP would be quantified  
1037 by the functional variations, while the DoV would be defined by the variations of, e.g. incidence and Mach  
1038 number, over which the aero tables have been drawn from test data. Through interfaces with  
1039 neighbouring components, the blade section will typically **operate** at every time-step by transferring  
1040 motions and forces to neighbouring components, through a solution process that is defined, verified and  
1041 validated. Such interfaces also need to be defined (e.g. joints, rigid, elastic), together with constraints,  
1042 such as attachments to the rotor hub with flap-stops and pitch links.

1043 **3.3.2 Domains of physical reality and validation**

1044 The degree of detail and level of complexity in the FSM aerodynamic modelling has proved important to  
1045 achieving a level of fidelity appropriate for use in vehicle design, and this is expected to be even more true for  
1046 RCbS. Of relevance to fidelity are the range and limits of approximations used in the FSM that need to be defined,  
1047 with supporting evidence, as part of the validation process. Such ranges/limits define the domain of physical  
1048 reality of the components; e.g. in terms of compressibility or dynamic stall conditions. Accordingly, each  
1049 component, or collection of components, will have their own domain of validation, encompassing conditions  
1050 that might fall outside of the domain of prediction at aircraft level.

1051 **3.3.3 Examples of tabulating FSM Requirements**

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1054 Table 3-5 to Table 3-8 provide (non-exhaustive) examples for cataloguing the requirements in a form that  
1055 captures the aforementioned properties. In the examples, the 'fidelity metrics' and 'driving requirements' are  
1056 largely left blank, but are included for applicants to complete, if and when appropriate. References to  
1057 component fidelity will feature in Section 10, as appropriate. This Guidance recommends that the  
1058 documentation of such requirements be undertaken as a comprehensive process, providing a traceable  
1059 foundation to support diagnostic analysis, and ultimately decision-making concerning validation and  
1060 extrapolation domains of the components and the whole aircraft. This approach to component-level  
1061 requirements and fidelity can be extended to the whole FSM and FS, i.e. aircraft-level, for simulating conditions  
1062 throughout the flight envelope, for application to de-risking for example, as illustrated in Table 3-8. It is  
1063 recognised that the results of component-level validation and fidelity assessment do not necessarily read across  
1064 to the same at aircraft level; in some cases, the whole can be more deficient than the sum of the parts, e.g. as a  
1065 result of integration and propagation effects. However, the 'weakest link' at component level, in terms of fidelity,  
1066 might impact fidelity at aircraft-level to a disproportional amount and always deserves careful attention.  
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Table 3-5: Example FSM Requirements

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

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Table 3-6: Example FS Requirements

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

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Table 3-7: Example FTMS Requirements

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

Table 3-8: Example FSM Requirements

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

1081 **3.4 SUMMARY: PHASE 1**

1082 The activities contained within Phase 1 are summarised below.

- 1083 a) Phase 1; assembly of the RCbS Requirements Specification
- 1084 i. ACRs from the Certification Specifications are identified for RCbS,
  - 1085 ii. the four domains within which the RCbS will be carried out are defined, (DoV, DoP, DoE, DoR),
  - 1086 iii. the Influence and Predictability Level matrices are defined for the selected ACRs,
  - 1087 iv. the relevant aircraft design data are collected together with related uncertainties,
  - 1088 v. preliminary description of expected complexity content for the FSM, FS and FTMS needed to
  - 1089 achieve 'sufficient fidelity' for each of the selected ACRs,
  - 1090 vi. analysis and metrics for fidelity assessment, together with tolerances for sufficiency, are
  - 1091 defined, in preparation for meetings with certification authorities,
  - 1092 vii. definition of test data requirements to characterise the DoV including programme for pre-
  - 1093 certification flight trials and ground tests,
  - 1094 viii. analysis and metrics for uncertainty characterisation and CR for credibility assessment are
  - 1095 defined,
  - 1096 ix. Output; the (preliminary) RCbS Requirements Specification assembled based on the above,
  - 1097 using a comprehensive descriptive framework (see Section 2).

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## 1100 4 ROTORCRAFT FLIGHT MODELLING & SIMULATION

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### 1101 4.1 INTRODUCTION

1102 Following a requirements-based development approach ensures that the types of flight simulation conducted  
1103 are appropriate to the selected ACRs, aircraft configurations and flight conditions of interest. This Section  
1104 discusses, in general terms, the range of flight modelling and simulation options available in the RCbS process;  
1105 specifically, real-time pilot-in-the-loop, offline desktop, hardware-in-the-loop, and flight with virtual pilot, prior  
1106 to the more detailed materials in Section 5 and Section 6.

### 1107 4.2 SIMULATION TYPE

1108 In the RCbS process, it is likely that a family of  
1109 FSMs will be used, ranging from moderate to very  
1110 high levels of complexity. The decision as to  
1111 which will be used for an application will be  
1112 driven by the requirements. For example, if  
1113 closed-loop responses and subjective pilot  
1114 assessment (e.g. for controllability and  
1115 manoeuvrability) are important, a real-time  
1116 pilot-in-the-loop simulation, in a FS, will be  
1117 required. Conversely, open-loop handling  
1118 qualities and performance analyses may typically  
1119 be performed with a standalone FSM in an off-  
1120 line desktop simulation environment. In certain  
1121 cases, manoeuvre control by a virtual pilot (see  
1122 text box) may be advantageous. If pilot-in-the-  
1123 loop simulation is required, it is necessary to  
1124 provide not only the capability to simulate with  
1125 an adequate level of accuracy the aircraft and the  
1126 environment, but also all the elements of the  
1127 flight simulator that contribute to the perceptual  
1128 fidelity, e.g. visual and vestibular motion cues.  
1129 But even here, the complexity of the FS depends  
1130 on the application. Handling Qualities (HQs) and  
1131 human-factors assessments require a cockpit  
1132 and flight controls that are, at least, substantially  
1133 equivalent to the certification aircraft. In other  
1134 cases, a generic engineering flight simulator may  
1135 provide adequate realism to evaluate or  
1136 demonstrate compliance and obtain partial or  
1137 full credit in the conditions of interest. Decisions  
1138 about the simulation type will be strongly  
1139 informed by the requirements, which emphasises why the latter need to be sufficiently detailed, i.e. complete,  
1140 substantiated, measurable etc.

#### The Virtual Pilot

This Guidance is not prescriptive about the form such a virtual pilot could take, but the intention is that the algorithms running such a computerised pilot need to be sufficiently realistic that meaningful conclusions can be drawn and relevant certification decisions can be made. One benefit of using a virtual-pilot, or indeed any off-line analysis, is that the simulation does not need to run in real-time, so higher-complexity numerical (continuum-mechanics) models can be included, albeit that they also need to be verified and validated. A second benefit of using a virtual pilot is that a massive coverage of the whole flight envelope can be undertaken in batch-mode, isolating critical conditions for further investigation, for example through piloted simulation. The virtual pilot model may also be used to support so-called abuse-case testing to, e.g., evaluate the sensitivity of an emergency operating procedure described in the Rotorcraft Flight Manual to realistic variations representative of the average pilot in operation.

It is recognised that as the applications of RCbS evolve over the coming years, so too will virtual pilot models become more realistic and it is expected that their use in RCbS will expand considerably, for the reasons given above. Future developments of this Guidance should address this evolution. But, with the current state-of-the-art in virtual pilot modelling, whenever the results are close to the certification limits, then a pilot-in-the-loop simulation is likely to be necessary for ultimate proof of compliance testing.

1141 Relating to the selection of the simulation type, an element to consider during Phase 1, requirements capture  
1142 and build, is whether or not the susceptibility of the aircraft to adverse rotorcraft-pilot-couplings (RPCs) or  
1143 involuntary Pilot Assisted Oscillations (PAO) [13] warrants specific off-line desktop analyses, or whether piloted  
1144 simulation with appropriate kinaesthetic and vestibular cueing is required for the selected ACR. While the CSs  
1145 and FARs do not specifically address this topic, the research to date suggests testing methods that can reveal an  
1146 aircraft's susceptibilities to such PAOs. In addition, recent work on the susceptibility of tiltrotor aircraft to RPCs  
1147 is discussed in [14] along with recommendations for testing techniques.

1148 FSMs, particularly those used within a real-time FS environment, typically are not suitable for structural loads  
1149 analyses, as may be required for proof of compliance with the relevant section of the CS (e.g. CS-29 sub-part C).  
1150 Nevertheless, such simulations can provide inputs for more detailed off-line analyses using higher order  
1151 (structural or aeroelastic) models, or may be used to evaluate high-level pass-fail criteria such as touchdown sink  
1152 rate and ground speed in lieu of a detailed emergency landing gear loads prediction.

1153 HITL simulation can be considered whenever there are vehicle subsystems, that the requirements suggest should  
1154 be included, e.g. in the real-time simulation flight loop. Alternatively, it may be difficult to build reliable  
1155 simulation models, due to complexities in the physics, and/or difficulties in collecting the data necessary, e.g.  
1156 for commercial reasons. In such cases, the requirements on the inputs/outputs and interfaces between the  
1157 simulator and the hardware components need to be clearly defined and conformity checks must be performed.

### 1158 4.3 STRENGTHS OF M&S

1159 Before progressing to examine the details within the  
1160 three elements of Phase 2 in the RCbS process, the  
1161 opportunity is taken to discuss some of the additional  
1162 merits of using modelling and simulation in the  
1163 certification process. Some of these may be well known  
1164 and understood in the design and development  
1165 departments, but might be less familiar to the testing  
1166 community. The value to applicants of such discussion  
1167 within Guidance is that it can open-up new dimensions  
1168 of awareness during the certification process,  
1169 important for establishing the goals of the I-P matrix.  
1170 The real strength of the describe and predict capability  
1171 of modelling and simulation is that it provides access to  
1172 robust understandings of the connections between  
1173 causes and effects; connections that are sometimes  
1174 very difficult, or impossible, to make by examining the  
1175 test data themselves (see text box).

Describe and Predict – mathematics in action

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

1176 One example of this strength is brought out through an examination of the changes in the forces and moments  
1177 on components (or the whole aircraft) following a perturbation in a single state. A small perturbation in sideslip  
1178 (or sway) velocity can reveal the changes in, say, roll and yaw moments. Increasing the magnitude of the  
1179 perturbation can reveal the extent of any nonlinearity in these moments and deeper analysis can expose how  
1180 different components are contributing to the nonlinearities. Ultimately, such analyses can contribute to  
1181 developing a full understanding of, for example, lateral-directional static and dynamic stability shortcomings.  
1182 The latter may have been identified as a problem through piloted simulation, or even flight test, but the source  
1183 of the problem could only be discovered through the kind of diagnostic analysis described above.

1184 Another example of the strength of simulation comes from understanding the sources of problems relating to  
1185 unexpected increases in main and tail rotor power, at both low and high speed. It is not unusual for poor power  
1186 predictions to feature in the design and development phases, and often corrected by adjusting parameters in  
1187 the rotor inflow model (low speed) or fuselage aerodynamic drag model (high speed). The importance of the  
1188 correct physics in understanding poor predictions in the RCbS application requires a more clinical approach  
1189 aimed at diagnosing the sources of mismatches between real flight and predictions. Increased effort will  
1190 normally be required with higher-complexity FSMs and potentially increased pre-certification flight testing. The  
1191 rewards of the increased efforts are likely to be found in both safety and efficiency during the certification  
1192 process.

1193 A third example addresses the whole gamut of de-risking, through the computation and management of 'large  
1194 data' obtained from multiple, offline, simulation runs, aiding the identification of cases for further analysis. The  
1195 use of algorithms that can search throughout the flight/configuration envelope for boundaries of defined trim,  
1196 stability or response characteristics or critical cases arising from failure modes analysis, can make such  
1197 identification very efficient. The design of such algorithms is likely to feature large as modelling and simulation  
1198 finds its place in the certification world.

1199 The exploration, within the RCbS process, of 'what-if' type questions through offline analysis and piloted  
1200 simulations can also lead to discoveries that can impact the certification. Such exploration, without constraints,  
1201 can be particularly valuable during the Phase 3 'Credibility' phase when extrapolation is under the microscope.  
1202 We return to this in Section 8.

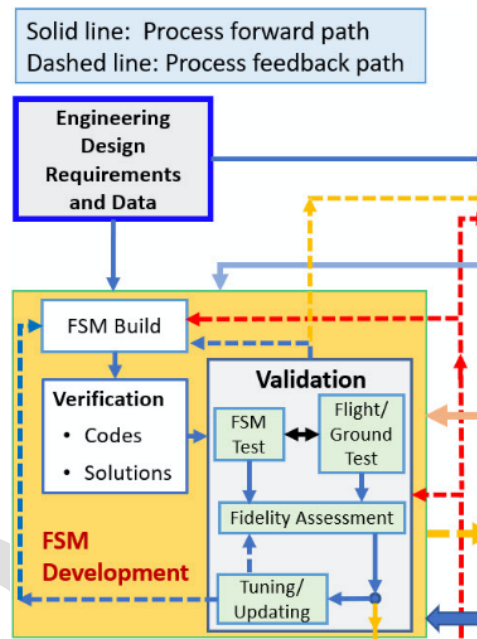
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## 1205 5 FLIGHT SIMULATION MODEL DEVELOPMENT (PHASE 2a)

### 1206 5.1 INTRODUCTION

1207 Figure 5-1 illustrates the elements of the FSM development phase (Phase 2a), with major inputs from the  
1208 Requirements Capture/Build phase and the Engineering design data. Inputs from the parallel Phases 2b (FS) and  
1209 2c (FTMS) are also shown. The dashed lines indicate iteration pathways within Phase 2a and from outside, in  
1210 both the parallel phases and the later credibility assessment phase.



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

### 1213 5.2 FLIGHT SIMULATION MODEL BUILD

#### 1214 5.2.1 Component-based adaptable fidelity modelling

1215 Put simply, an FSM used for certification compliance demonstration purposes should include the physics  
1216 necessary to achieve sufficient fidelity for the cases and conditions of interest, the ACRs. For a high level of  
1217 confidence in the results, the FSM is applied within the DoV subset of the DoP. Beyond this, in the DoE, physics  
1218 should guide the model content, and the levels of confidence in the results will depend on the credibility analysis  
1219 introduced in Section 3 and expanded on in Section 8. The modelled physics shall describe the behaviour of the  
1220 aircraft and predict the three essential aspects of flight, i.e. trim, stability and response. The FSM should,  
1221 therefore, be *physics-based*, i.e., expressed in terms of, or derived from, the physical laws applied in the creation  
1222 of the mathematical model and in the operation of the numerical simulation. The use of phenomenological sub-  
1223 models for components is not considered to be prohibited. In some cases, full phenomenological models could  
1224 be considered if P1 Predictability level, i.e. interpolation only, is sought. However, for those cases, the  
1225 identification of the associated DoR, and the assurance to not fall outside it, must be undertaken. The use of  
1226 such models in critical applications is a novelty and should be highlighted to the certification authority.  
1227 Preliminary guidelines are applicable and are available in [9]. Early coordination with the certification authority  
1228 is advised.

1229 Appropriate (virtual) flight test monitoring parameters should be included in the FSM to ensure that it is not  
1230 used beyond the limits of the DoR. Ultimately, the limits of validity of the FSM reflect the DoR boundaries; where  
1231 the underlying model data and/or the mathematical approximations to the physics break down for modelling  
1232 the various FSM components. These limits are expressed in terms of both global variables, such as those that  
1233 define the flight envelope, and local variables, including the mathematical approximations to the physics being  
1234 modelled for a component. The limits should be reflected in the domains of validation and physical reality for  
1235 the FSM, with the implication that the aircraft domain of validation should be within the ensemble of component  
1236 limits of validity.

1237 As alluded to in Section 4.2, it is emphasised that it is not necessary that a single FSM be used throughout the  
1238 RCbS process to perform all assessments required in demonstrating the fulfilment of the full certification  
1239 specification. Multiple models, with different complexities and components, may be used, with the complexity  
1240 driven by, and adapted to, the application. This adaptable-fidelity approach for certification is driven by the  
1241 requirements on both the content of the modelling, especially but not exclusively for the aerodynamic forces,  
1242 and the higher-order 'degrees of freedom' necessary to capture flight behaviour correctly. Examples are the  
1243 importance of main rotor wake – tail rotor interactions for the assessment of low-speed controllability and the  
1244 impact of dynamic stall on the blade torsion loads and vibration levels at high speed. This adaptable-fidelity  
1245 approach contrasts with the models typically used for training simulators which are required to have appropriate  
1246 fidelity (from a training perspective, [15]) over the full flight envelope, but for which non-physical tuning may be  
1247 acceptable. Guidance for the related process of the configuration management for adaptable-fidelity models is  
1248 described in Section 9.

1249 Although other approaches may be conceived, a typical rotorcraft flight simulation model is composed of  
1250 integrated components, or building blocks, assembled together, often following a Multi-Body Dynamic System  
1251 (MBDS) logic. Figure 5-2 shows components that may be used in a typical helicopter simulation model. Similarly,  
1252 Figure 5-3 shows components used in a typical tiltrotor simulation model. FSM requirements for both types of  
1253 rotorcraft will be similar although it is recognised that the latter are not certified according to CS-27/29  
1254 standards. A MBDS features multiple degrees of freedom (DoFs), represented typically in the FSM by component  
1255 motion states and their velocities, or other states representing the evolution of the dynamic system (e.g.  
1256 dynamic inflow states, pressures in actuators, turbine thermo-states). These would normally include the 6-DoFs  
1257 of fuselage velocities, coupled with rotor flap and lag or gimbal motions, engine and drive train dynamics etc. In  
1258 the current state of the art, finite-state rotor inflow models are typically used for real-time applications to  
1259 capture local rotor blade section incidence and to estimate rotor wake interference on the fuselage and  
1260 empennage.

1261 Before turning the specific focus to fidelity, it is worth discussing a relatively new development relevant to the  
1262 RCbS process. This Guidance advocates the application of physics-based modelling for the sake of the credibility  
1263 of the simulation, particularly for extrapolated conditions. With the advent of Machine Learning (ML), it has  
1264 become possible to derive rapid-execution, high-dimensionality surrogate models from test data and high-order  
1265 physical modelling such as CFD. These data-driven methodologies such as Artificial Neural Networks, while not  
1266 physics-based themselves, rely on training data that stem from testing or physical modelling. In principle, ML  
1267 methods can be used for extrapolation beyond the training data set. The extent to which this can be done reliably  
1268 and accurately for rotorcraft flight characteristics is a subject for research. As such, this Guidance does not  
1269 advocate such techniques for the first practices of RCbS, but early adopters are encouraged to investigate these  
1270 avenues for exploitation in the future.

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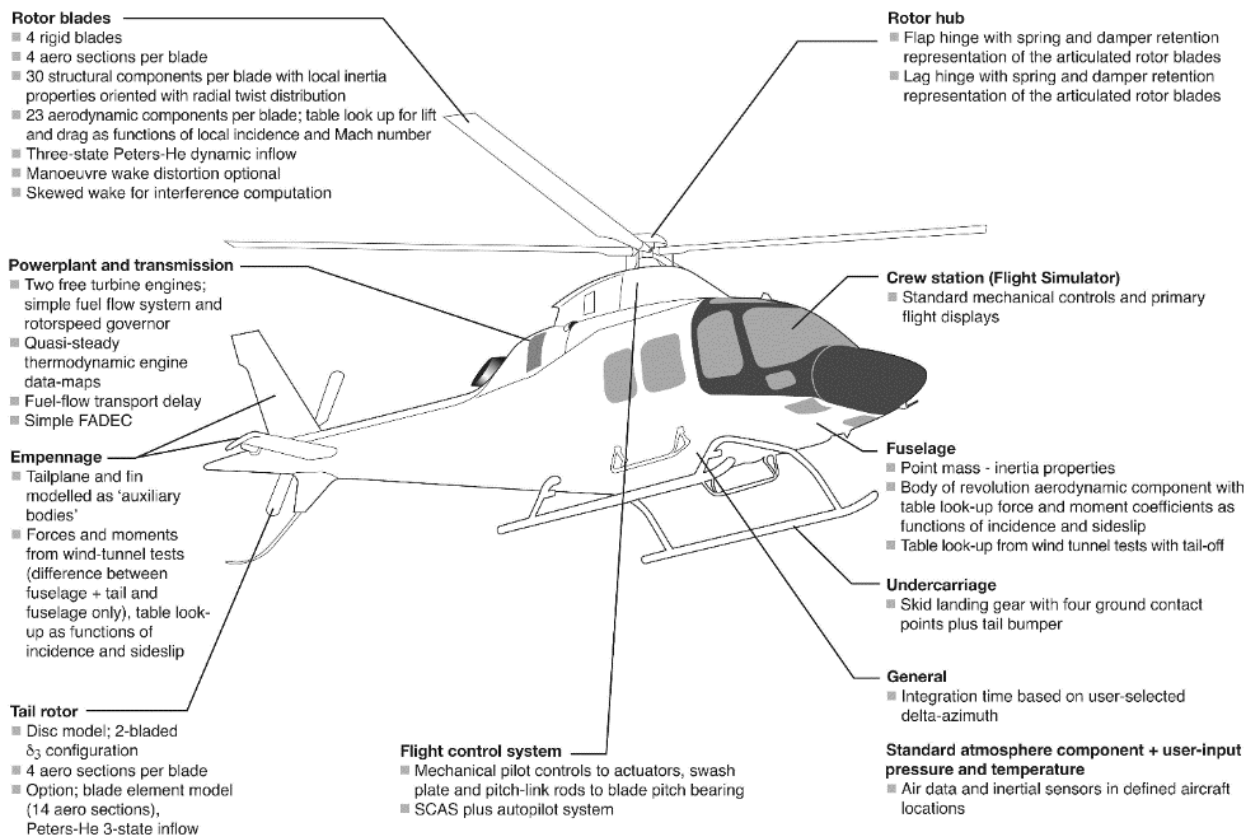


Figure 5-2: A schematic example of a component-based helicopter flight simulation model

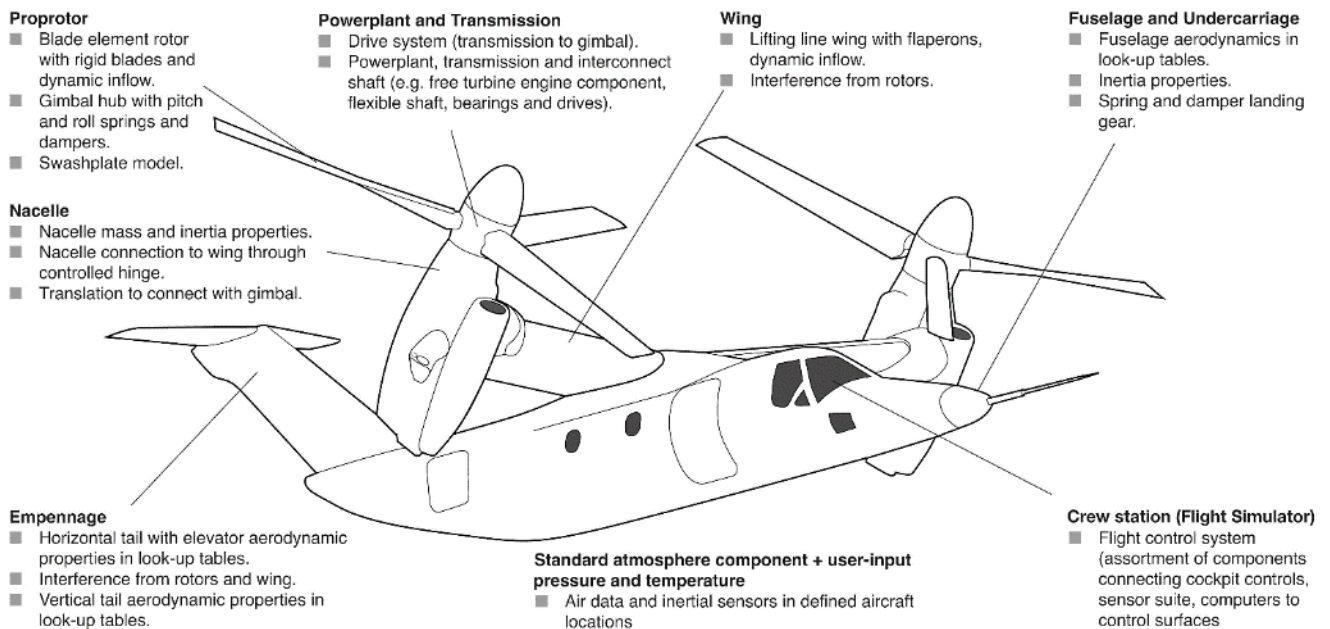


Figure 5-3: A schematic example of a component-based tilt-rotor flight simulation model

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## 5.2.2 Required fidelity; sufficiency

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To emphasise, this Guidance advocates that the required fidelity, defined in the Requirements Specification for the relevant ACRs, is what is judged to be sufficient for the RCbS activity by the Applicant and the Authority, and evidenced through metrics across the DoV. What exactly is 'sufficient' will depend on the application and it is

1281 the goal of this document to, ultimately, provide guidance in this respect (in terms of DoV metrics and associated  
1282 tolerances) for specific ACRs for which the RCbS process has been exercised. Nevertheless, expert judgement  
1283 will be required to ensure that the fidelity is indeed sufficient for the particular configuration and application.

1284 Interpreted in the 'frequency domain', an FSM operates over a wide range of frequencies and amplitudes and  
1285 typically includes components whose 'natural' frequencies are higher than the range normally associated with  
1286 flight mechanics and piloted flight control (e.g. 0.1 – 10 rad/sec), e.g. rotorblade aeroelastics,  
1287 engine/rotorspeed/transmission dynamics, control actuators. The interaction of these components with the  
1288 aircraft's flight mechanics and control can be important for achieving a 'sufficient' level of fidelity for certification  
1289 purposes. In this context, a dynamic characterisation (e.g. eigen-analysis) can be carried out to identify the  
1290 prediction domain in terms of the frequency ranges of component behaviour. Such characteristics are useful for  
1291 establishing the excitation frequencies in the control-input designs used in the pre-certification flight tests to  
1292 support flight mechanics model validation. Such results can also be used to compare with frequency response  
1293 functions derived from test data. Metrics based, for example, on the 'allowable error envelopes' of the so-called  
1294 'maximum unnoticeable added dynamics' (MUADs) [16] can then, in principle, be used to quantify what can be  
1295 considered sufficient fidelity, if the associated envelopes are demonstrated to be applicable to the configuration  
1296 and flight condition under consideration. Such caveats will apply to all fidelity metrics that require evidence-  
1297 based justification to use in RCbS. In taking a frequency domain view such as described above, it is important to  
1298 recognize that it may yet be required to include the higher frequency dynamics in the simulation if relevant for  
1299 the ACR in question and even if, nominally, it has no dominant role in the flight mechanics of the aircraft.

1300 The degree of complexity in the aerodynamic modelling on all relevant components of an FSM has proved critical  
1301 to achieving a fidelity sufficient for use in vehicle design, and this is expected to be the case for certification  
1302 support. Of relevance to fidelity are the range and limits of aerodynamic approximations used in the FSM and  
1303 these should be clearly defined, with supporting evidence, as part of the definition of the domain of physical  
1304 reality and the related validation process.

### 1305 **5.2.3 Trim, Stability and Response**

1306 The level of FSM fidelity relates to the three aspects of rotorcraft flight dynamics relevant to certification, as  
1307 discussed in Section 2, namely 1) trim, 2) stability and 3) dynamic response. In general, the fidelity of the FSM  
1308 for all three aspects should be sufficient for the application, even if the application itself revolves mainly around  
1309 a single aspect. That is, a model that is able to accurately predict trim for a control margin assessment, but poorly  
1310 predicts short-term open-loop control response is considered unsuitable for the former application. The FSM  
1311 fidelity relative to flight test can be quantified with reference to these three aspects, using appropriate metrics.  
1312 For example:

- 1313 1. Trim; linking in current certification specifications with, e.g. the control margins throughout the flight  
1314 envelopes and the static stability characteristics, the latter quantified in terms of control gradients for  
1315 perturbations in lateral and forward speed. Trim computations are made with the non-linear FSM, to  
1316 derive the control displacements required to ensure equilibrium flight, e.g. in terms of airspeed, sideslip,  
1317 vertical velocity and turn rate.
- 1318 2. Stability; linking in current certification specifications with the dynamic stability characteristics,  
1319 quantified in terms of the damping and number of oscillations in a period of time. Techniques to  
1320 establish stability typically involve the pilot/computer applying (open-loop) doublet-type control inputs  
1321 and allowing the free response to evolve sufficiently long that period and damping can be computed.  
1322 An FSM can also be linearised by perturbing each state and control in turn and creating a derivative-  
1323 model, with the eigenvalues of the natural modes computed to provide stability characteristics. The  
1324 eigenvalues can be plotted on the frequency-damping (eigen) chart for comparison with the  
1325

1326            aforementioned open-loop response analysis on the non-linear FSM. Such comparisons can provide  
1327 information on the impact on stability of any nonlinearities in the FSM. It is noted that the military  
1328 standard, ADS-33E-PRF (ADS-33) [17] also includes requirements for ‘closed-loop’ stability in terms of  
1329 attitude bandwidth and phase-delay.

1330  
1331            3. Dynamic response (open- and closed-loop); linking, for example, with controllability and  
1332 manoeuvrability requirements in the current certification specifications. A case might be the response  
1333 of the rotorcraft to some control input or external disturbance (e.g. gust) computed as transient time-  
1334 varying evolutions of the aircraft motions. Such cases are typically used in the validation process to  
1335 establish the quality of the prediction of the short-term response. Another case could be the frequency  
1336 response, computed in the form of transfer functions, e.g. pitch attitude response to longitudinal cyclic,  
1337 generated through frequency sweeps on control inputs. Response analysis may also include the  
1338 evolution of the system to triggering events, or even entire (emergency) procedures, e.g. failure of sub-  
1339 systems of the rotorcraft. The link with the concepts of controllability and manoeuvrability also  
1340 emphasise the potential value of pilot-in-the-loop simulation in the compliance demonstration process.

1341 The ‘describe and predict’ strengths of M&S can sometimes weaken because of difficulties in explaining the  
1342 causes of flight behavioural characteristics through analysis with the coupled, multi-body, nonlinear, dynamic  
1343 system. Linearisation can be used to provide insight in some cases and it is considered worthwhile as part of this  
1344 Guidance to expand on this point in the following text box.

#### The value of linearisation for gaining insight into flight behaviour

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

1345 The question of how to relate the qualitative descriptions of dynamic response into quantifiable requirements  
1346 for civil rotorcraft certification is a topic of ongoing research; such metrics do not currently feature in the  
1347 certification specifications. In the military handling qualities/performance standard, ADS-33 [17], the minimum  
1348 acceptable dynamic response requirements are quantified in terms of parameters such as attitude quickness,  
1349 control power and inter-axis couplings. Also, the comparison of dynamic response features in the validation of  
1350 the FSM for use in the certification of training simulators (e.g. FSTD(H) [15], see Section 6).

1351 An important part of the development for an FSM relates to model-updating and tuning (also referred to as  
1352 calibration in other disciplines (e.g. [3]); i.e. the process of improving the fidelity of the FSM to ensure sufficiency  
1353 for purpose, e.g. for the use in certification. Complementary fidelity assessments, using trim, stability and  
1354 response analysis, can provide insight into the required 'physics-based' updates in this updating/tuning process.

1355 Before progressing to examine the verification and validation processes relevant to RCbS, some detail on specific  
1356 components and interactions are discussed.

#### 1357 **5.2.4 Flight control and automatic flight control system**

1358 The Flight Control System (FCS) interacts with the (real or virtual) pilot and may vary in complexity from a fully  
1359 Automatic Flight Control System (AFCS) with auto-pilot, to a basic SAS or an unaugmented mechanical system.  
1360 The pilot is not a component of the FSM (unless it is virtual), but is the centre-of-attention in the FS, as discussed  
1361 in Section 6. And, as further discussed in Section 6, the data feeding through from the FSM to the FS is a key  
1362 ingredient of the FS fidelity. The FCS is no different to any other component in the FSM, featuring functional sub-  
1363 components, inputs and outputs and interfaces with, for example, the rotor systems, aircraft electrical and  
1364 mechanical power systems and the inertial and air-data sensor systems, as well as the computerised autopilot  
1365 and SAS. Likewise, simulated FCS sub-components will also have their own domains of prediction, validation,  
1366 extrapolation and physical reality. The latter needs to take account of nonlinear dynamic characteristics e.g.  
1367 displacement and rate limits in the electro-mechanical actuation systems, or backlash and stiction in control  
1368 runs. The ways in which redundancy is achieved and managed is also an important function within the FCS. It is  
1369 this aspect that becomes crucial when ACRs relating, for example, to AFCS failures are being considered for RCbS.  
1370 The aircraft failure modes, effects and criticality analysis will have defined the kinds of failure that require  
1371 recovery action, either by the system itself or the pilot. In this application, the FSM must therefore include these  
1372 failure modes and the consequent system behaviour will be scrutinised in the validation process. For some  
1373 failure cases, the absence of validation data, precluded for safety reasons, places them firmly in the domain of  
1374 extrapolation. As discussed in Section 3, credibility analysis for such cases, including deriving the related  
1375 confidence ratios, becomes particularly important. One of the case studies reported in Section 10 of this  
1376 Guidance document explores this topic in more detail.

1377 It should be noted that a significant amount of current certification flight testing is conducted with the AFCS  
1378 engaged, since this is the normal mode of operation for aircraft certified to CS-29, and in some cases to CS-27.  
1379 This does not reduce the importance of ensuring that the flight characteristics of the so-called bare-airframe  
1380 FSM meet the required fidelity standards. However much the AFCS might suppress natural handling qualities  
1381 deficiencies, understanding the physics at work in the bare-airframe flight behaviour is considered vital in RCbS  
1382 applications. This is particularly true for failure cases of course but also, more generally, to reinforce credibility  
1383 of results in the DoE. The presence of an AFCS may, however, significantly reduce the impact of uncertainties  
1384 related to the bare airframe, making the validation of the FSM more straightforward. So, we acknowledge that  
1385 in some applications, e.g. AFCS upper-modes analysis and P1 predictability level, the validation of the aircraft  
1386 with AFCS-on may suffice.

1387 In many practical applications, the applicant might elect to use an exact software copy of the AFCS, or even  
1388 perform HITL testing, to ensure the fidelity is as high as possible. However, this does not obviate the need for  
1389 comprehensive V&V analysis for such hardware/software. In a similar vein, it is not uncommon to find that the

1390 autopilot or AFCS designs contain proprietary data, so that the exact details of the design are not available, even  
1391 to the rotorcraft OEM, but only to the AFCS design organisation. This will typically require either black box  
1392 integration or reverse engineering of the design, effectively a model creation, based on input-output data. The  
1393 level of complexity can increase significantly if there are multiple functions drawing on the same controls, e.g.  
1394 stability augmentation, response-type augmentation, load alleviation or flight envelope protection. How the FCS  
1395 performs when multiple constraints are approached simultaneously should have been addressed in the design  
1396 specification, produced by the rotorcraft manufacturer. However, such behaviour needs to be verified (does the  
1397 behaviour meet the design specification?) and validated (is the design specification correct?). Again, the  
1398 validation of the complete system can be inhibited for flight safety reasons, emphasising the importance of  
1399 credibility assessment.

#### 1400 **5.2.5 Engine, rotorspeed and transmission dynamics**

1401 A similar situation, through the potential unavailability of commercially restricted data and the need for reverse-  
1402 engineering, can arise for the engine component. The main function of the engine is to deliver the required  
1403 power and torque to the rotors in trims and manoeuvres. The engine also provides power to the  
1404 mechanical/hydraulic and electrical systems and how this distribution is managed, particularly when close to the  
1405 power limits needs to be modelled correctly. The inputs to the engine model include fuel flow, with rates  
1406 controlled by the rotorspeed governor and air from the atmospheric component. The engine intake will 'shape'  
1407 the airflow from the atmospheric model into the compressor stage of a turboshaft engine. These details may  
1408 point to the need for including models of the thermodynamic processes within the engine, developing through  
1409 the four thermos processes in the control volumes of the compressor, combustor, gas generator and power  
1410 turbine. Options here include a fully unsteady dynamic combustion, or a quasi-steady look-up table for the  
1411 thermodynamics of the compressor-combustion processes. These details will be very important in edge of the  
1412 envelope performance analysis, but for stability and dynamic response prediction it is the rotorspeed response  
1413 and torque reaction on the fuselage from both main and tail rotors that are paramount. This is especially true in  
1414 the simulation of engine failure conditions where it is vital to accurately predict the torque response and  
1415 available power of the engine(s). The reverse engineering process often assumes a state-space model with  
1416 variable parameters (e.g. functions of power, hence nonlinear) defining the time constants and gains relating  
1417 rotorspeed to torque and torque to fuel flow. Elasticity in the drive shafts will impact the natural frequencies  
1418 within this component and may need inclusion if these fall within the range defined as necessary in the  
1419 requirements specification.

#### 1420 **5.2.6 Environment modelling**

1421 Creating a standard atmosphere model is a straightforward task, with air density, ambient pressure and  
1422 temperature being a function of altitude. The flight simulation validation envelope will be defined by the flight  
1423 test conditions required and achieved within this atmospheric model, with simulated test points adjusted for  
1424 the real-world test conditions. Complications occur when, during flight test, the air is moving relative to the  
1425 Earth's surface with potential vertical and horizontal shears/gradients. Such 'winds' are usually unsteady,  
1426 containing gusts and turbulence, whose characteristics vary with altitude and proximity to the terrain and  
1427 objects. Humidity levels impact the density, noting that humid air is less dense than dry air, and the modelling is  
1428 even more challenging when precipitation occurs. Granted that it is best practice (and at times a firm  
1429 requirement) to perform flight testing in calm weather conditions, the atmospheric model that forms part of the  
1430 FSM may need to feature the primary effects of these complications, if they are suspected to have significantly  
1431 affected the data gathered during the pre-certification flight test campaign and a basis for validation of these  
1432 effects is available from measurements. Random turbulence can, in principle, be modelled based on extracted  
1433 air-data system measurements in trim, prior to test inputs being applied. More structured unsteadiness, for  
1434 example non-idealised gusts, are more difficult to model and can appear as so-called process noise on the signals  
1435 from the sideslip and incidence vanes. Developing a process for addressing the impact of atmospheric

1436 unsteadiness within the RCbS may prove to be important. Moreover, whereas flight testing in closely controlled  
1437 unsteady atmospheric conditions is not possible in practice, flight simulation, piloted or otherwise, offers the  
1438 ability to explore the aircraft response to well-defined unsteady conditions in a repeatable manner. For example,  
1439 the impact of turbulence on controllability and pilot workload is known to be potentially significant and piloted  
1440 simulation provides the opportunity to quantify this impact directly, rather than, e.g. by requiring a minimum  
1441 level of residual control authority in trim. Yet another example in which unsteady environmental effects may be  
1442 important is in the assessment of pilot workload in failure conditions.

1443 It is noted that, although the simulations may be external to the FSM, other elements that fall under the category  
1444 of 'environment', include ground contact/friction and obstacle air wake models, Air Traffic Control (ATC), and  
1445 other airspace users. The relevance of these will depend on the application scenario and, in case of the latter  
1446 two elements, whether or not pilot workload is an important aspect in the evaluation being undertaken.

### 1447 **5.2.7 Coupling with the Flight Simulator (Phase 2b)**

1448 As shown in Figure 2-1, a primary 'artery' from the FSM (Phase 2a) to the FS development (Phase 2b) is a  
1449 validated FSM. However, the FS will need a 'prototype' FSM prior to the formal release at the end of Phase 1a.  
1450 This would be used to support the development of many of the FS features (if not already developed and verified  
1451 in prior activities) for which the validated FSM is not critical. The characteristics of such a prototype need to be  
1452 defined within the FS requirements to ensure that Phases 2a and 2b evolve efficiently. Inevitably, the use of  
1453 piloted simulation in support of partial or full-credit Influence will need to await results of the FSM fidelity  
1454 assessment. Of course, certification tests using the FSM and FS take place after the credibility assessments in  
1455 Phase 3, but there are obvious efficiency benefits in Phases 2a and 2b being completed at the same time. Fidelity  
1456 assessment will define the domain within which the predictive metrics demonstrate sufficient FSM fidelity for  
1457 application to the ACR. Consequent FS fidelity assessments will then focus on ensuring that the FS is also suitable  
1458 for the ACR. These assessments will normally address non-FSM related features, such as visual and vestibular  
1459 motion cueing, pilot inceptor control forces and cockpit ergonomics critical for flight-related ACRs. However, it  
1460 may be that pilot feedback, as part of the perceived fidelity assessment, draws attention to some FSM  
1461 characteristics related, for example, to trim or dynamic response. The FS verification and validation processes  
1462 should ensure that the FSM is coupled into the FS such that its behaviour is essentially the same as the  
1463 standalone version documented in the output from the FSM development Phase 2a. The pilot perceives the FSM  
1464 outputs through the filters of visual and vestibular motion cueing systems in the FS, which themselves need to  
1465 pass through V&V processes. It is not unusual for a pilot to 'blame' the flight model for an FS fidelity deficiency,  
1466 even though the FSM fidelity assessment has been successfully 'passed'. There are multiple ways that FS features  
1467 can contribute to perceived deficiencies that need to be thoroughly investigated before re-visiting the FSM  
1468 fidelity assessment. This topic is returned to in Section 6.

## 1469 **5.3 VERIFICATION & VALIDATION**

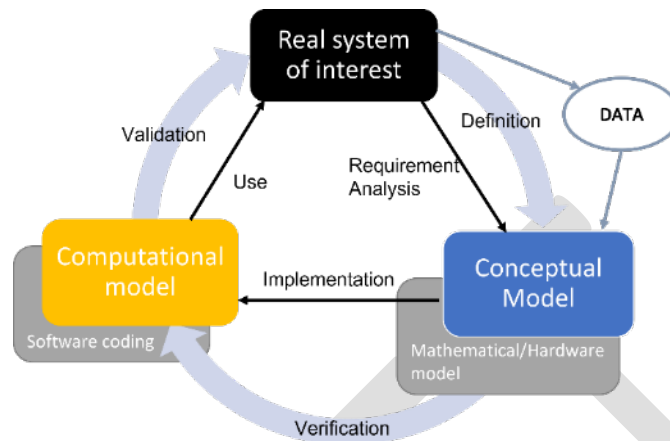
### 1470 **5.3.1 Introduction**

1471 As described in previous sections, flight simulation attempts to replicate the relevant aircraft flight physics using  
1472 computer models and, if applicable, simulator hardware. Within the FSM development process illustrated in Fig  
1473 5-1, Phase 2a, sit the two 'checking' processes that ensure that the FSM build is verified (all model requirements  
1474 are correctly met) and validated (the model requirements were correct and the replications are successful). The  
1475 V&V processes are so vital to the success of RCbS that some additional 'conceptual' background is considered  
1476 useful in this Guidance as build-up to the discussion on V&V.

1477 The creation of a simulation in the generic sense may be represented through a triangular process where on one  
1478 vertex is positioned the real system of interest, on the second vertex there is the conceptual model, i.e. the

1479 collection of assumptions and abstractions applied to develop a physical model of the system of interest, and on  
1480 the third vertex is placed the computational model. In turn, each of these boxes is composed of several sub-  
1481 boxes that detail the different phases, shown in Figure 5-4.

1482



1483

1484

Figure 5-4: Process to create a simulation model

1485 The development process starts at the system of interest, in this case the rotorcraft, or a subsystem thereof.  
1486 Through requirements analysis, considering the operational conditions under which the system needs to be  
1487 analysed/simulated, the accuracy required, etc., a conceptual model can be defined. This model can be  
1488 transformed into a mathematical form, which is converted to a computational model with appropriate numerical  
1489 discretisation, and finally implemented in the form of a computer code.

1490 It is important to be able to trace back through all the aforementioned steps. This, together with the knowledge  
1491 of the source of the data that are included in the model, will provide the information required to define the  
1492 domain within in which the model should function and operate correctly, with the required level of fidelity – the  
1493 *domain of physical reality*, the DoR.

1494 For physics-based models, the assumptions that define the conceptual model focus on what physical  
1495 phenomena will be included and what will be ignored. As an example, consider the blades of a helicopter rotor  
1496 as our real system of interest. Depending on the requirements, the blades can be represented as rigid bodies, as  
1497 linear elastic beams, or more complex non-linear structures with sophisticated constitutive laws. Each of these  
1498 conceptual models can then be represented by a variety of mathematical and computational model forms, each  
1499 one with its own pros and cons that will make it more or less suitable depending on the requirements. At the  
1500 same time, different sets of data will be required depending on the conceptual model choice. The models will  
1501 have a different DoR, the limits of which depend on the nature of the loading applied to the blade. For example,  
1502 the DoR for the structural aspects of an elastic blade element could be related to displacement and stress-strain  
1503 amplitudes that satisfy linear constitutive equations. The DoR for the aerodynamic blade segment might be  
1504 expressed in terms of the Mach number and angle of attack range included in the look-up data tables, combined  
1505 with assumptions on local sweep angle and unsteady aerodynamic effects. Expression in terms of frequency and  
1506 amplitude of dynamic response is another, general, approach to DoR description. However, since it will usually  
1507 be difficult, if not impossible, to know exactly how far an approximation is from the DoR boundary, the best that  
1508 might be achievable is a description based on comparison with a higher-order, more complex numerical model.

1509 A similar process can be followed for the FS software and hardware. In this case, starting from the requirements,  
1510 the necessary cues can be established for the pilot to acquire the correct awareness of the flight conditions, and  
1511 up to what degree of realism they must be reproduced. This constitutes the bulk of the conceptual model for  
1512 the FS. Then, it is necessary to define the software and hardware for the systems used to provide the cues to

1513 the pilot. Finally, as described in Section 6, the hardware/software systems are developed to translate the  
1514 conceptual model into real cues, with associated DoRs for the FS features.

1515 Once a simulation of reality has been built following the process outlined in this Section, the next crucial steps  
1516 will be the V&V of the simulation. In the context of the above introductory paragraphs, *Verification* is the process  
1517 of determining that a computational model accurately represents, within the required limits of accuracy, the  
1518 underlying conceptual and mathematical models and its solution. The process can be divided into two steps:  
1519 code verification and solution verification. *Validation* is then the process of determining the degree to which a  
1520 model is an accurate representation of the real world from the perspective of the intended use. Usually,  
1521 validation is performed by comparing the results obtained by the simulation with the results of experiments.  
1522 However, in some cases, the reference data, or '*the referent*', could be data, information, or knowledge gained  
1523 by previous experiences, analogous systems, or even by other validated simulation models.

1524 In basic scientific analysis, the predictive capability of a simulation model commonly deals with the ability of the  
1525 underlying theory to be falsified by experimental observations. However, in engineering, the objective is to check  
1526 to what extent the predictions meet the accuracy standards set in the requirements. So, the approach to  
1527 validation is rather based on deciding the acceptable level of disagreement between experiments and  
1528 simulations. The level of disagreement is a *measure of the fidelity* of the simulation and validation revolves  
1529 around defined *fidelity metrics* that are used to quantify the degree of accuracy of the model.

### 1530 **5.3.2 Component-based building-block approach**

1531 It is advisable to undertake the V&V process, much like the FSM-build, in a hierarchical way starting from the  
1532 simplest components up to the entire system that will be the object of the analysis, in this case represented by  
1533 the aircraft. This can be described as a building-block approach, illustrated through a pyramidal structure as  
1534 shown in Figure 5-5. In this approach one moves from the lowest level, or tier, toward the top, increasing in  
1535 complexity and the degree of coupling between different components. Validation at the lower levels is based on  
1536 component-level experiments. In a general sense, rising up the tiers toward the top of the pyramid can obscure  
1537 the coherence between causes (at low levels) and effects (at high levels), while the errors and uncertainties in  
1538 measurements and relationships can increase, e.g. through propagation. The systematic step-by-step approach  
1539 advocated in this Guidance should minimise the risk of this obscurity and ensure a higher control on the quality  
1540 of the models both from a testing and analysis point of view, and may help in isolating the cause of unexpected  
1541 or erroneous results and should prevent modelling errors or deficiencies from being masked.

1542 This Guidance recognises the dual nature of top-down and bottom-up perspectives in V&V. In the validation  
1543 process particularly, the comparisons of greatest interest lie at the highest, aircraft, level. However, mismatches  
1544 here can normally only be understood, and ultimately resolved, at a deeper, lower-tier or component level. So,  
1545 the two perspectives go hand in hand and a thorough grasp of the tier-connectivity is considered important in  
1546 the RCbS process. Ultimately, the applicant shall make a credible case to the authority as to the lowest levels of  
1547 modelling and validation that must be considered for the application.

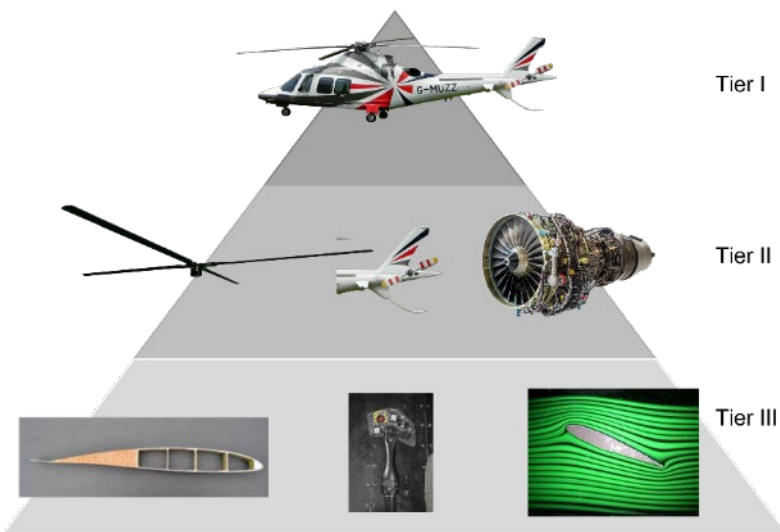


Figure 5-5: Building block approach for an FSM

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1549

1550 The requirements-based description of FSM development ensures that all interactions between components  
 1551 and associated tiers are fully defined. In the tier structure, this can be interpreted as couplings between the  
 1552 modelling in the adjacent tiers. In principle, all the coupling should be two-way interactions. However, there are  
 1553 cases where the influence in one 'direction' is much weaker and might be neglected, or where the mathematical  
 1554 and/or computational formulations do not allow the implementation of a two-way coupling. In these cases, a  
 1555 one-way causal coupling is the only available option, e.g. impact of undercarriage with surfaces. The  
 1556 consequences of the introduction of these one-way couplings must be thoroughly assessed, because they may  
 1557 limit the domain of the physical reality of the model and/or affect the component-level validation. Consider, for  
 1558 instance, the case where the model of a helicopter rotor is coupled with the modelling of the aerodynamic forces  
 1559 on the fuselage. The presence of the fuselage affects the rotor flow, but the rotor wake also affects the  
 1560 aerodynamic forces generated on the fuselage. Therefore, even though the isolated fuselage and rotor models  
 1561 may be validated for a large range of flight velocities and incidence angles, the range of conditions for which the  
 1562 prediction error of the coupled model is acceptable, as determined from validation at a higher tier, is likely to  
 1563 be narrower.

1564 It is possible that not all the details of the subcomponents up to the lower level of the pyramid are available to  
 1565 the applicant, e.g. because the aircraft is an assembly of subsystems developed and provided by third parties.  
 1566 This may be the case for instance for the engine, the landing gear, the avionic components, or the flight control  
 1567 systems. In these cases, if detailed modelling is required, it is advisable for the applicant to request a (traceably)  
 1568 validated simulation model from the subsystem providers, developed following requirements and conventions  
 1569 specified by the applicant and transparent in its formulation and implementation, so that it can be integrated  
 1570 into the FSM. If two-way interactions with the subsystem are essential, it is necessary to identify all inputs and  
 1571 outputs of the model required to perform the simulations. It is stressed that the requirements, in terms of V&V  
 1572 and documentation of the supplier subsystem model, are identical to those at the FSM level.

1573 **5.3.3 The application domains re-visited**

1574 In Section 2, the domains relevant to the RCbS process were introduced. The domains feature large in the V&V  
 1575 and fidelity assessments in Phase 2a. While the definition of the DoP is relatively straightforward since it is  
 1576 derived directly from the requirements, the other domains require more detailed analysis to define. This is aided  
 1577 by Figure 5-6 that illustrates, in 2-dimensional conceptual form, how the domains relate. Generalised flight  
 1578 envelope variables  $p_1$  and  $p_2$  are used on the axes, but it is noted that the domains are multi-dimensional and  
 1579 should be described as such by the applicants.

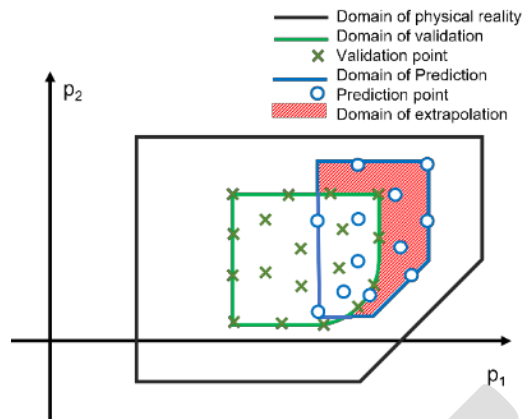


Figure 5-6: Sketch of the application domains and their relationship

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1581

1582 To define the DoR of the aircraft, it is useful to follow the building-block pyramid, as this relates the physics used  
 1583 on lower tiers to the coupled components at higher tiers. Typically, for each component at the base of the  
 1584 pyramid it should be straightforward to define the sets of inputs and outputs appropriate for the modelled  
 1585 physics. Then rising to the higher tiers, it is necessary to:

- 1586 a. Identify the relationships between the input/outputs of the coupled model and the inputs/outputs of its  
 1587 components.  
 1588 b. Identify the relevant input/output ranges of the coupled model that generate inputs/outputs of the  
 1589 component models that are within the respective domains of physical reality.  
 1590 c. Verify that the coupling physics in these ranges are correctly represented within the required accuracy.  
 1591 Alternatively, define the ranges over which the coupling effects could be neglected while meeting the  
 1592 requirements in terms of fidelity.

1593 With the adoption of this approach, the coupled models will always have a domain of physical reality that is  
 1594 equal to, or smaller than, the domain of the physical reality of the component models.

1595 In some cases, elements of the building-block pyramid for an FSM may be composed of phenomenological  
 1596 models, i.e., empirical models that are the result of the fitting of experimental data or predictions from higher-  
 1597 order numerical models. If so, care must be taken that these types of models are not used beyond their relevant  
 1598 DoV, i.e., the domain that contains all data used to tune the coefficient of the model [9]. This could be true for  
 1599 the top of the pyramid, if a model with only one level is developed. However, the logical consequence is that  
 1600 such a model will be used only for P1 predictability levels, i.e. interpolation only.

1601 The DoV is determined by the available test data and will be the result of the V&V process. It is, however,  
 1602 important to note that the DoV and DoP must always lie within the DoR. This is particularly important for the  
 1603 DoP, to avoid extrapolation beyond the limits where the model is expected to provide physically meaningful  
 1604 results.

1605 Note that, in many cases, although a simulation might be operating in the global DoE, many of the components  
 1606 will be functioning in their local DoV. However, the inverse may also be true. As such, it is important to trace  
 1607 how component models are operating relative to their local DoP and DoV boundaries.

#### 1608 5.3.4 Verification

1609 The verification sub-phase assures that the implementation of the mathematical model through numerical  
 1610 algorithms is as intended. It is composed of two aspects, code verification and solution verification.

1611 *Code verification*, establishing the correctness of the code itself, is independent of the physical problem in the  
 1612 RCbS process. In essence, code verification is concerned with ensuring that for a given set of inputs, the coded

1613 form of a modelled component generates the intended outputs. The first set of verification operations is  
1614 described as numerical algorithm verification, usually performed by comparing the solutions computed by the  
1615 simulation software with solutions generated by so-called *verification benchmarks*. These benchmarks can be:  
1616 (a) manufactured solutions, (b) analytical solutions, or (c) numerical solutions appropriately generated.  
1617 Applicants are referred to the literature, e.g. [18] for a thorough discussion on the different options. In general,  
1618 cross-comparison against other verified codes is not considered the preferred approach, but in some cases may  
1619 be the only option. By comparing the computed solutions with the benchmarks, it must be shown that by  
1620 increasing the sampling, the discretization error tends to zero with an appropriate rate of convergence. By its  
1621 nature, code verification must follow a building block approach, starting from verification of components (e.g. a  
1622 finite-element flexible beam element) and moving up to include component interactions (e.g. a rotating finite-  
1623 element rotor blade with aerodynamic loading).

1624 The second set of operations under code verification involves software quality assurance and pertains to  
1625 verification that the code is reliable and produces repeatable results in a specified hardware and software  
1626 environment. The bulk of code verification is often performed by the code provider. This is particularly the case  
1627 when commercial software packages are used, e.g. NASTRAN, FLIGHTLAB [19], in which case, the applicant needs  
1628 to collect evidence that verification has been undertaken by the code provider. In addition, whenever the  
1629 hardware or software is modified, it is important to verify that the 'new' code is still generating the results as  
1630 intended. The latter requirement falls into the category of Configuration Management as addressed in Section  
1631 9 of this Guidance. In some cases, it may be useful to ask the software providers to include the documentation  
1632 to enable the applicant to repeat code verification tests. Finally, it is important that the impact on the FSM  
1633 predictions of identified or known code defects is assessed as part of the solution verification process.

1634 *Solution verification* is performed after code verification and is an activity with the objective of *estimating* the  
1635 discretisation error of the FSM for a specific validation or prediction case. Through solution verification, as shown  
1636 in detail in Ref. [20] for CFD applications, it is the intention to assess the numerical uncertainty  $u_{num}$  of the  
1637 model in the conditions being assessed. A pragmatic approach is to consider the numerical uncertainty  $u_{num}$  as  
1638 epistemic, i.e., an interval without associated probability distribution, where the bounds of numerical uncertainty  
1639 for a given output parameter of interest, obtained at a practical level of numerical discretization, are defined equal  
1640 to  $\pm$  the magnitude of the error relative to the solution obtained at a higher, ideally asymptotically converged, level  
1641 of discretization.

1642 The numerical uncertainty, in turn, is one of the ingredients for performing the validation described in the  
1643 following paragraph, and also the credibility assessment described later in Section 8. In this context, it is  
1644 important to ensure that the solution verification encompasses the DoV and the DoE.

1645 It is also important to include all supplier and user-defined tools and scripts used to perform the pre- and post-  
1646 processing activities in the verification process. In the case of time-constrained solutions (e.g. real-time  
1647 application), there are also time-based convergence constraints in which case the solution iteration may be  
1648 halted before the established convergence criteria have been met. Requirements for how the solution process  
1649 deals with such constraints need to be defined and the verification process should check that these requirements  
1650 are satisfactorily met.

### 1651 **5.3.5 Validation and fidelity assessment**

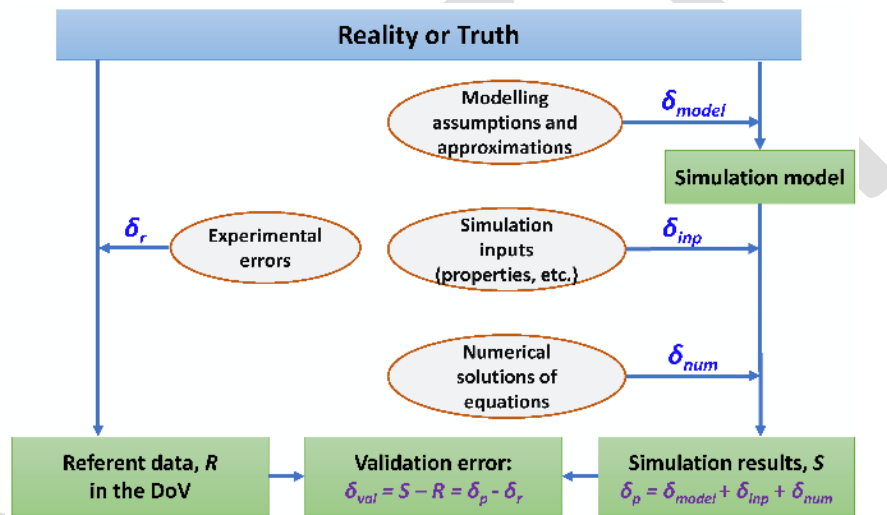
1652 Validation involves the comparison of FSM results with a referent, which generally is the result of an experiment,  
1653 commonly from flight testing in the RCbS process. The most common aircraft-level referent anticipated in this  
1654 Guidance will be the prototype of the aircraft to be certified and data gathered during pre-certification flight  
1655 tests. However, experimental referents may also be obtained from ground tests on components, from scaled  
1656 models, or from experiments conducted on an analogous system, e.g., flight test results from an aircraft variant  
1657 that has a similar configuration. In some cases, experimental results may not be available so, other forms of

1658 referent can be considered, e.g. results obtained by higher-fidelity continuum mechanics models. However, this  
 1659 Guidance emphasises that comparison with such data is not strictly ‘validation’. Such higher-fidelity modelling  
 1660 falls into the FSM toolset in RCbS and should receive the same level of scrutiny, in terms of V&V, as the core  
 1661 FSM.

1662 The goal of the validation process is to ensure the FSM predictions meet the tolerance requirements defined in  
 1663 Phase 1, for the comparison of fidelity metrics with test data. Following on from this, the goal of credibility  
 1664 assessment is to collect enough compelling evidence that would convince, beyond a reasonable doubt, a group  
 1665 of peers that the predictions of an FSM are sufficiently correct. Credibility is returned to in Section 8. In  
 1666 performing validation, it must be remembered that experiments are also affected by errors and uncertainty and  
 1667 that these should also be assessed (see Section 7).

### 1668 5.3.6 Validation error and uncertainty

1669 Figure 5-7, derived from References 21 and 38, is used to support the description of key errors. So, we see that  
 1670 both the referent (typically experimental data)  $R$  and the simulation result  $S$  have errors relative to the ‘truth’.



1671  
 1672 Figure 5-7 Overview of the derivation of the validation or comparison error

1673 As previously discussed in Section 3.2.1, fidelity deficiencies, and hence prediction errors, should be contained  
 1674 within the prediction error uncertainties. Referring to Figure 5-7, this applies for the three elements of the  
 1675 prediction error,  $\delta_p$ , for the simulation result  $S$ ;

- 1676 a) the errors due to modelling assumptions  $\delta_{model}$ , including those generated by the choices made in the  
 1677 conception of the model that are, by nature, related to epistemic uncertainties,
- 1678 b) the numerical errors,  $\delta_{num}$ , stemming from the methodology used to solve the underlying equations of  
 1679 the FSM,
- 1680 c) the errors,  $\delta_{inp}$ , arising from the input parameters of the FSM. These errors may be related to epistemic  
 1681 or aleatoric uncertainty, or both at the same time.

1682 The validation error  $\delta_{val}$  refers to the error observed between the referent and the simulation in the DoV.  
 1683 Including the referent error,  $\delta_r$ , the validation error  $\delta_{val}$  can be written in the form:

1684  
 1685  
 1686 
$$\delta_{val} = |\delta_{model} + \delta_{num} + \delta_{inp} - \delta_r| \quad (2)$$

1687 Hence, the error due to modelling assumptions, i.e. the error an applicant needs to quantify and understand in  
1688 the DoV validation process, can be written as:

$$1689 \quad \delta_{model} = \delta_{val} - |\delta_{num} + \delta_{inp} - \delta_r| \quad (3)$$

1690 To emphasise, a distinction is made between the validation error  $\delta_{val}$ , defined with respect to the referent (and  
1691 featuring only in the DoV), and the prediction error  $\delta_p$ , defined with respect to the (unknown) truth.

1692 The absolute-value term on the right of (3) is composed of terms that are of unknown magnitude and sign.  
1693 Assuming the errors are effectively independent (see Reference 38), the associated validation uncertainty  $u_{val}$ ,  
1694 can be defined as:

$$1695 \quad u_{val} = \sqrt{u_{inp}^2 + u_{num}^2 + u_r^2} \quad (4)$$

1696 The simulation model error  $\delta_{model}$  cannot be uniquely identified, but falls within the range:

$$1697 \quad \delta_{model} \in \delta_{val} \pm u_{val} \quad (5)$$

1698 The measurement (referent) or experimental uncertainty  $u_r$  is determined by the measurement set-up and  
1699 encompasses not only systematic and random errors in the data acquisition and instrument calibration, but also  
1700 random error or variability due to atmospheric conditions and piloting technique. The numerical uncertainty  
1701  $u_{num}$  is obtained from the solution verification process described in the previous section. Finally, the input  
1702 uncertainty  $u_{inp}$  can be derived through uncertainty quantification methods as discussed in Section 8.

1703 If the validation error is significantly larger than the validation uncertainty, then the error due to modelling  
1704 assumptions  $\delta_{model}$  can be expected to be close to  $\delta_{val}$ , and so the model must be improved. Alternatively, when  
1705  $|\delta_{val}| \leq u_{val}$ , it can be concluded that the model is within the precision achievable given the data and software  
1706 available. The uncertainty  $u_{val}$  provides a target to be reached when performing model validation in the DoV.  
1707 At the same time, a validation error significantly larger than the uncertainty will be an indicator that something  
1708 that is relevant has likely been neglected, and so calls for a revision of the setup for the conceptual model used  
1709 and the associated modelling assumptions. In this process, it should be stressed that characterising the  
1710 uncertainty of the validation measurements  $u_r$  is equally important as characterising the modelling  
1711 uncertainties.

1712 Although the level of detail in the analysis may vary depending on the ultimate FSM application, it is advised to  
1713 follow the same hierarchical building-block approach as employed during model development for the validation  
1714 process. Starting from a robust validation of systems at the base tier, typically characterized by a lower number  
1715 of relevant parameters, the assessment at higher levels can concentrate on the interactional effects between  
1716 the subsystems. FSM validation is thus recommended to be performed using this hierarchical approach,  
1717 focussing on component-level tests and analysis before validation of whole aircraft behaviour against flight test  
1718 data is attempted. Similarly, the validation of complex manoeuvres should be preceded by tests and analyses in  
1719 relevant steady-state conditions and simpler manoeuvres. This type of bottom-up approach enables modelling  
1720 deficiencies to be positively identified and, if possible, remediated. Here, support from diagnostic analysis can  
1721 be helpful.

### 1722 **5.3.7 Validation in parallel with development**

1723 An effective validation process will proceed in parallel with the development of the FSM itself, and also the  
1724 development of the experimental processes and systems, particularly the FTMS (Section 7). The availability of a  
1725 prototype model before conducting validation experiments will enable the 'design of experiments' to progress  
1726 efficiently, e.g. by selecting the relevant points to be tested and the quantities to be measured. This can also  
1727 provide opportunities to solve problems related to a lack of information on the experimental conditions, quality

1728 of the different measures, etc., that are typically encountered when models are developed only after the  
1729 completion of the test phases. The experiments dedicated to validating the FSM must be planned specifically for  
1730 this purpose, identifying all quantities that need to be measured accurately to validate the FSM, which in some  
1731 cases may be only loosely connected with the evaluation of the overall performance of the helicopter. These  
1732 points are emphasised in this Guidance to alert the applicant to the importance of having the validation data  
1733 gathering an integral part of the FSM development.

1734 Inherent test variability should always be considered and addressed to avoid the risk of relying on validation  
1735 based on outlier data points, i.e. data points that fall significantly outside of the typical variability observed  
1736 during a test or series of tests. Additionally, in these cases, the availability of a model before the test allows the  
1737 applicant to build up knowledge on expected reference outcomes that can help in identifying possible outliers  
1738 that require further investigation.

### 1739 **5.3.8 Validation flight testing**

1740 To relate to the certification specifications, flight tests for FSM validation should consider both steady-state  
1741 (trim) and transient (stability and response) phases where relevant. Depending on the application, frequency-  
1742 domain validation with associated system identification flight testing may be appropriate when the intention is  
1743 to establish the veracity of the FSM across a frequency range. The bounds and tolerances for the so-called  
1744 MUADs [16] provide an example metric in this case. Alternatively, transient responses to control inputs can  
1745 provide insight into short-term damping and control sensitivity comparisons, as well as cross couplings.

1746 When flight test data in the exact conditions of interest are not available or impractical to obtain, validation  
1747 using interpolation is appropriate in the DoV. In the DoE, validation is more challenging of course but a plan for  
1748 the credibility assessment and related uncertainty analysis will need to have been laid out in Phase 1. The FSM  
1749 will, of course, still be governed by the laws of physics in the DoE and the credibility assessment should  
1750 determine how the flight behaviour might 'stretch' the modelling assumptions to their limits. Such analysis will  
1751 be key to validation and fidelity assessment within the DoE.

### 1752 **5.3.9 Fidelity metrics**

1753 While an initial comparison between the referent and the FSM can be qualitative to assess the correctness of  
1754 the conceptual approach chosen, a quantitative analysis is required to assess the sufficiency of fidelity for the  
1755 model's use in RCbS. It is possible to distinguish between different scenarios when defining metrics to quantify  
1756 fidelity:

- 1757 a. Cases where the objective is the evaluation of the trim value of a quantity of interest, e.g. a control  
1758 margin. Here, the fidelity can be measured through the percentage errors between the referent and  
1759 the result of the simulation. Ideally, the allowable error is referred to a meaningful performance  
1760 characteristic related to the ACR, e.g., the minimum control margin for manoeuvrability or gust  
1761 tolerance.
- 1762 b. Cases where the objective is to compare the evaluation of a response over time, e.g. in dynamic stability  
1763 assessment where period and damping are computed. Percentage errors across the time response, or  
1764 metrics based on peak errors can be considered. The choice in metric should be strongly influenced by  
1765 the nature of the ACR being addressed.
- 1766 c. Cases where the objective is the comparison of frequency response functions, e.g. to characterise and  
1767 validate the frequency content of the various FSM components. The cited MUAD metric [16] has been  
1768 established to connect with a pilot's perception of modelling errors across the frequency range of  
1769 interest in pilot simulations.
- 1770 d. Cases where the aircraft behaviour in an ACR involves large excursions from a trim condition, e.g.  
1771 following failures or when pilots need to exercise the full manoeuvrability of the aircraft, e.g. for

1772 obstacle avoidance. The moderate-large amplitude response quickness metric from ADS-33 is an option  
1773 for fidelity assessment in such cases [21].

1774 In cases where there are multiple quantities of interest in the fidelity assessment, it is possible to define a  
1775 weighted sum of all quantities with the weights reflecting the relative importance of the different quantities  
1776 [22].

1777 As illustrated in Figure 5-1, validation and fidelity assessment should be considered an iterative process that  
1778 starts with the fidelity requirements and associated flight test points (both defined in Phase 1) and advances to  
1779 a tuned/updated model that meets the sufficiency requirements. The model updating process is also likely to be  
1780 iterative, as fidelity at aircraft-level is derived from component-level assessment and developments.

1781 **It is emphasised here that the sufficiency criteria in terms of FSM fidelity in the DoV should be defined in Phase**  
1782 **1, based on the Influence/Predictability for the ACR and agreed with the certification authority.** In principle,  
1783 the 'acceptable' FSM mismatch-tolerances require a degree of engineering judgment based on the experience  
1784 from other applications. For example, error tolerances from the certification specifications for flight simulation  
1785 training devices may be used as a guideline where appropriate. More generally, a systematic approach is  
1786 recommended to connect the physics-based nature of the FSM **with the requirements of the ACR.**

### 1787 **5.3.10 Investigating FSM error**

1788 One of the challenges in the validation and fidelity assessment of an FSM lies in the systematic exploration of  
1789 the model error  $\delta_{model}$  and related (epistemic) uncertainties in the predictions. That is, those errors and  
1790 uncertainties relating to approximations in the mathematical expressions used to model the underlying physics.  
1791 The following deals with the qualitative exploration of the model error, whereas quantification is discussed in  
1792 Section 8.

1793 The engineer knows that their model is not perfect. He/She may have some knowledge of the imperfections and  
1794 so should be able to estimate the boundary of the DoR, to try to ensure that predictions do not cross this.  
1795 However, in several respects, the engineer will be uncertain about the location of this multi-dimensional  
1796 boundary. Also, in the DoR, and even within the DoV, he/she will likely have different degrees of uncertainty  
1797 about the accuracy, the predictive ability, of their model. Such uncertainties will be well informed by experience  
1798 and, although experience is a good teacher, it can also deceive. As with most aspects of the Guidance, there is  
1799 no substitute for a systematic process to assessing these kinds of uncertainties. Herein are suggestions for the  
1800 elements of such a process.

1801 Every input-output (mathematical) relationship in a FSM approximates reality. The mathematical  
1802 approximations are reflected in assumptions about how the physical processes work. Here, for the benefit of  
1803 clarity, we distinguish between (mathematical) approximations and (physical) assumptions. Understanding the  
1804 physical assumptions and how they are represented by the mathematical approximations is part of the  
1805 foundation for exploring the modelling errors in an FSM. This understanding is considered critical to the  
1806 successful application of RCbS.

1807 A significant benefit accruing from the use of an FSM, for both design and certification, is the ability to explore,  
1808 identify and quantify the physical sources of the contributions to input-output relationships. Predictive capability  
1809 has long been underpinned by understandings of the relationship between a cause and effect (the physical  
1810 manifestations of input and output). In the limit, such cause-effect analyses can be used to quantify the impact  
1811 of all modelling assumptions, and their approximant parameters, on mismatches between test and FSM  
1812 predictions, i.e. the fidelity of the FSM. Of course, on their own, such diagnostic investigations do not necessarily  
1813 identify the specific source or complete cause of a mismatch, but they can be used to compute sensitivities and,  
1814 hence, point to likely suspects in the search for modelling errors.

1815 At the global level, FSM fidelity can be expressed in terms of the relationships between the forces and moments  
1816 acting at the aircraft centre of gravity and the resultant evolution of aircraft motion states. For small  
1817 perturbations, the relationships are traditionally quantified in the form of 6-DoF stability and control derivatives,  
1818 or more generally, N-DoF generalised force and moment derivatives (e.g. including rotor dynamic and  
1819 aerodynamics states). Such global analysis is also possible using test data, creating phenomenological models  
1820 (p-models) e.g. using System Identification techniques to support fidelity assessment. As discussed in Section  
1821 5.3.6, and later in Section 10, component-based force and moment derivatives can be used as a guide to FSM  
1822 updating through fidelity renovation.

1823 An FSM contains a myriad of computational pathways from interconnected local components to the global flight  
1824 behaviour in the form of trim, stability and response predictions. Along these pathways, throughout the process  
1825 network, data flows that provide the source of information that can be used in uncertainty analysis. Virtual  
1826 (diagnostic) sensors within the network allow the user, or computer associate, to interrogate very detailed  
1827 behaviour to establish where processes are relative to the boundaries of the DoP and DoV.

1828 The sources of modelling deficiencies lie at the local level, propagating errors along the various pathways to the  
1829 global level, e.g. in the magnitudes and directions of local flowfield or in the way that component forces and  
1830 moments react to the flowfield. Another example might be the way that a control actuation system might  
1831 saturate because of demands from the pilot/autopilot on the one side and/or loads induced by rotor-blade  
1832 torsion on the other. Some of the usual suspects of modelling deficiencies are shown later in Table 8-2.

1833 Once the primary source(s) of FSM error have been identified, the question becomes how to repair or renovate  
1834 the deficiencies in fidelity. That brings us to the model tuning/updating process in Figure 5-1.

### 1835 **5.3.11 Model tuning and updating**

1836 In pre-certification FSM development, it is not unusual for fidelity to be insufficient for the intended RCbS ACR.  
1837 In the event the validation against test data reveals unacceptable discrepancies, the first step should be to  
1838 investigate and reveal the cause of the discrepancy and postulate physics-based updates to the FSM. The update  
1839 process could include modifying the modelling assumptions and/or adding previously un-modelled dynamics.  
1840 Both might require the gathering of additional experimental data as illustrated by the iteration with flight testing  
1841 in Figure 5-1. Another option is to tune the FSM parameters to achieve the required sufficiency. Every design  
1842 parameter in the FSM will have a degree of uncertainty and, within this established measure of uncertainty,  
1843 sensitivity analysis can reveal the limits for parameter modification, or tuning, to increase fidelity. In the process  
1844 care must be taken to keep all parameters within physically meaningful bounds and to ensure that the aircraft-  
1845 level tuning does not deteriorate the correlation against component-level test data. In case of doubt, it may be  
1846 necessary to explore the limits of validity of a given parameter by comparison against a higher fidelity simulation  
1847 approach. It is noted that, when taking into account simulation model validation uncertainty, the DoFs for  
1848 improving the correlation with test data through input parameter variations (i.e. tuning) are naturally exercised  
1849 and finding the unique combination of parameters that provides the 'best' match is not necessarily of particular  
1850 value.

1851 If a system-level p-model is used, then all possible model-updating techniques could be applied, keeping always  
1852 in mind that such model can be used only for P1 predictability levels, i.e. interpolation only, since its DoR cannot  
1853 extend, by definition, beyond the DoV.

1854 A wide range of model-updating methods has been explored and documented by the NATO Research Task Group  
1855 AVT-296 [22]. AVT-296 explored a range of different approaches applicable across the life-cycle of a rotorcraft,  
1856 including for use in improving FSM fidelity for training simulators and for certification. The physics-based update  
1857 methods (Methods 3–6 in [22]) are generally applicable to the certification process if applied within appropriate  
1858 limits. AVT-296 also documented a variety of fidelity metrics commonly used as a part of the update process.

1859 Many of the methods described in the NATO report make use of System Identification methods to create a p-  
1860 model, derived from flight test measurements. Comparison of the parameters identified in the p-model  
1861 structure with the equivalent parameters extracted from the FSM then provide the basis for fidelity  
1862 improvement activity. Example parameters are the 6DoF stability and control derivatives (see text in Section  
1863 5.2.1), rotor inflow deformation parameters, or constants in the rotorblade retention modelling. Clearly, as with  
1864 FSM parameter tuning, any adjustments to the FSM parameters based on such comparisons must be fully  
1865 justified.

1866 Finally, if the simulation model is used to obtain proof of compliance in the DoE, the credibility of the simulation  
1867 model and validity of the underlying tuning must be explained and demonstrated. Credibility assessment is the  
1868 topic of Section 8.

#### 1869 5.4 SUMMARY: PHASE 2a

1870 To summarise, activities in Phase 2a, development of the FSM based on the (preliminary) Requirements  
1871 Specification, include:

- 1872 i. FSM build, verification and validation and fidelity assessment, including updating/tuning,
- 1873 ii. Prototype FSM supplied to the FS and FTMS developers to support parallel activities,
- 1874 iii. Input of pre-certification ground and flight test programme to support validation of FSM,
- 1875 iv. Multiple iterative pathways managed and exercised as required throughout Phase 2a,
- 1876 v. Updates to Requirements Specification based on Phase 2a activities,
- 1877 vi. Outputs; FSM validated for intended purpose, documented in fidelity assessment reports.

1878

1879

1880 **6 FLIGHT SIMULATOR DEVELOPMENT (PHASE 2b)**

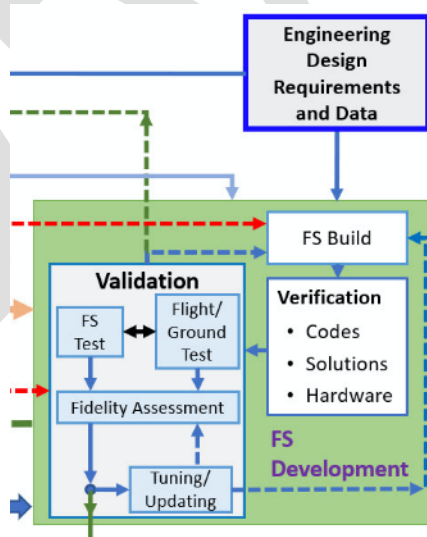
1881 **6.1 INTRODUCTION**

1882 The focus of the Guidance in this Section is on real-time, piloted simulations. The FS is intended to create an  
1883 illusion of reality for the crew, so that they behave, react and perform as if they were in the real aircraft. Many  
1884 factors contribute to this illusion. The fidelity of the various simulator features are obvious contributors, but also  
1885 the protocols around how tests are conducted can reinforce or spoil the illusion. The test team must ‘pretend’  
1886 that they are conducting a real flight test and, as far as possible, engage in communications as if it was ‘for real’.  
1887 Even with a perfect FSM fidelity, the pilot’s reactions, for example to failures, will depend on the cueing fidelity,  
1888 not exaggerated, such that the failure identification, control strategy reactions and closed-loop recovery  
1889 strategies are realistic. Achieving this kind of realism is no easy task, but rather calls for a development and  
1890 validation discipline matching that described for the FSM. With the pilot in-the-loop, the term ‘behavioural  
1891 fidelity’ is also considered appropriate.

1892 Figure 6-1 illustrates the elements of the FS development phase (Phase 2b), with major inputs from the  
1893 Requirements Capture/Build phase and the Engineering Design Data. Inputs from parallel Phases 2a (FSM) and  
1894 2c (FTMS) are also shown. The dashed lines indicate iteration pathways within Phase 2b and from outside, in the  
1895 parallel phases and the later credibility phase. The steps required in the FS Development are:

- 1896 1. Flight Simulator Build
- 1897 2. Flight Simulator Verification
- 1898 3. Flight Simulator Validation, including fidelity assessment.

1899 It is acknowledged that there may be legacy FS facilities available to the applicant. In this case, the FS Build phase  
1900 may be non-existent and the V&V activities may rely, in part, on past efforts, given appropriate configuration  
1901 management practices are in place. The remainder of the activities within Phase 2b will then focus on the  
1902 assessment and, if needed, the updating of the FS for the selected ACR.



1903  
1904 *Figure 6-1: The Flight Simulator Development; Phase 2b*

1905 An FS is comprised of different features (Figure 6-2) which provide cues to the Evaluation Pilot EP enabling them  
1906 to undertake an ACR. This Guidance draws on the definitions in Notice of Proposed Amendment - “Update of  
1907 the flight simulation training device requirements” [12] and ICAO 9625 [11] for ten FS features. The FSM feature

1908 developed in Phase 2a is a key component of the FS development as it provides inputs to the other FS features,  
 1909 e.g., the vestibular motion cueing system (VeMCS), and receives outputs from features, e.g., the flight control  
 1910 positions and forces. The FSM content is discussed in detail in Section 5 and only the inputs/outputs to other FS  
 1911 features are discussed in this section. For some ACRs, not all FS features will be required and these will be  
 1912 addressed in the following sections.

1913 The Operator Station (OS) is the outer region of the FS schematic and interacts with the FSM and other features.  
 1914 The FSM provides inputs to the other FS features to generate cues to the EP who is at the centre of the FS  
 1915 schematic. The cues that can be provided to the EP are visual (sense of sight), auditory (sense of hearing),  
 1916 vestibular (sense of balance and orientation in space), proprioceptive and kinaesthetic (awareness of position  
 1917 and movement of joints respectively), and tactile (sense of touch). Each FS feature may generate one or more  
 1918 of these types of cues.

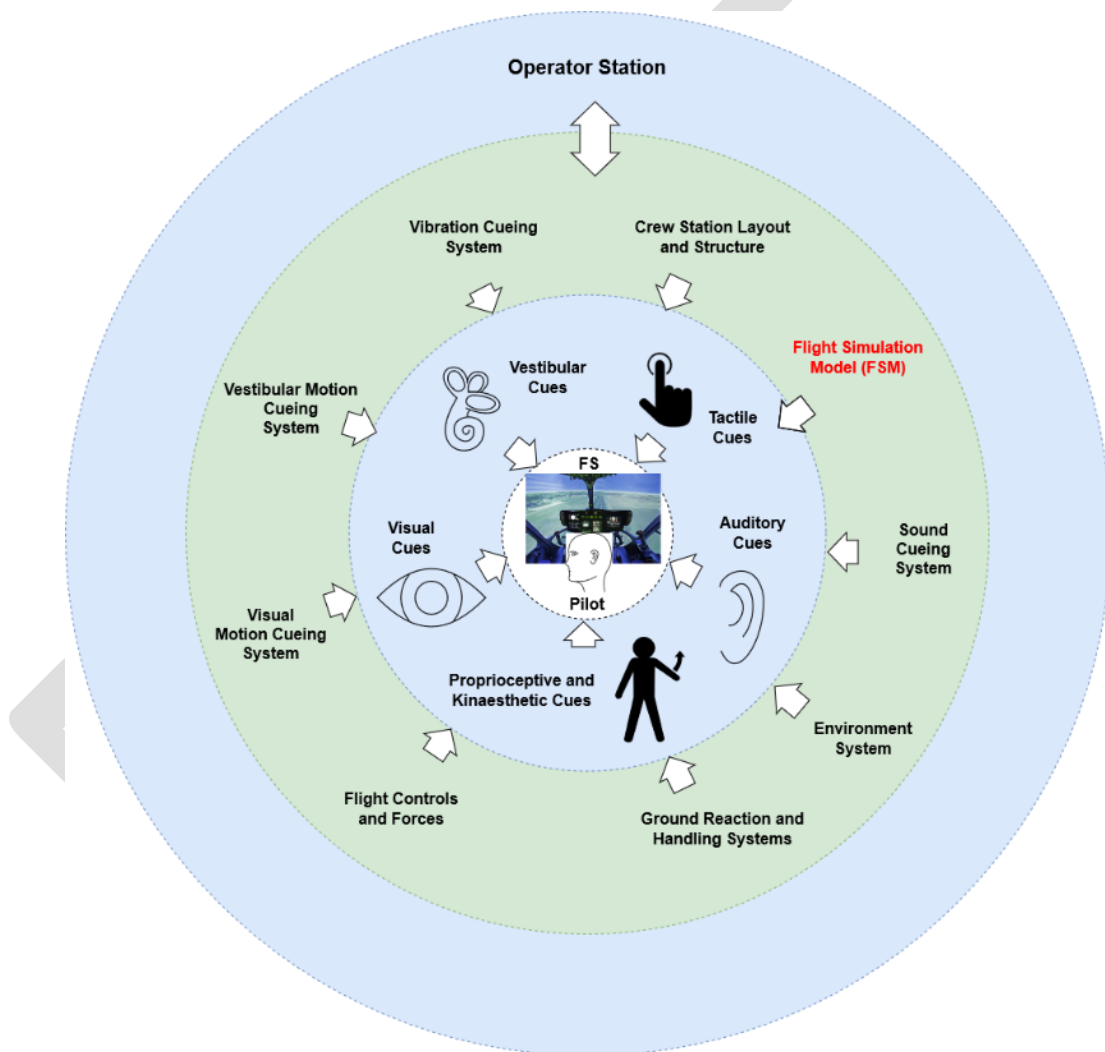


Figure 6-2: Schematic of FS Features

1919 During the fidelity assessment, predicted and perceptual fidelity metrics, defined in Phase 1, will be employed.  
 1920 The fidelity of the FS features should be sufficient to provide an EP with the cues needed to undertake an ACR  
 1921 without 'significant' adaptation. An example of a perceptual (behavioural) fidelity metric is the Simulation  
 1922 Fidelity Rating (SFR) scale [23]. The SFR scale requires the EP to compare the task performance achieved and the  
 1923 task strategy used between flight and simulation to assess the fidelity of the FS. Quantifying task performance  
 1924 is normally straightforward, but strategy is more complex. An example of an adaptation metric, based on  
 1925 changes in control compensation is described in Refs [24], [25]. The SFR method differs from current flight  
 1926  
 1927

1928 simulator training guidance [15] which defines Levels of Fidelity, e.g. specific, generic, and representative to  
1929 clearly differentiate certification guidance and allow more nuance in feature requirements. The content of the  
1930 FS features should be such that they provide cues with sufficient fidelity for an ACR. Examples of the FS feature-  
1931 content information are provided in the next sub-section.

## 1932 6.2 FLIGHT SIMULATOR BUILD

1933 The design and build activities of the FS are based on the requirements specification for the selected ACRs. It is  
1934 crucial to ensure all FS features have sufficient fidelity to generate the cues needed by an EP to undertake ACR  
1935 testing with representative task performance and without significant adaptation. Cue fidelity is further  
1936 facilitated through a fidelity assessment in the validation step of FS development. The Guidance in this section  
1937 discusses the kinds of feature content that might be considered for an ACR.

1938 The FSM is considered to be one of the features of the FS, but since its development and fidelity assessment are  
1939 undertaken in parallel with Phase 2a (Section 4), it is not detailed here. A 'prototype' FSM, supplied by Phase 2a,  
1940 can be used in the FS development to examine the sufficiency (or necessity) of cues such as the vestibular motion  
1941 cues provided by the VeMCS.

1942 An FS may be used for more than one ACR, so it is necessary to consider the fidelity requirements of multiple  
1943 ACRs during the build step of the FS development process. Use of Engineering Design Requirements and Data  
1944 from the real aircraft, e.g. an aircraft cockpit Field of View (FoV) diagram, is also required during the FS build, to  
1945 ensure sufficient fidelity of the FS cues.

1946 It is recommended that applicants consider the design requirements for each FS feature in a structured way as  
1947 detailed in Section 3 (Phase 1), where the following characteristics are considered:

- 1948 1. Function
- 1949 2. Operational modes
- 1950 3. Data structures
- 1951 4. Inputs
- 1952 5. Outputs
- 1953 6. Interfaces
- 1954 7. Constraints
- 1955 8. Domains of prediction and validation

1956 It is acknowledged that the concept of the domains of prediction and validation becomes somewhat nebulous  
1957 when considering a FS feature rather than the FSM. Consider the following example; piloted FS validation has  
1958 been performed for a specific ACR resulting in a certain range of motion inputs from the VeMCS, thereby defining  
1959 the DoV for the VeMCS. It is then found that the compliance demonstration trials in the simulator result in  
1960 motion amplitudes/rates that are larger, i.e., the DoP exceeds the DoV. In this case, the applicant will need to  
1961 show, e.g., by validation at FS feature level to extend the DoV, that the fidelity of the cueing from the VeMCS is  
1962 sufficient within the full DoP.

1963 The following sections define the nine FS features (not including the FSM) and discuss feature-content  
1964 considerations for an ACR. The data structures and communication protocols for sharing information across  
1965 features must be defined during the FS Build process.

1966 Transmission of data between simulation features, and the time taken for a feature to cycle the data through a  
1967 computation step, will introduce time delays in the FS environment, namely latency and transport delays.  
1968 Latency is defined in CS-FSTD(H) [15] as the difference in the time taken for a real aircraft's system to respond

1969 and that taken for an FS feature to respond. The time taken for an FS feature to process an input signal from the  
1970 EP's controls is defined as a transport delay. Transport delays will affect any solution produced by an FS feature,  
1971 or collection of features, and must be quantified in the verification of the FS solutions. Recommendations for  
1972 maximum transport delay values, also considered applicable for RCbS, can be found in documents such as CS-  
1973 FSTD(H).

### 1974 **6.2.1 Operator Station**

1975 **Definition:** The Operator Station (OS) is comprised of the computer terminal(s) from which the FS features are  
1976 initialised, managed and monitored by the operator. The OS feature is not defined in [12], but for a certification  
1977 FS the OS has content that needs consideration.

1978 **Design Considerations:** The OS must enable the certification team, including the EP, flight test engineer, and the  
1979 engineers operating and monitoring the FS, to gather data from the FS to demonstrate that the aircraft  
1980 performance and piloting requirements for the ACR have been achieved. To support this process, the FS OS can  
1981 be utilised to trim the FSM with the pre-certification flight test conditions flown (e.g. airspeed, weight, altitude,  
1982 environment conditions) and record data from the simulated task. For example, in demonstrating compliance  
1983 with ACR 29.143 (Controllability and Manoeuvrability) the OS can be used to interact with the Environment  
1984 System (ES) feature to load the required visual database, and with the FSM to trim the model in a ground  
1985 referenced hover in the presence of 17kts winds for a range of azimuths.

1986 The OS can record data obtained from the FSM, e.g. aircraft states, and the Flight Controls and Forces feature,  
1987 e.g. pilot inceptor positions, for use in FSM and FS validation, fidelity and credibility assessment. The OS could  
1988 include a real-time visualisation of the simulated aircraft's performance and the EP's control activity to enable  
1989 the certification team to assess whether performance criteria have been met and/or whether the test point  
1990 quality satisfies the ACR or if it needs to be repeated.

### 1991 **6.2.2 Environment System**

1992 **Definition:** The Environment System (ES) feature represents the FS components needed for the ACR which are  
1993 not part of the FSM, but are configured through the OS. These ATC, navigation signals, atmosphere and weather  
1994 effects on the visual conditions (e.g. fog), as well as surface features such as aerodromes and terrain/landscape.

1995 **Design Considerations:** The required characteristics of the ES are dependent on the ACR. For example, in CS-29,  
1996 Appendix B, VII for IFR flight, the 'Environment – Atmosphere and Weather' characteristic should be able to  
1997 represent Instrument Meteorological Conditions (IMC) in the Visual Motion Cueing System (VzMCS), including,  
1998 visual range and precipitation effects, which are controlled by the OS. When the ACR includes navigation tasks,  
1999 navigational data should be included to provide inputs to the instrument panel in the Helicopter Systems feature.  
2000 The ES feature includes the visual terrain database which comprises visual models of the terrain and provides  
2001 height above terrain inputs to the Ground Reaction and Handling System, Crew Station and Layout Structure  
2002 features, as well as to the FSM. If required for an ACR, landing areas and ground markings should be modelled  
2003 with a sufficient level of detail, texture and contrast.

### 2004 **6.2.3 Ground Reaction and Handling System**

2005 **Definition:** Helicopter ground reaction and (ground) handling responses in an FS which are derived from the  
2006 FSM.

2007 **Design Considerations:** Although the landing gear/undercarriage component is a part of the FSM, it is included  
2008 here as a separate FS feature as the input/output relationship needed for its operation, e.g. input from the ES  
2009 system feature to the FSM and vice versa, must be considered during the FS design and build. The ES system  
2010 feature will provide height above terrain information as an input to the FSM to calculate the undercarriage

2011 deflections, friction and side forces. The outputs from these calculations are conveyed to the EP through the  
2012 VeMCS and the VzMCS to aid in identifying the ground state of the aircraft, e.g. skidding or rolling motions. The  
2013 height above terrain information is also needed for aerodynamic ground effect modelling in the FSM, which in  
2014 turn affects the ground handling simulation. This simulator feature is not required for any ACR that does not  
2015 involve landing, taxiing, contact with the terrain surface, or In Ground Effect (IGE) operations.

#### 2016 **6.2.4 Crew Station Layout and Structure**

2017 **Definition:** The Crew Station is defined as the area in an aircraft where the flight crew members work and where  
2018 the EP's inceptors, flight instruments and interfaces to helicopter systems such as the engine controls, are  
2019 located.

2020 **Design Considerations:** The content of this feature includes flight instruments, caution and warning displays,  
2021 secondary aircraft controls such as buttons and switches to power and electrical systems, and navigation and  
2022 communication systems. Some elements of the helicopter system, such as the SCAS and autopilot, are  
2023 components of the FSM, and appropriate interfaces in the FS will be required to enable the EP to provide inputs  
2024 to the FSM.

2025 The construction, positioning and configuration of the content of this feature should be such that they do not  
2026 significantly modify the task strategy employed by an EP while performing an ACR, e.g., change in visual cues  
2027 due to crew station framing and seating position. This feature could be developed with the use of a physical  
2028 replica of flight hardware, or via a virtual representation of the cockpit. Engineering Design data are required to  
2029 enable the fabrication of the cockpit, or the generation of a 3D model for virtual applications.

2030 The crew station layout and structure feature design will depend on the configuration of the VzMCS. A Virtual  
2031 Reality (VR) VzMCS will require a digital recreation of the crew station, rather than a physical one. This may  
2032 reduce the required complexity of the crew station significantly, but increase the complexity of the VzMCS in  
2033 turn.

2034 All aircraft systems required for an ACR should be available and appropriately located in the Crew Station,  
2035 especially for tasks that include emergency procedures. It should enable any interactions required by the EP  
2036 during the ACR with relevant aircraft systems. All systems required for accomplishing an ACR should be operable  
2037 by the flight crew with no input from the simulator OS required.

#### 2038 **6.2.5 Flight Controls and Forces**

2039 **Definition:** This feature is defined as the physical control inceptors used by the EP in the Crew Station and their  
2040 force and damping characteristics.

2041 **Design Considerations:** The FS inceptors can be broadly divided between 'unloaded' and 'loaded' (also known  
2042 as 'force-feedback') systems. The former is typically associated with desktop simulation and will generally not  
2043 represent the control ranges and forces that a pilot would experience in the aircraft. As such, their use would  
2044 not normally be expected in the RCbS use of a FS, and must be justified if used for an ACR. Loaded systems can  
2045 allow customisable mechanical characteristics of the inceptors, e.g. breakout force and spring force gradient, to  
2046 be generated to represent those of the aircraft. The requirements for sufficiency of the fidelity of these  
2047 characteristics will be dependent on the ACR being assessed. The characteristics of the inceptors are typically  
2048 provided by a control loading system, including control loading computer and motor, and can be configured  
2049 through the OS.

2050 The EP should be able to apply control inputs in terms of amplitudes, forces and frequencies in a manner that is  
2051 required for the ACR and that satisfy fidelity requirements. The output from the movement of the FS inceptors

2052 are inputs to the FSM's FCS component which, in turn, provides inputs to the FSM rotor components and  
2053 SCAS/autopilot.

#### 2054 **6.2.6 Visual Motion Cueing System**

2055 **Definition:** The VzMCS is any type of display technology including dome projection and virtual, augmented and  
2056 mixed reality (VR/AR/MR), that provides out-the-window (OTW) visual motion cues that the EP uses for an ACR.

2057 **Design Considerations:** Development of the visual cueing system must consider the required FoV, Field of Regard  
2058 (FoR) (the total area that can be captured by a movable sensor), and appropriate levels of lighting and contrast  
2059 to provide the EP with 'useful' visual flow information to attempt an ACR. For example, to enable ACR 29.143  
2060 (Controllability and Manoeuvrability) to be undertaken, the FoV and display resolution should provide sufficient  
2061 visual motion cues to enable the EP to perceive similar height above ground and vehicle drift cues to that  
2062 experienced in real flight.

2063 For a projection system, the design eye-point is required from the Engineering Design Data to locate the pilot's  
2064 head in the FS. For multi-channel projection systems, blending and warping of the visual channels on the  
2065 projection screen/dome should not introduce any perceivable distortion in the OTW visual scene.

2066 Although currently considered immature for use in certification, VR systems have been certified for use in  
2067 rotorcraft simulator training [26]. It is anticipated that suitable options for creating the OTW visuals using VR,  
2068 AR or MR systems will be commercially available in the future, and a brief description is included here. In VR, all  
2069 visual cues are provided to the EP through a headset that generates the OTW cues and, possibly, a virtual cockpit  
2070 (VR). In the case of VR, the EP does not see the physical simulator cockpit structure, nor their limbs and hands.  
2071 Unless hand tracking and hand visualisation is included, a VR solution can only be used in ACRs where EP  
2072 interaction with cockpit content other than the main inceptors (collective, cyclic and pedals) is not required, e.g.  
2073 button presses. In the AR case, the EP can see the Crew Station Layout and Structure through the AR headset,  
2074 while the OTW view is 'augmented' using a 'black mask'. In the AR case the Crew Station windows need to be  
2075 blanked with black material or the room around the Crew Station needs to be dark or heavily dimmed. In the  
2076 MR case, the real-time video image from two cameras mounted on the headset (one per eye) is mixed with a  
2077 virtual representation of the OTW view (using a mask of the Crew Station or making use of chroma-key  
2078 techniques). In the MR case, specific aspects of the video pass-through need to be considered, such as time delay  
2079 of the video image, degradation of the image quality and the distortion caused by the offset between the pilot's  
2080 eye location and the camera position in front of them.

2081 With AR/VR/MR devices the following aspects need to be considered when choosing the hardware. The vision  
2082 of the pilot is restricted by the FoV of the headset, while in simulators with a projection system the OTW FoV is  
2083 restricted by the projection system. On the other hand, the FoR of head-mounted devices (AR/VR/MR) is 360°,  
2084 whereas the FoR of a projection system is limited by the physical structure. The minimum FoV/FoR required for  
2085 an ACR demands specific consideration. Too small a vertical FoV can lead to adaptation of the EP's eye scanning  
2086 and increased head movements and discomfort. The latency between tracking of head movement and image  
2087 rendering can cause 'cybersickness'. Furthermore, reference [27] suggests that having a frame rate less than 90  
2088 frames per second can cause misperception of motion also leading to cybersickness. A mismatch of the distance  
2089 between the centres of the EP's eyes, the inter-pupillary distance, and that set in the hardware can cause fatigue  
2090 and cybersickness. For the MR case, care needs to be taken with the camera position to prevent and parallax  
2091 issues and false motion perception during head rotation. Further guidance related to reducing cybersickness in  
2092 VR is provided in [27].

2093 These emerging technologies are being investigated and their utility will be evaluated in a case study in Section  
2094 10.

2095 **6.2.7 Sound Cueing System**

2096 **Definition:** The sound cueing system is any technology that provides auditory cues to the EP.

2097 **Design Considerations:** In flight, the EP receives sound cues from several sources, providing feedback on the  
2098 helicopter's state, e.g. engine/rotor speed, gearbox whine and indications such as audio cautions and warnings,  
2099 e.g. low rotor speed warning. The inputs to sound cueing system are provided by the FSM and other features,  
2100 such as ATC communications from the ES. The presence of unrealistic, or incoherent, sound content can impact  
2101 an EP's situational awareness and sense of realism, and the sufficiency of the sound cue feature in the FS must  
2102 be considered for each ACR. Particularly in failure cases where the pilot's attention is focussed on the outside  
2103 world visual cues, such a during a Category A rejected take-off, sound cues may have an impact on task  
2104 performance. Sound cueing systems should also include intercom facilities that allow the EP to communicate  
2105 with other crew members and the FS operator. Tones and voices from the avionic system are a source of  
2106 information for the pilot, and, in several situations, being able to 'pick-up' rotorspeed changes from the  
2107 rotor/engine/gearbox tones will be important.

2108 **6.2.8 Vestibular Motion Cueing System**

2109 **Definition:** The VeMCS provides angular/linear  
2110 displacement, rate and acceleration cues to the EP.

2111 **Design Considerations:** The human vestibular system  
2112 contains two important motion sensors, located in the  
2113 inner ear: the semi-circular canals for rotational cues, and  
2114 the otoliths for translational cues. The semi-circular  
2115 canals are sensitive to angular velocities and  
2116 accelerations, while the otoliths sense specific force, i.e.  
2117 the non-gravitational forces acting on the body per unit  
2118 mass. The latter are often simplified as (lateral or  
2119 longitudinal) accelerations, but this simplification only  
2120 holds when the aircraft or simulator is not tilted relative  
2121 to the gravity vector. A human in a tilted aircraft without  
2122 any acceleration (e.g. a hovering helicopter) will still  
2123 experience a non-zero specific force cue. The VeMCS  
2124 produces the vestibular cues through the Motion Drive  
2125 Algorithms (MDA), or motion filters. By tuning the  
2126 parameters of the MDA, the fidelity of the vestibular cues  
2127 can be optimised with the need to keep the movable  
2128 cabin of the VeMCS within its available motion space.

2129 A wide range of VeMCSs may be employed that can vary  
2130 in the number of the Degrees of Freedom (DoF) they  
2131 provide, the maximum velocities and accelerations they  
2132 can produce, and the envelope of the system, i.e. the  
2133 maximum linear or angular displacements achievable by  
2134 the moving platform. The VeMCS is driven with the linear  
2135 accelerations and angular rates calculated by the FSM  
2136 which are scaled and filtered, using the MDA, to keep the resulting platform motion within its operating  
2137 envelope. The MDA filters have coefficients that can be used to tune the response of the VeMCS.

Considerations in the tuning of the MDAs with a small-medium motion system

The tuning parameters within the motion drive laws can be optimised for individual test manoeuvres. Failure to do this introduces the risk that adverse motion cues might reduce perceived fidelity below sufficiency level. Aspects that need to be considered in this tuning process include:

- a. Envelope of expected motion in a flight task about each axis in terms of accelerations and rates,
- b. Distinguish between primary and secondary motion/control axes; this supports optimising the distribution of MDA commands to platform 'legs',
- c. How might translational-rotational motion compensation be achieved to correct for adverse cueing in a task, e.g. roll-sway or pitch/surge,
- d. Define expected ranges of pilot 'gains' in the task. This can be useful in the tuning to optimise for medium gain levels (e.g. moderate level aggression),
- e. Ensure the matching of transport delays in the visual and vestibular motion systems.

2138 Careful considerations of the MDA filter coefficients, the gains and break-frequencies, are needed to ensure the  
2139 EP receives correct and sufficient vestibular cues for an ACR. The VeMCS should not provide any adverse cues  
2140 as perceived by the EP. Ideally an MDA should use a high gain to provide sufficient onset cues, whilst also having  
2141 a low phase shift to reduce adverse cues. Sinacori [28] proposed a set of predictive VeMCS fidelity levels using  
2142 gain and phase criteria. Use of a high gain will result in more of the motion platform envelope being utilised,  
2143 potentially reaching a limit, and will also require more motion washout, resulting in a larger phase shift between  
2144 the flight-model output and the motion platform response, to return the platform to the platform's neutral  
2145 position. The motion platform washout should occur at a level that is not 'intrusive' to the EP and that keeps the  
2146 phase shift at an 'acceptable' level. More recently, the Objective Motion Cueing Test (OMCT) [11] has been  
2147 proposed as a predictive fidelity metric. It compares the calculated motion response of a flight model (motion  
2148 system input) to the actual movement of the VeMCS (output) as modified by the MDA. The MDA coefficients  
2149 will need to be tuned for each motion platform DoF or combination of DoFs, according to the ACR, to provide  
2150 sufficient positive cues to an EP. An example of a process that could be used to determine MDA filter coefficients  
2151 is provided in [29] where it was shown that sufficient vestibular motion cues could be achieved by careful  
2152 harmonisation of the 2 DoF motion filter gains for a roll-sway task, outside of the criteria defined by Sinacori.

### 2153 6.2.9 Vibration Cueing Systems

2154 **Definition:** Vibration cueing systems are any technology that provides proprioceptive, tactile and vestibular  
2155 motion cues to the EP in the frequency and amplitude range associated with pilot seat vibrations.

2156 **Design Considerations:** The motion frequency range that a VeMCS can produce is normally limited (0-10Hz in  
2157 the heave axis and lower in the surge and sway axes [15]). High-frequency VeMCS motion can put additional  
2158 unwanted loading on other FS features such as the VzMCS. To generate higher-frequency vestibular motion cues  
2159 that may be associated with, e.g. retreating blade stall or vortex interactions in the translational lift phase, a  
2160 separate Vibration Cueing system, e.g. in the form of a vibration seat or platform, could be included in the FS.  
2161 The DoFs in the Vibration System will be dependent on the ACR.

## 2162 6.3 FLIGHT SIMULATOR VERIFICATION

2163 The codes, solutions and hardware of each FS feature must be verified during the FS development process, i.e.  
2164 the construction, functionality and operation of each feature must be consistent with the requirements of the  
2165 FS specified in Phase 1. Each feature will have inputs to/from other features in the FS, e.g. the FSM provides  
2166 inputs to the VeMCS to generate vestibular motion cues, the ES and the Ground Reaction and Handling System  
2167 both have inputs to the FSM to produce ground contact responses using height above terrain information. The  
2168 applicant needs to demonstrate the requirements specified in Phase 1 have been correctly realised during the  
2169 FS verification assessment.

### 2170 6.3.1 Codes

2171 The FS features will have associated computer codes which must be verified. The applicant should ensure that  
2172 any codes that operate on an input correctly produce the expected output. This process identifies errors that  
2173 might occur due to, for example, inconsistency of units used, rounding errors in calculations and definitions of  
2174 axis reference systems. The applicant needs to demonstrate that they have an appropriate configuration  
2175 management process (see Section 8) in place so that the effect of any updates to codes are verified before  
2176 implementation into an FS feature. Codes are typically compiled into a real-time version and the data generated  
2177 by the real-time version should be compared with the data generated by the source code to ensure they agree.

2178 An example of the verification process is provided as follows. The FS requirements related to testing for an ACR  
2179 might dictate the use of a motion platform to provide vestibular motion cueing for the EP. Outputs from the

2180 FSM are inputs to the MDA, which in turn drives the motion platform actuators. A simulation model of the  
2181 motion platform response to actuator demands could be independently developed and the response of the FS  
2182 VeCMS compared for verification. This could be achieved by inputting step or sinusoidal signals into the MDA  
2183 and comparing the response with the input demand. This approach has been proposed in the OMCT in [11].

### 2184 **6.3.2 Solutions**

2185 Most FS code is deterministic. However, with an FS having multiple interacting features, using different time  
2186 clocks to produce solutions, this may result in non-deterministic behaviours, or behaviour that is very difficult to  
2187 predict. A check is required to ensure that these solutions are as expected and permit execution in real-time.

2188 For example, the ES provides height above terrain information to the FSM. Contact between the undercarriage  
2189 component of the FSM and the terrain surface must be detected and then trigger a series of calculations to  
2190 compute forces and moments on the undercarriage and the resulting vehicle motions. The output from the FSM  
2191 is then transmitted to other features such as the VzMCS, VeMCS and the sound cueing systems. These complex  
2192 interactions must be verified to produce consistent solutions, if these effects are required for the ACR being  
2193 simulated.

2194 Within a single feature, there may also be 'variability' in solutions based on inputs. For example, the graphics  
2195 engine in the ES will require computation time to produce a solution following an input from the FSM, i.e. an  
2196 update of the aircraft inertial position. The computation time, and the resulting framerate of the graphics signal  
2197 produced, may vary based on the detail in the visual scene, for example, the number of polygons used to  
2198 represent macro-textures, and the resolution of micro-textures. The framerate should be maintained above  
2199 requirements defined in Phase 1 of the RCbS process, informed, for example, by values contained in documents  
2200 such as CS-FSTD(H) [15].

### 2201 **6.3.3 Hardware**

2202 The construction and function of any FS feature hardware must be verified to match the requirement  
2203 specification for that feature. This process may include the following:

- 2204 1. Checking physical dimensions and movement ranges of inceptors against technical drawings,
- 2205 2. Checking that 'input' functions of hardware devices drive the intended mechanical or computational  
2206 response, e.g. a button press generates an on/off signal as required,
- 2207 3. Checking that 'output' functions of hardware devices respond to commands as intended, such as  
2208 speakers playing a sound, without unexpected distortion, at an appropriate volume.

2209 Relevant delays that exist in the real-world system, e.g. pressure instrument lag, should be appropriately  
2210 modelled in the FSM, or associated FS feature, and verified in the FS. The output from an FS feature such as the  
2211 displacement of an EP's inceptor, should be verified against the value received and used by the FSM FCS  
2212 component.

2213 If Phase 1 (FS requirements) specifies the use of a VeMCS for an ACR, its response to input commands should be  
2214 verified. An example of this process is given in ICAO 9625 in the form of the OMCT [11]. The OMCT defines a  
2215 matrix of translational and rotational inputs, of varying amplitude and frequency, to evaluate the ability of the  
2216 VeMCS to reproduce these commands. The resulting platform motion can be verified using accelerometer  
2217 measurements.

2218 In case of an existing FS, part of the hardware verification can be derived from documentation from past  
2219 activities assuming proper configuration management has been exercised.

## 2220 6.4 FLIGHT SIMULATOR VALIDATION

2221 The FS validation process is intended to ensure that the cues that the FS features generate are of sufficient  
2222 fidelity to enable the EP to undertake an ACR realistically, i.e. effectively equivalent to flight. At its heart, the  
2223 sufficiency assessment is, therefore, a comparison between task performance achieved and control strategy  
2224 employed in the FS and the real aircraft. The validation process illustrated in Figure 6-1 is divided into three  
2225 iterative steps:

- 2226 1. Testing
  - 2227 a. FS Test
  - 2228 b. Flight/Ground Test
- 2229 2. Fidelity Assessment
- 2230 3. Tuning & Updating

2231 The testing step is divided between flight/ground test of the aircraft, and testing using the FS. These steps can  
2232 take place in parallel, but it is expected that they will be informed by a common strategy. The following sections  
2233 will address each of these steps in more detail.

2234 It is assumed at this stage that the FSM is sufficiently 'mature' to conduct FS validation. As mentioned previously,  
2235 a prototype FSM can be used during the FS development. However, it is recognised that the validation processes  
2236 may take place in parallel to some degree, and the FS development can also support the FSM validation process  
2237 through subjective evaluation if FSM tuning/updating is required.

### 2238 6.4.1 FS Test

2239 FS testing is used to assess the features of the simulator and the cues that they produce to enable step 2 of the  
2240 FS validation process, the fidelity assessment. It is expected that applicants will use a structured approach to  
2241 planning a FS test campaign to design repeatable, performance-bounded tasks relevant to an ACR. This starts by  
2242 defining the aim of the testing, descriptions of the manoeuvres to be flown, aircraft test configuration, and the  
2243 data to be gathered. In Phase 1 of the RCbS process, objective and subjective metrics will have been defined to  
2244 assess FS fidelity, which are then adopted in the FS test campaign.

2245 A process for designing flying tasks is provided in ADS-33 [17], where performance requirements for Mission  
2246 Task Elements (MTEs) are defined based on the role of the aircraft. It is suggested here that a similar approach  
2247 is adopted to develop performance requirements for tasks associated with an ACR.

2248 It is recommended that a FS test trial document is developed and reviewed by the test team prior to testing. It  
2249 is suggested that, where possible, EPs are selected that have flight experience of the ACR and on the aircraft to  
2250 be certified to provide 'informed' feedback during the validation process. It is expected that a trial briefing is  
2251 completed prior to any testing so that it is clear to the test team what tasks will be flown and that any  
2252 clarifications on test requirements are addressed, e.g. task performance, control strategy.

2253 The task and aircraft configuration are controlled using the FS OS feature. During testing, the EP can be reminded  
2254 of the task description and performance requirements prior to undertaking a test point. Feedback can be  
2255 provided to the EP regarding the task performance achieved using data recorded by the OS. It is recommended  
2256 that EP feedback is sought and recorded on all elements of the FS test campaign, in support of validation.

2257 A subsequent de-brief session enables the test team to review the results of the tasks flown, the EP feedback  
2258 including any ratings awarded, and to provide supporting data for use in the Credibility Assessment, Phase 3. A  
2259 trial report should be produced to collate this information.

2260 **6.4.2 Flight/Ground Test**

2261 Data should be gathered from flight/ground testing, within the domain of validation, to support FS fidelity  
2262 assessment. It is suggested that tests are designed to enable comparisons with FS testing, where it is safe to do  
2263 so. The aircraft should be instrumented, as defined in the Requirements Specification, to provide data for both  
2264 FSM and FS fidelity assessments; more information on the FTMS is provided in Section 7. Data for FS fidelity  
2265 assessment could include measurements of control activity, or subjective handling qualities ratings for MTEs  
2266 related to the ACR.

2267 A similar process to that defined in Section 6.4.1 can be used for testing on the aircraft. However, the ground  
2268 testing procedure may differ if a pilot is not required. For example, for some aircraft the mechanical  
2269 characteristics of the flight controls can be validated via ground test measurements. However, for aircraft with  
2270 changing mechanical characteristics over the flight envelope (e.g. due to force feedback through pitch-link rods),  
2271 additional measurements during flight might be required.

2272 **6.4.3 Fidelity Assessment**

2273 The fidelity assessment process evaluates whether the FS fidelity is sufficient for the relevant ACRs and I-P Levels.  
2274 It uses outputs from the FS and flight/ground testing to compare objective and subjective metrics. If fidelity of  
2275 the FS is assessed as sufficient, then the applicant can proceed to the Credibility Assessment phase. If FS fidelity  
2276 is lacking after assessment, then a 'tuning/updating' process should be undertaken to correct identified  
2277 deficiencies for use in future iterations of the FS validation process.

2278 The fidelity assessment process is informed by objective and subjective metrics and associated tolerance  
2279 margins, defined in Phase 1 of the RCbS process. Unless deficiencies are encountered and tuning/updating of a  
2280 specific FS feature is required (Section 6.4.4), the FS fidelity assessment, in principle, only considers the full  
2281 aircraft and the interactions with the pilot. The related metrics fall into two categories:

- 2282 1. Task performance  
2283 2. Task strategy

2284 For objective measures, a comparison of the task performance achieved in flight and simulation cover  
2285 parameters specified in the task definition for FS and flight/ground test. For example, the task developed for CS  
2286 29.62 Rejected take-off: Category A, may have performance requirements on the touchdown conditions of the  
2287 aircraft, which can be directly compared between FS and FTMS data.

2288 Task strategy can be quantified through analysis of the pilot's control activity. Biometric measures can also be  
2289 used to inform such comparisons. For example, pilot control strategy can be quantified by computing control  
2290 input displacement/rate using the so-called attack activity [30] or other time- and frequency-domain metrics  
2291 [25]. Biometric measures may include head and eye tracking data, heart rate, or brain activity  
2292 (electroencephalography), and an applicant would need to demonstrate that these measurements indicate  
2293 sufficiency of the FS fidelity for an ACR in terms of comparative pilot compensation, FS vs FT.

2294 Subjective methods should also be used during the fidelity assessment to capture the EP's experience. These  
2295 methods rely on feedback from the EP on the sufficiency of the FS fidelity for an ACR. This feedback can be  
2296 sought through, e.g., the use of subjective rating scales, such as the Cooper-Harper Handling Qualities Rating  
2297 (HQR) scale [31], or the Bedford workload rating scale [32]. These scales allow an EP to assess the level of  
2298 performance achieved and the associated compensation required (HQR scale) or the spare capacity for a task.  
2299 Comparisons of such ratings, awarded in FT and FS testing, allow a fidelity assessment to be made. In addition,  
2300 it is recommended that the SFR scale [23] is used in the fidelity assessment process as it was specifically  
2301 developed to provide a framework for FS fidelity evaluations. Whilst the SFR scale was initially developed for  
2302 application to training tasks, there is a direct read-across for RCbS. Use of the SFR scale addresses two aspects:

- 2303 1. Comparisons between flight and simulation task performance, i.e. the precision with which a task is  
2304 completed, and,  
2305 2. Task strategy adaptation, i.e. the degree to which the pilot is required to modify their behaviour (change  
2306 the form of compensation) when transferring from simulator to flight and vice versa.

2307 The robustness of the awarded SFR will depend on the pilot's ability to reflect on their task strategy and the  
2308 achieved task performance. Therefore, the pilot must be proficient in both the vehicle and the task, and must  
2309 also have operational currency so that a meaningful fidelity assessment can be made. Caution is advised during  
2310 the fidelity assessment process, as a pilot can quickly adapt to FS deficiencies. Capturing this adaptation via pilot  
2311 reflection needs to take this into account. A fidelity questionnaire is useful in the assessment process to identify  
2312 any FS deficiencies.

#### 2313 **6.4.4 FS Tuning/Updating**

2314 The source of any perceived FS fidelity deficiency needs to be unambiguously traced to the related FS feature to  
2315 support FS tuning/updating. For example, the FS fidelity requirements defined in Phase 1 might dictate the use  
2316 of a specific feature e.g. a VeMCS, and during the ACR fidelity assessment the EP might perceive false 'motion'  
2317 cueing. This can arise due to VeMCS content deficiencies, e.g. in the motion filter gain and break frequency, but  
2318 also due to deficiencies in the FSM or VzMCS. In some cases, subjective fidelity assessment of the related  
2319 feature(s) can be conducted using an appropriate rating scale, such as a motion fidelity rating scale [33], to aid  
2320 in identifying and correcting the feature content. It is recognised that tracing the source of FS fidelity deficiencies  
2321 can be challenging, but this Guidance stresses the importance of facing such challenges purposefully.

2322 The results of any tuning of the FSM would need to be assessed in the FSM development phase (2a) prior to re-  
2323 evaluation in the FS fidelity assessment process.

### 2324 **6.5 SUMMARY: PHASE 2b**

2325 Summarising the activities in Phase 2b, development of the FS based on the (preliminary) Requirements  
2326 Specification:

- 2327 i. Prototype FSM supplied to the FS to support parallel activities,  
2328 ii. FS build, verification and validation and fidelity assessment,  
2329 iii. Draw on pre-certification flight test programme to support validation of the FS,  
2330 iv. Multiple iterative pathways managed and exercised as required throughout Phase 2b,  
2331 v. Updates to Requirements Specification based on Phase 2b activities,  
2332 vi. Outputs; FS validated for intended purpose, included in fidelity assessment reports

2333

## 2334 7 FLIGHT TEST MEASUREMENTS FOR FSM/FS DEVELOPMENT (PHASE 2c)

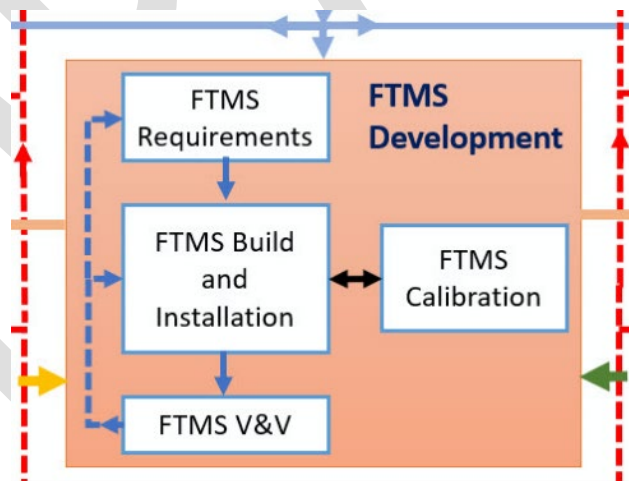
### 2335 7.1 INTRODUCTION

2336 Critical to the success in the validation process of both the FSM and FS is the quality of the flight test  
2337 measurements used in the comparisons between reality and simulation. To set the scene, we recall a famous  
2338 adage, of unknown origin (although something similar has been attributed to Albert Einstein), related to the  
2339 development and validation of rotorcraft simulation models.

2340 *No-one believes the simulation result, except the person who created it,*  
2341 *while everyone believes the flight test data except the person who measured it.*

2342 The message here is that, while there will always be doubts about the fidelity of simulation, and while we expect  
2343 flight test measurements to be the 'truth', those who have been closely involved in designing, building and using  
2344 an FTMS, understand the meaning of the second part of the adage. They are aware of the significant number of  
2345 pitfalls involved in the design and build of an FTMS, and they understand the importance of the care and  
2346 attention to detail required to mitigate or avoid these pitfalls and to minimize measurement uncertainty.

2347 The increased use of M&S in support of certification will require not only increases in FSM/FS fidelity but also a  
2348 sustained emphasis on the quality of the test data used in pre-certification validation activity. Another important  
2349 point to make is that the achievement of the envisaged levels of fidelity and credibility are likely to require in-  
2350 flight measurements from the rotor systems, to support validation and understanding of physics-based model  
2351 updates. To emphasise this point, it is no exaggeration to state that the lack of rotor measurements can  
2352 sometimes make it very difficult, if not impossible, to determine the cause of flight behaviour poorly predicted  
2353 by the FSM.



2354  
2355 *Figure 7-1: Phase 2c in the RCbS process; FTMS development*

2356 Figure 7-1 shows the sub-phase from Figure 2-1. Although requirements for the FTMS will have been developed  
2357 in Phase 1, along with requirements for the FSM and FS, the inclusion of a Requirements 'box' within the FTMS  
2358 development acknowledges the potential for some of these to be augmented once the on-board environment  
2359 is quantified. In this Section, we describe some of the important issues to be addressed when designing, building,  
2360 calibrating, installing and using a FTMS, including the extraction of data from the system and its use by the  
2361 FSM/FS engineers. The five topics will be addressed separately, noting that at each stage, quality can be

2362 preserved or degraded through the decision making and practice of the FTMS engineers or shortcomings in the  
2363 initial FTMS requirements specification. This Section ends with a discussion on the expected content of a pre-  
2364 certification FTG, noting that the certification FTG will also be augmented by companion testing with the FSM  
2365 and FS.

2366 The V&V for the FTMS follows a similar process to the FS. In a general sense, the integrated H/W+S/W FTMS  
2367 must be proven to meet the documented requirements (Verification) and must operate such that it provides  
2368 the intended outputs (Validation), i.e. the requirements were correct. The calibration process (Section 7.4) is  
2369 critical in this regard as it is where physical quantities of interest (e.g. accelerations, aerodynamic velocities,  
2370 rotor flap motion) are sensed and converted into electronic information for comparison with a 'validated'  
2371 benchmarks, e.g. instrumented inertial platform. The FTMS is the source of validation data for both the FSM and  
2372 FS and S/W that converts raw measurements into the information required for the validation must pass  
2373 thorough a V&V process.

## 2374 7.2 FTMS DESIGN

2375 As emphasised for the creation of the FSM, the design specification of the FTMS should be based on  
2376 requirements. The requirements must address the measurement functions, their precision, resolution and  
2377 range, allowable levels of measurement and process noise, methods of calibration and installation, and the  
2378 process of data capture; including sampling rates, synchronization, any relevant analogue-to-digital signal  
2379 conversion, associated filtering and the interface of the FTMS with the crew and ground station. The design  
2380 specification should also include requirements relating to the building of the FTMS. Measurement redundancy  
2381 should be taken advantage of in the design of the system and associated data processing (e.g. velocities from air  
2382 data, inertial data and satellite navigation data). The requirements set for a comprehensive rotorcraft FTMS will  
2383 be extensive and need to be developed in close collaboration with the developers of the FSM itself. Depending  
2384 on the FSM requirements set in Phase 1 and the validation activities foreseen, it may be necessary to include a  
2385 model of the FTMS (a virtual prototype), as part of the FSM, featuring sensor locations, updateable calibrations  
2386 and data processing. The same argument applies for embodying a prototype FSM within the FTMS development  
2387 of course. A plan for verifying and validating the design should be included as part of the design (e.g. as in [34]).

## 2388 7.3 FTMS BUILD

2389 The requirements for the building of a FTMS should emphasise the integrated nature of the system,  
2390 maintenance requirements and usability; and the purpose of the system, which will include the acquisition of  
2391 data for use by flight simulation experts in model validation. The FTMS will be built as an integrated set of sub-  
2392 systems; e.g. the air data, the inertial data, flight controls, rotor flap and lag dynamics, rotor loads,  
2393 engine/transmission, satellite navigation and so on. There will likely be a requirement to include measurements  
2394 used by any control augmentation system, e.g. stability, autopilot, load alleviation, as well as flight information  
2395 available to the crew, e.g. presented by a glass-cockpit system, noting the challenges involved in accessing data  
2396 from proprietary systems. The integration process should ensure that the FSM expert is presented with a  
2397 coherent, consistent set of data, digitized to the same real time. A common clock for all sub-systems is normally  
2398 required to ensure measurements can be related coherently but, even then, time shifts in sampling will result  
2399 in time shifts in time histories. The maximum time shift between two time histories is likely to be related to the  
2400 minimum sampling rate. For example, if blade flap and lag angles are required every 5° of rotor azimuth to  
2401 capture dynamic stall effects, a sample rate of several hundred Hz will be required; the same for the tail rotor  
2402 might increase by a factor of 5. In contrast, an adequate sampling rate for dynamic pressure, sideslip and  
2403 incidence, normally measured on a boom attached to the front fuselage, might be 100 Hz or lower. The variable

2404 sampling rates mean it is important to consider the post-measurement data integration processing as part of  
2405 the FTMS. The need for data in the 'rotating system' should be addressed in the design specification including  
2406 how these are transmitted to the recording system (e.g. through slip-rings or radio transmission), and  
2407 synchronised with non-rotating data.

## 2408 7.4 CALIBRATION

2409 Calibration requirements fall into two categories; off-board and on-board. For example, inertial measurement  
2410 systems are commonly calibrated on an off-board motion table, while rotorblade flap angles usually require on-  
2411 board calibration. If two different sources of calibration are available, it is advisable to compare the two, and  
2412 quantify the levels and characteristics of the measurement and process noise present in the on-board data. This  
2413 particularly applies to air data measurements using a boom. For example, a pitot-static and vane system can be  
2414 calibrated in a wind tunnel for comparison with on-board calibration data. The latter can be derived from flights  
2415 in still air involving tracking a ground pace vehicle, with the aircraft trimmed at various pitch/incidence and  
2416 heading/sideslip angles. The wind-tunnel calibrations will need to take account of the process noise due to  
2417 tunnel wall effects. The on-board system measurements will include the effects of rotor wake impingement on  
2418 the boom, a source of process noise that is difficult to quantify. At some speed, the level of such process noise  
2419 will be so large that confidence in the measurements becomes too low for use in validation. If low airspeed  
2420 measurements, and related sideslip and incidence, are critical to the fidelity level required, then an appropriate  
2421 sensor system must be used. Calibration of controls should consider the pathway from the pilot station, through  
2422 the powered actuation system(s), the swashplate and control linkages to individual blade pitch angles; a set of  
2423 measurements that may have different static and dynamic behaviours. Accurate measurement calibration is  
2424 clearly critical to the successful use of a FSM in certification.

## 2425 7.5 INSTALLATION

2426 The locations and attachment methods used for the FTMS and its sub-systems are also important. For example,  
2427 fuselage motion sensors are best located close to a nominal centre of mass, with translational motion sensors,  
2428 e.g. accelerometers, isolated from translational vibration and the anti-nodes of structural bending, while  
2429 rotational motion sensors, e.g. rate gyros, isolated from rotational vibration and the nodes of structural bending.  
2430 Requirements for the installation of sensors that capture control motions and rotor system behaviour should  
2431 address the acceptable levels of 'intrusion' to preserve the integrity of the measurements. The interfaces of the  
2432 data capture system with the crew and ground stations are important for real-time monitoring and review of  
2433 data quality, involving the installation of dedicated telemetry and cockpit display systems. These aspects are  
2434 further considered in the next section.

## 2435 7.6 USAGE, INCLUDING FLIGHT TESTING

2436 The stage is set as they say; the FTMS design, build and calibration is complete and the system, having met the  
2437 design requirements, is installed in the aircraft and on-board calibrations are completed. The productive part of  
2438 the process now begins with the FTMS usage and FT campaign. As already emphasised, pre-certification flight  
2439 trials to validate the FSM will take on a new level of importance as they gradually replace the certification trials  
2440 themselves. The pre-certification flight test campaign will be defined in a comprehensive trial plan, including  
2441 aircraft configurations to be tested, coverage of the flight envelope and, critically, crew instructions for the  
2442 characterisation of aircraft behaviour in terms of trim, stability and response in defined weather conditions. The  
2443 test campaign should involve close coordination with the development of the FSM and FS. Effectively, test points

2444 flown in the real aircraft can be pre-tested with the FSM, either offline or in a piloted simulation environment,  
2445 as appropriate. Comparisons between the FSM and FT enable the identification of FSM flaws and the assessment  
2446 of potential updates. This integration of the FT campaign with the FSM development can have a major impact  
2447 on progress, but is so important, to the avoidance of nugatory testing on the one hand, and to facilitate efficient  
2448 model-updating on the other, that it should be embraced as a fundamental aspect of pre-certification flight  
2449 trials. The need, and scope, for innovation in this area is significant. In this respect, it is anticipated that a more  
2450 detailed FTG will be developed in collaboration with certification agencies and applicants and included in a  
2451 future release of these preliminary guidelines. In advance of this, the following sub-section discusses key aspects  
2452 of the content of the FTG.

### 2453 **7.6.1 Pre-certification Flight Test Guide**

2454 As with all activities within the RCbS process, the pre-certification FTG must be based on, and reflect, the  
2455 requirements of the FSM/FS validation and fidelity assessment processes. The close-coupling between  
2456 requirements for the FTMS with those for the FSM and FS is reinforced within the content of the FTG and  
2457 documented within the context of the DoV relevant to the ACR under consideration. For example, in the 4-  
2458 dimensional matrix of design conditions for quantifying static and dynamic stability (airspeed, density altitude,  
2459 c.g. location and aircraft mass), 70% might be selected for the DoV (30% in the DoE). Of these DoV points, 60%  
2460 might be selected for CbS. With this plan, across the whole of the DoP (DoV + DoE), only 28% of points would be  
2461 flight tested in Certification. In the pre-certification testing, a subset of such points might also be selected for  
2462 fidelity assessment.

2463 In support of FSM validation and fidelity assessment, linking with the content of Section 5, a typical set of test  
2464 points at each flight condition/aircraft configuration might include:

- 2465 a) Step/pulse control inputs to exercise the air data measurement system across its anticipated range of  
2466 variation. This provides the core data for the so-called kinematic consistency analysis intended to ensure  
2467 that air data system and inertial data system measurements of aircraft velocities form a consistent set.  
2468 Any calibration error corrections derived from this analysis will need to be applied to data derived during  
2469 sorties to capture data for fidelity metrics in the DoV.
- 2470 b) Trims across the required ranges of incidence and sideslip to provide the core data for quantifying static  
2471 stability or controllability in low speed manoeuvres.
- 2472 c) Control frequency sweeps (one control axis in turn) that provide the core data for system identification  
2473 analysis to create p-models for use in the fidelity assessment and updating of the FSM. Real-time, or  
2474 post-run, analysis to check the coherency across the frequency of interest should be conducted and the  
2475 sweeps repeated until input-output coherence, and hence the test data, meets the defined quality  
2476 requirements.
- 2477 d) Multi-step control inputs (one control at a time) to provide the core data, for example for frequency and  
2478 damping of the lateral-directional oscillation to derive its stability characteristics using pedal control  
2479 doublets. Another example might be related to the RTO, recording responses to collective and cyclic  
2480 control in steep descent conditions. Data from, for example, 2311-type multi-steps can be used in the  
2481 'validation' of the p-models before they are used to support the FSM fidelity assessment.
- 2482 e) Two repeats of test points for all the above are advisable to support the resolution of any anomalies.

2483 In addition, flight test points in support of the FS validation and fidelity assessment will be required, linking with  
2484 the content of Section 6. These could include:

- 2485 f) Tests to exercise failure modes in cases where the expected severity level is 'minor', e.g. SCAS lane  
2486 failures. In addition to capturing data for the FSM (response) fidelity assessment, such tests would  
2487 enable the pilot to assess the various failure cues, including vestibular motion, in support of the FS  
2488 fidelity assessment.

2489 g) Mission-task-element testing to support the FS fidelity assessment for ACRs that involve task flying, e.g.  
2490 CAT A rejected take off, controllability and manoeuvrability in cross-wind hover. Such examples could  
2491 involve the use of the SFR scale to enable evaluation pilots to quantify the sufficiency of the FS cueing.

2492 It is suggested that the FTG be written by the RCbS engineer in close collaboration with the evaluation pilot(s)  
2493 and FTMS engineering team. Agreed criteria for test point quality and success/failure need to be defined and in-  
2494 flight judgements and decisions made, based on such criteria. Evaluation team training in the application of  
2495 (open-loop) test inputs can be conducted in the FS to ensure maximum data quality, e.g. duration and steadiness  
2496 of trim prior to control input, input magnitude and shaping, input and response duration, criteria for recovery.

2497 It is recognised that 'pre-certification' testing implies that additional flight and simulation testing will be required  
2498 for the Certification process itself, conducted at the selected DoV points. Some of these points may be the same  
2499 as those already flown in the pre-certification tests, while others will form the matrix of points 'within' which  
2500 interpolation will be performed using the FSM/FS. The distribution of the pre-cert and cert points in the DoV will  
2501 be established as discussed in the first paragraph to this sub-section and will be influenced by the Influence  
2502 Level(s) selected for the ACR. The extent of the DoE will also be a factor in establishing the distribution of points  
2503 in the DoV, since an understanding of the trends in fidelity and the extent of fidelity updating within the DoV  
2504 will be factors in quantifying uncertainty and hence confidence in the DoE results.

2505 The significance, and hence importance, of flight test data quality is highlighted here, recognising that the  
2506 distribution of RCbS points across the DoP, although initially defined by the I-P matrix in Phase 1, will probably  
2507 not be finalised until the fidelity assessment within the DoV is complete. The FTG should be written to  
2508 accommodate this flexibility.

2509

## 2510 7.7 SUMMARY: PHASE 2c

2511 To summarise, activities in Phase 2c, development of the FTMS based on the (preliminary) Requirements  
2512 Specification, include:

- 2513 i. FTMS design, build, calibration and installation,
- 2514 ii. Alignment between FSM/FS validation needs and FTMS,
- 2515 iii. Create the pre-certification Flight Test Guide,
- 2516 iv. Execution of pre-certification ground and flight test programme to support validation of FSM,
- 2517 v. Multiple iterative pathways managed and exercised as required throughout Phase 2c,
- 2518 vi. Updates to Requirements Specification based on Phase 2c activities,
- 2519 vii. Outputs; FTMS and validation test data for Phase 2a and 2b.

2520

## 2521 8 CREDIBILITY ASSESSMENT AND CERTIFICATION (PHASE 3)

### 2522 8.1 INTRODUCTION

2523 With Phase 2 and the initial fidelity assessments of both the FSM and FS complete, the applicant moves into  
2524 Phase 3, Credibility Assessment and Certification (Figure 8-1). Within this phase are the defining moments for  
2525 the achievement of certification, so it is expected that Certification Authorities will be even more closely  
2526 involved. Credibility addresses the complete set of RCbS results for the chosen ACRs across all I-P Levels (Table  
2527 3-2 and 3-4).

2528



2529

2530

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

2531 Demonstrating credibility within the DoV (using interpolation) is anticipated to be relatively straightforward, and  
2532 rooted in the results of fidelity assessment and FSM/FS validation, including updating/tuning. In the DoV, the  
2533 uncertainty analysis can give the model developer a scale to assess the fidelity, noting that when the comparison  
2534 error is comparable with the uncertainty the model is within the precision achievable given the data and  
2535 software available (see Section 5.3).

2536 Results within the DoE, however, will need further evaluation in Phase 3 before the case for Certification can be  
2537 sufficiently well evidenced and this Section discusses how such evidence may be presented.

2538 Several general kinds of extrapolation can be considered. The first, typically in Predictability Levels 2 and 3 (Table  
2539 3-2), involves cases where the extrapolations consist of extensions of fidelity assessments made within the DoV,  
2540 e.g. based on a validated model with proven physics-based updates. Extrapolating assessments made at low-  
2541 altitude into the high-altitude regime could be an example here. Another might be the extrapolation of level  
2542 flight dynamic stability to climbing/descending or turning flight. Three considerations are suggested to maximise  
2543 confidence and the credibility of these kinds of extrapolations:

- 2544
- 2545 a) Develop an extrapolation from a sufficient number of points within the DoV,
  - 2546 b) Understand, through analysis, the physical sources of variation in predictions in the DoV (e.g. of  
2547 performance margins or fidelity deficiencies),
  - 2548 c) Understand, through analysis, how these physical sources may change in the DoE and what other kinds  
of physical sources might need to be considered (e.g., dynamic stall).

2549 The second kind of extrapolation, typically in predictability Level 4 (Table 3-2), involves cases where the ACR  
2550 being considered is not supported by directly comparable results in the DoV, e.g. landing following total power  
2551 loss. But even in such cases, there are likely to be fidelity analyses that can be drawn on from the DoV that inform  
2552 fidelity assessment and credibility, e.g. results from autorotation flight tests conducted at altitude, including  
2553 entry and recovery.

2554 A third, and special, kind of extrapolation could relate to STC applications, e.g. hoist or external protuberance  
2555 installations, maximum take-off weight extensions, or additional flight control modes for specialist operations,  
2556 for which the compliance demonstration may in certain cases partly rely on similarity. While this Guidance does  
2557 not feature examples or case studies in this category, it is envisaged that the proposed RCbS process will still  
2558 need to be followed, and founded on the original certification process. Close collaboration with the OEM will be

2559 required to enable such STC applications. More generally, having established an RCbS basis for a rotorcraft, the  
2560 application of the process for any such life-cycle developments by the OEM is likely to be very efficient.

2561 For all kinds of extrapolation, applicants need to describe the location within the DoE, relative to the boundaries  
2562 of the DoV and the DoP.

2563 The credibility of the results from extrapolation can be informed by Uncertainty Analysis and Quantification  
2564 (UAQ), a topic touched on briefly in Sections 3 and 5, and expanded on in this Section.

2565 As with fidelity, the notion of sufficiency is also important for Credibility. To emphasise the point, at the RCbS  
2566 process point reached by Phase 3, to achieve sufficient simulation Credibility, it is essential that;

2567 1) A thorough verification and validation has been conducted to identify and address, to the extent  
2568 possible, the various sources of simulation error that might influence prediction accuracy.

2569 2) Fidelity within the DoV has been quantified and errors and uncertainties for the FSM/FS predictions and  
2570 FTMS are characterised.

2571 3) Extrapolations into the DoE are informed by the three considerations, a), b) and c) described above, as  
2572 well as past-experience from the applicant regarding the evolution of simulation model error and  
2573 uncertainty along the extrapolation dimension (if any).

2574 4) The development and exploitation of the simulation framework has been performed by a team with the  
2575 necessary expertise and experience following a controlled development process, akin to what is  
2576 proposed in this Guidance.

2577 The fourth point has already been highlighted on several occasions in this Guidance and its importance will  
2578 feature strongly as the results of the Credibility Assessment are presented to the certification authority.

2579 The various sources of test data error and simulation error addressed in the validation process have been  
2580 discussed in Sections 5–7 of this Guidance. The current section deals with how believable the results of  
2581 simulation are, their Credibility, along with the evidential basis, simulation uncertainty and its characterisation.  
2582 As recommended throughout this Guidance, it is assumed that the applicant has employed physics-based  
2583 modelling and updating for the FSM, exercised throughout the DoR.

2584 It is important to re-emphasise at this point that the V&V processes within the FMS, FS and FTMS developments  
2585 (Phase 2) are intended to ensure that, first, the three elements, the FMS, FS and FTMS, all meet their  
2586 requirements defined in Phase 1 (verification) and, second, that the functions and operations within the three  
2587 elements meet the fidelity requirements defined in Phase 1 (validation). In this way, applicants are expected to  
2588 strengthen confidence in their ability to quantify uncertainty through the V&V and fidelity assessment processes,  
2589 and hence credibility in predictions.

## 2590 **8.2 SIMULATION CREDIBILITY AND UNCERTAINTY**

### 2591 **8.2.1 Simulation credibility assessment**

2592 In the current context, simulation credibility refers to the extent to which the predictions from the FSM or FS  
2593 can be relied upon to assess the compliance of the aircraft to the selected ACRs, considering the potential  
2594 uncertainties of the simulation. The essential elements of a credibility assessment have been enumerated above,  
2595 and previously in Section 3. To re-iterate, the concept of simulation credibility is particularly (but not exclusively)  
2596 relevant in a certification context where the DoP extends beyond the DoV into the DoE, a region where the  
2597 simulation error cannot be fully assessed based on a comparison with test data, and so extrapolation is required,

2598 considering simulation uncertainty. Credibility in the DoE relies on the applicant’s perception, ultimately shared  
2599 by the certification authority, that they are addressing what are normally described as known-unknowns (as  
2600 opposed to so-called unknown-unknowns), that inform and underpin the quantification of confidence.

2601 While a generally accepted framework for flight simulation credibility assessment currently does not exist,  
2602 numerous efforts have been made in various fields of science and engineering [10], [20], [35], [36], [37]. There  
2603 is also an ASCE/ME Journal of Risk and Uncertainty in Engineering Systems dedicated to this topic, that would  
2604 be expected to report up-to-date research relating to mechanical and civil engineering. It is emphasised that the  
2605 Guidance herein does not advocate any particular method. What is important from a regulatory perspective is  
2606 that the essential elements of simulation credibility assessment are adequately addressed by the applicant.

2607 One of the essential elements expanded on here is the use of uncertainty analysis and quantification.

## 2608 **8.2.2 Uncertainty analysis and quantification**

2609 In [35], uncertainty quantification is expressed in terms of four elements;

- 2610 a) *Identification (Where are the major sources of uncertainty?),*
- 2611 b) *Characterization (What form are they, and what are their mathematical descriptions?),*
- 2612 c) *Propagation and Aggregation (How do they combine to determine total uncertainty in the analysis*  
2613 *results?), and*
- 2614 d) *Analysis (What are their impacts and implications?)*

2615 Reference [35] discusses these four elements in detail and makes an important point relevant to RCbS;  
2616 “Community-wide adoption of addressing analysis uncertainty using the structure of these four elements will  
2617 facilitate clear communication between applicants, regulatory authorities and other industry stakeholders.” This  
2618 Guidance therefore endorses this recommendation in pursuit of the same communication goal.

2619 In Section 5, the three important elements of validation uncertainty were introduced: the uncertainties due to  
2620 numerical errors  $u_{num}$ , those associated with experimental error  $u_r$ , and those due to uncertainty in the input  
2621 parameters  $u_{inp}$ . Solution verification is the process by which  $u_{num}$  is estimated (see Section 5.3.4). Regarding  
2622 flight test data, the experimental uncertainty should be determined within the FTMS development and  
2623 calibrations. Uncertainty due to input parameters should be part of the data provided at the initial stages of  
2624 RCbS from the design department, supplemented with expert insights on the type of modelling included in the  
2625 FSM.

2626 Typical FSM computational models make use of parameters that are quantified through specific experiments or  
2627 in some cases inferred from design requirements and data. In principle, all these data should have uncertainties  
2628 associated with them that could either be of an epistemic nature, with no knowledge of the probability  
2629 distribution, or aleatory due to known random variations that exist from one aircraft or component to another  
2630 or from time to time. In any case, given estimates of these data uncertainties, it is possible to estimate the effect  
2631 on the output quantity of interest that is connected with  $u_{inp}$ . Two different types of approaches can be used  
2632 to obtain such estimates:

- 2633 a. Local linear analyses using, e.g., Taylor series expansions for the simulation result of interest to  
2634 determine the (linear) sensitivity coefficient derived from the FSM. The input parameter uncertainty  $u_{x_i}$   
2635 must also be estimated. This approach leads to a local assessment, i.e. close to the values of the nominal  
2636 parameters values.
- 2637 b. A more general, global, statistical approach without assumptions of linearity, based on Monte Carlo or  
2638

2639 other similar stochastic methods. Typically, the required numerical effort is higher, and, as with  
2640 sensitivity analysis, the input parameter uncertainty must be estimated a priori, in this case in the form  
2641 of probability distributions. The numerical burden falls on the computer, of course, and it is the physical  
2642 interpretation of the results that enables the user to draw meaningful conclusions.

2643 Input parameter uncertainties can sometimes be estimated from prior experiments, and, for an input  $X_i$ ,  $u_{X_i}$  may  
2644 be characterised not only in terms of an interval (epistemic uncertainty), but also in terms of a statistical  
2645 distribution. Lacking more detailed information, the simplest assumption is a uniform distribution, i.e., an  
2646 interval within which all values are equally likely. The assumption of a Gaussian distribution requires the  
2647 definition of a mean and standard deviation. Finally, rather than a specified uncertainty, one could assume the  
2648 (conservative) worst-case parameter value, if indeed this limit can be justified (e.g., minimum specification  
2649 engine power, or conservative control rigging). The concept of Conservatism is further discussed later in this  
2650 Section. If statistical data are lacking, it is useful to seek expert opinions to gain, e.g. information on intervals.  
2651 Even in their simplest forms, these approaches provide the applicant (and certification authority) with an  
2652 understanding of the simulation output variability and primary parameters of influence which need to be  
2653 characterised with a high degree of certainty.

2654 It is worth noting that the input parameter uncertainty analyses described above also extend to the virtual pilot  
2655 (see Section 5). In this case, the analyses may be used to explore the effects of the uncertainty in piloting  
2656 strategy. The approach may be akin to a form of so-called 'Abuse Case Testing' in which deviations from the  
2657 Rotorcraft Flight Manual specified procedures are deliberately introduced to verify the efficacy of the specified  
2658 alternate procedures. In taking this route, the applicant must carefully consider the interrelationship between  
2659 aircraft model input uncertainty and the uncertainty due to the virtual pilot model and its parameters.

2660 For cases where the simulation is applied in the DoE, an assessment must be made on how the prediction errors  
2661 and uncertainties from the DoV are expected to evolve along the extrapolation dimension. This assessment may  
2662 be aided by, for example, access to historical (flight test and simulation) data, or comparisons with higher-order  
2663 numerical prediction methods. The extrapolation limits specified in the FAA's AC 29.45 [5] have been established  
2664 based on historical flight test experience and contemporary analytical and simulation methods; e.g. "a predicted  
2665 controllability model developed for high altitude may be used if verified by limited flight testing with steady  
2666 ambient winds. The extrapolation guidelines in AC 29.45 b(2) are still applicable. These high-altitude  
2667 controllability tests could typically be conducted in conjunction with take-off, landing and performance tests."  
2668 and "Controllability can usually be extrapolated up to a maximum of 2,000 feet above the highest test site  
2669 altitude." It is noted that the FAA refer to 'verification by limited flight data', using the term verification rather  
2670 than validation as used in this Guidance. As required in the FAA/EASA standards, the present Guidance advocates  
2671 that applicants exercise engineering judgement to evaluate whether the defined limits for extrapolation are  
2672 applicable, particularly for novel aircraft configurations and advanced analytical and simulation techniques.

2673 It is essential, for the assessment of simulation credibility, that the uncertainty throughout the prediction domain  
2674 is adequately characterised. Within this context, it is useful to again make the distinction between aleatory and  
2675 epistemic uncertainty. Epistemic uncertainty (EpU) is present in the simulation if there is a specific lack of  
2676 knowledge, or shortcomings in understanding, about the physical processes being modelled. Included in this  
2677 definition are model-form/structure uncertainties due to the approximate representation of reality, e.g., in the  
2678 form of the rotor wake and interference modelling. In principle, epistemic uncertainties can be reduced by  
2679 gathering additional test data or by using increased complexity, or higher-order, numerical tools such as  
2680 Computation Fluid/Structural Dynamics to gain further insight into the physics being simulated. In the latter  
2681 case, the knowledge gathered from the higher-order solution may, e.g., be used to reduce the uncertainty  
2682 bounds on specific input parameters.

2683 Aleatory uncertainty (AlU) is due to the (multiple) inherent variations in the physical system and its parameters  
2684 and is probabilistic in nature. This type of uncertainty might include variations in aerofoil properties (due to

2685 manufacturing tolerances, erosion and repairs), vehicle moments of inertia, control riggings, atmospheric  
2686 turbulence, etc. AIUs can be addressed in several ways, typically requiring many simulations to be run. In fact,  
2687 this is a clear benefit from the use of the structured RCbS process to replace flight test, given that simulation  
2688 provides an efficient means of evaluating a very large number of variations on a given scenario.

2689 AIU can, in principle, be addressed in a probabilistic manner using Uncertainty Quantification (UQ) techniques  
2690 [35]. This approach relies on the identification and characterisation of the sources of uncertainty in the modelling  
2691 and aggregating and propagating these throughout the model to obtain output probability distributions. The  
2692 benefits of this approach to UQ can only be fully realised when the capability to interpret such distributions, in  
2693 the context of extrapolation, are well developed by the applicant.

2694 Another approach to dealing with uncertainty (in an input parameter or at prediction level) can be described as  
2695 conservatism. That is, by introducing conservative or worst-case assumptions and/or limitations in the FSM or  
2696 FS cueing environment, leading e.g. to under-prediction of margins, or by imposing conservative limits of  
2697 acceptability on the compliance parameters. In this case, it must be shown that the assumptions are indeed  
2698 worst-case and/or that the effect of the assumptions are large enough to account for the prediction uncertainty.  
2699 The problem with this approach is, of course, that it may lead to suboptimal, or unnecessarily reduced, aircraft  
2700 performance if used excessively. Furthermore, it needs to be shown that the conservatism does not invalidate  
2701 the physical modelling. That is, the conservative assumptions must be physically meaningful so that the  
2702 simulation does not deviate from the DoR. The approach of dealing with uncertainty through conservative  
2703 assumptions is not uncommon to the AMCs, as illustrated in AMC25.1309 11.e.4c, which states that “uncertainty  
2704 should be accounted for in a way that does not compromise safety”.

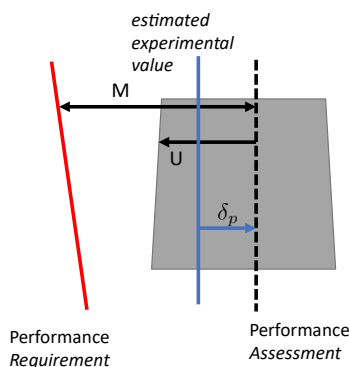
### 2705 **8.2.3 Confidence ratio**

2706 Within the broader concept of simulation credibility, the predictive quality of the simulation hinges on the extent  
2707 of both the simulation error and predictive uncertainty. Increasing the credibility of the prediction requires  
2708 reducing both the error and the uncertainty, e.g. by FSM updating, or by reducing the uncertainties in the various  
2709 input parameters.

2710 The required level of credibility of the simulation prediction (initially estimated in Phase 1, see Section 3.2) is  
2711 tied to the proximity to non-compliance, i.e. the margin between the prediction and the boundary of the  
2712 performance requirement. Thus, the closer the case is to being non-compliant (small  $M$ ), the lower the required  
2713 uncertainty  $U$  of the simulation. As discussed in Sections 3 and 5, this dependency can be captured using the  
2714 concept of the Confidence Ratio,  $CR$ , illustrated again in Figure 8-2, and generally defined in terms of the ratio  
2715 of the ‘distance’ between the FSM prediction and the performance requirement, or the margin  $M$ , to the  
2716 uncertainty  $U$  in the prediction.

$$2717 \quad CR = M/U \quad (6)$$

2718 So, as the uncertainty  $U$  increases, confidence reduces. A large  $CR$  implies either that the case is far from being  
2719 non-compliant (large  $M$ ), or that the combined uncertainties ( $U$ ) in the simulation prediction are low compared  
2720 to the distance to the performance requirement. In Figure 8-2 the ‘estimated experimental result’, and related  
2721 (estimated) comparison/simulation prediction error  $\delta_p$ , have been added for reference. The estimated  
2722 experimental result in the DoE might be derived from extrapolation of the test data in the DoV. As discussed  
2723 previously, this error, unknown in the DoE of course, should be embedded in the uncertainty  $U$ . The embedding  
2724 can lead to increased or reduced  $CR$ , depending on whether the trend in the DoV was for under-prediction or  
2725 over-prediction of the margin  $M$ . This will be returned to when discussing stability margins later in this Section.



2726

2727

Figure 8-2 Schematic illustration of Confidence Ratio Parameters

2728 The CR was first introduced in Section 3 since applicants must make their initial estimates of credibility and  
 2729 related uncertainties for the Requirements Specification. There, in Table 3-3 reproduced below as Table 8-1, the  
 2730 relationships between the CR and an applicant’s confidence in the results of simulation for a specific ACR were  
 2731 suggested. In turn, how this confidence translates into the RCbS activity for particular ACRs was illustrated in  
 2732 Table 3-4. The case was speculative but reinforces the point already made that the closer the case is to being  
 2733 non-compliant, the higher should be the required confidence (i.e. the lower uncertainty), and therefore the  
 2734 credibility, in the conclusions drawn from simulation. Even if it may prove infeasible to define CR requirements  
 2735 that hold universally true, the concept does provide an intuitive normalized quantification of the confidence in  
 2736 the simulation predictions.

2737

2738

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

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

2739

2740 To emphasise, the CR concept described above applies to those parameters for which a performance  
 2741 requirement, and therefore a margin, exists within the ACR, e.g., the control margin for a controllability  
 2742 assessment, or the damping of an oscillation for a dynamic stability assessment, and is particularly relevant, but  
 2743 not exclusively, to cases in the DoE. It is anticipated that requirements on the CR should be ACR-specific.  
 2744 Generally, a CR greater than unity is required to account for “unknown unknowns” not featured in the  
 2745 uncertainty quantification efforts and thus included in U. Finally, as extrapolation will increase the uncertainty  
 2746 in the predictions, this will automatically be reflected in a reduction of the CR for cases of extensive  
 2747 extrapolation.

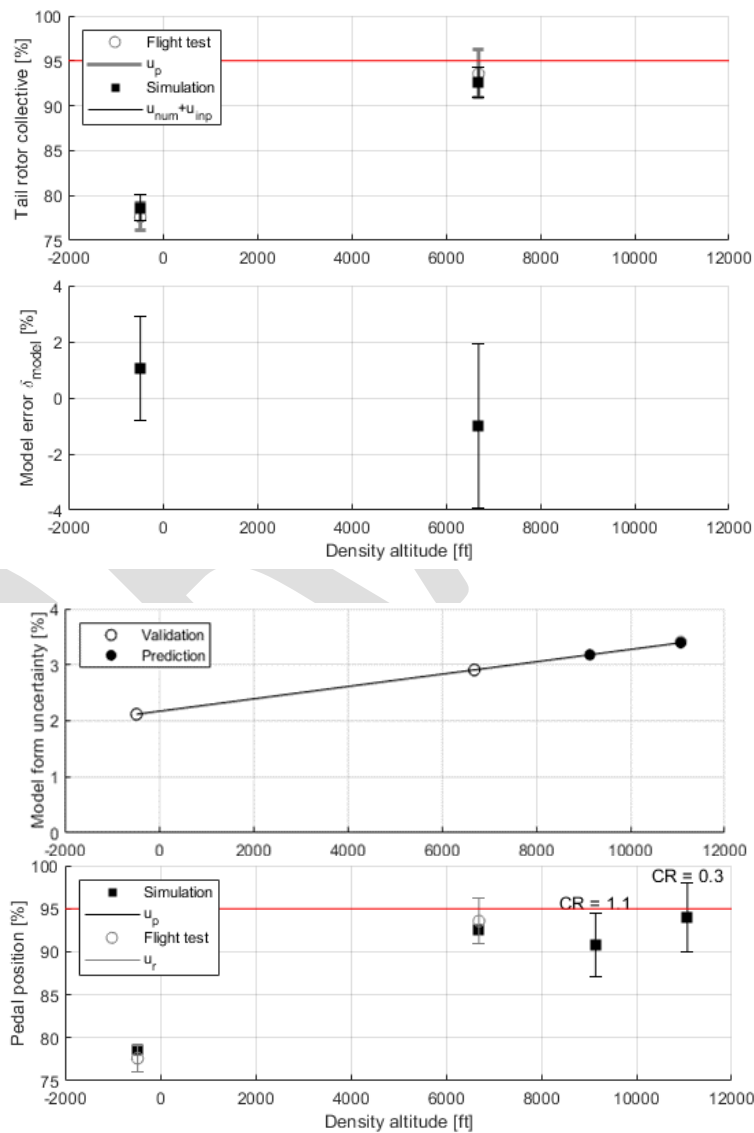
2748 An example is now presented to provide insight into how the CR might be used in practice.

2749 ACR 29.143(c) (Controllability and Manoeuvrability) requires that the “wind velocities from zero to at least 31  
 2750 km/h (17 knots), from all azimuths, must be established in which the rotorcraft can be operated without loss of  
 2751 control on or near the ground in any manoeuvre appropriate to the type.” The applicant has proposed that  
 2752 simulation is used to compute the trim pedal margins up to the maximum take-off and landing altitude for the  
 2753 so-called critical azimuth. The safe margin (i.e. the performance limit) is defined by the red line in Figure 8-3 and  
 2754 has been established based on flight testing in the DoV, demonstrating that the indicated margin ensures  
 2755 adequate control authority. The applicant is seeking partial-credit for this ACR, limiting the use of simulation to  
 2756 the prediction of the control margin.

2757 Figure 8-3 illustrates a possible set of results. The top two graphs present the outcome of the validation analysis  
 2758 in the DoV, expressed as a function of the intended extrapolation dimension (density altitude). The first graph  
 2759 plots the comparison between flight test and simulation with the uncertainty bars generally indicating an  
 2760 interval, or probability bounds, depending on the nature of the uncertainties. The uncertainty for the simulation  
 2761 predictions in the DoV, as plotted, reflects the sum of the numerical and input uncertainties. The associated  
 2762 model structure/form error  $\delta_{model}$ , and validation uncertainty  $u_{val}$ , are plotted in the second graph. The third  
 2763 graph shows the result of linear extrapolation of the validation (or model form) uncertainty into the DoE. The  
 2764 fourth and final graph then presents the result of subsequent application of the extrapolated model form  
 2765 uncertainty to the total prediction uncertainty  $u_p$  as computed by the expression:

2766 
$$u_p = \left( \sqrt{u_{num}^2 + u_{inp}^2 + u_{model}^2} \right)_p \quad (7)$$

2767



2768  
2769

2770

2771  
2772  
2773

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

2774 In this particular example, the simulation prediction clearly does not meet the minimum requirement of a CR  
 2775 greater than unity. At this point, the applicant is faced with the choice of accepting a take-off gross weight

2776 restriction, or improving the modelling and/or reducing the prediction uncertainty. That latter may be achieved  
2777 by gathering additional flight test data to reduce the amount of extrapolation, updating the model form of the  
2778 simulation, or by endeavouring to reduce the input uncertainties to which the prediction is most sensitive.

2779 Note that the extrapolation of the model form uncertainty does not inherently result in increased uncertainty,  
2780 though the data trends in that direction in this example.

2781

### 2782 8.3 EXPLORING DoV FIDELITY ASSESSMENTS EXTRAPOLATED INTO THE DoE

2783 Test data define the boundaries of, and are scattered throughout, the DoV, but uncertainties prevail. Two such  
2784 examples involving epistemic uncertainty are,

- 2785 a) Using the metrics defined in Phase 1, the initial comparison between flight and simulation show  
2786 insufficient fidelity at an ACR condition. A model update process is undertaken to reduce the mismatch  
2787 to within tolerance; but there is no statistical information available on the input parameters exploited  
2788 in the model updating.
- 2789 b) Interpolation is used to derive fidelity at condition Y based on validation at conditions X and Z, where  
2790 fidelity has been deemed sufficient. Uncertainty surrounds whether the (potentially different) model  
2791 updates applicable at conditions X and Z, or some combination of both, will also be applicable at  
2792 condition Y.

2793 The potential for gaining insight into fidelity uncertainties is much greater in the DoV due to the multiple  
2794 validation points analysed. A technique that has proved useful for the *analysis and characterisation* of epistemic  
2795 uncertainty in fidelity assessment is described as ‘renovation’. First, stability and control derivatives (Section  
2796 5.2.3) predicted by the FSM are compared with those estimated from flight, e.g. using System Identification  
2797 (SySID) techniques. Based on the comparisons, a subset of derivatives is selected that time and frequency  
2798 domain response metrics are shown to be particularly sensitive to; the sensitivity being quantified by user-  
2799 defined cost functions [38]. Delta derivatives can then be formed to augment the nonlinear FSM, and thence to  
2800 improve fidelity. In a further step, an examination of the component (e.g., main rotor, fuselage, tail rotor, see  
2801 Figure 5-2, Figure 5-3) breakdown of the predicted FSM stability and control derivatives can potentially provide  
2802 the required insight into the physical sources of modelling errors. Through this process, judgements can be made  
2803 on the sources of modelling deficiencies. In principle, if the renovation can be shown to be suitable also at  
2804 extrapolated conditions within the DoE, it can be used to minimise simulation error as well. This process is  
2805 exercised in the case studies in Section 10 but here an example is presented to assess the effectiveness of a  
2806 renovation made at one flight condition, applied to another.

#### 2807 8.3.1 Example scenario, CS-29 requirements for dynamic stability.

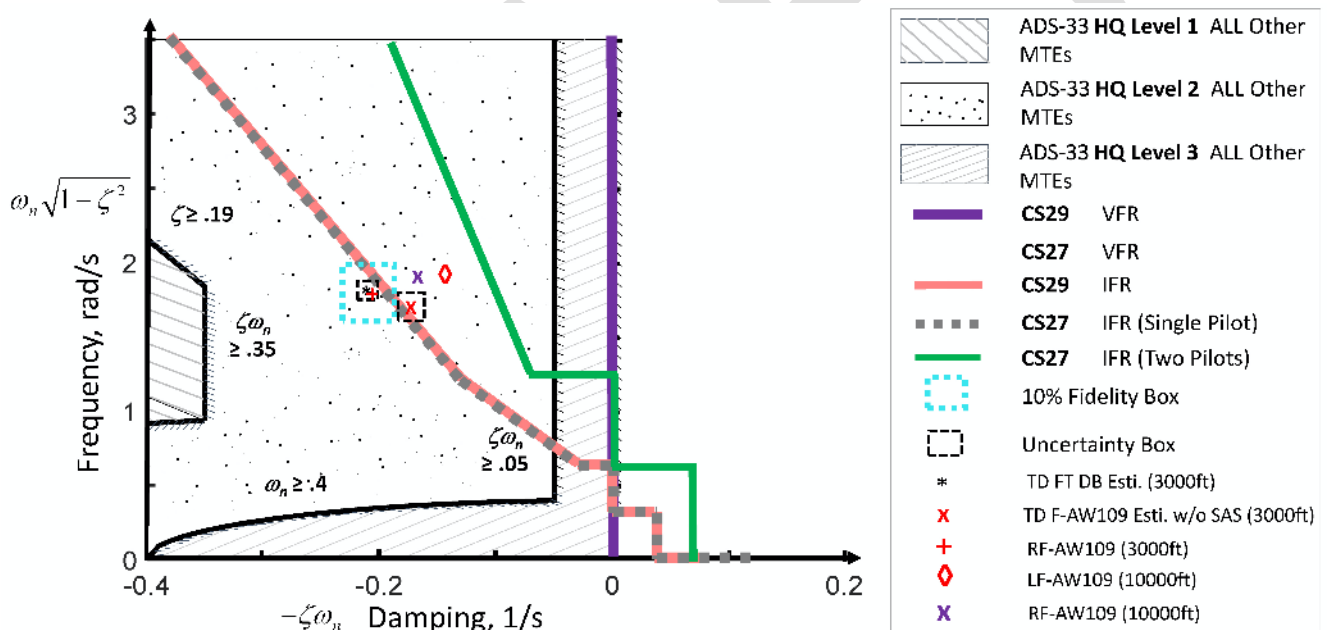
2808 “CS 29.181 Dynamic stability: Category A rotorcraft; Any short period oscillation occurring at any speed from  $V_Y$   
2809 (best rate of climb speed) to  $V_{NE}$  (never exceed speed) must be positively damped with the primary flight controls  
2810 free and in a fixed position.”

2811 This ACR also applies for VFR flight, the requirement being that short-period oscillations should be stable. The  
2812 standards set for IFR flight (CS 29, Appendix B) are more demanding and specify stability requirements in terms  
2813 of damping ratio of an oscillation (see Figure 8-4). Figure 8-4, the boundaries for the various certification  
2814 standards are shown on the frequency-damping chart, together with data points for the RoCS AW109 case study  
2815 on Dynamic Stability (DS), expanded on in Section 10. For this example, the validation process at one (altitude-  
2816 velocity) point (3000ft, 120kts) in the DoV revealed that the FSM prediction for the Lateral Directional Oscillation  
2817 (LDO) was just outside the CS-27/29 boundary (x, TD F-AW109), while estimates from flight test showed the LDO  
2818 to be just inside the certification boundary (\*, TD FT DB Esti). A simple renovation determined that an FSM-

2819 update involving a 10% increase in the yaw damping derivative was sufficient to bring this fidelity metric (+, RF-  
 2820 AW109(3000ft)) into the sufficiency range, defined in this example as a 10% (blue-dashed) 'box' around the  
 2821 mean flight test point The figure also shows uncertainty boxes wrapped around the flight test and simulation  
 2822 test points, based on the varying computations of frequency and damping using different sections of the pedal  
 2823 doublet-induced yaw response test data<sup>4</sup>. In the case of the simulation data, this included data derived from  
 2824 different control input magnitudes.

2825 Figure 8-4 also shows the FSM prediction (LF-AW109) for the 10000ft case, together with the renovation (RF-  
 2826 AW109) after application of the same 10% yaw damping improvement that was effective at the lower altitude.  
 2827 The applicant might argue that there were no significant differences in the flight characteristics (and hence FSM  
 2828 structure/form) at the two altitudes to justify a more extensive update, but they would, of course, need to offer  
 2829 explanations for the damping deficiency.

2830 The data points discussed above are for the bare airframe, or SAS-off, configuration. As shown in the figure,  
 2831 there is a significant stability margin for the CS29 VFR ACR, and CS27 VFR ACR, for which there is no quantified  
 2832 stability requirement. However, uncertainties for the 3kft case would make IFR certification questionable, with  
 2833 such a small stability 'margin'. The data suggest that, at the higher altitude, the aircraft would fail the IFR  
 2834 certification. This is, of course, not untypical of helicopters without stability augmentation.



2835

2836

2837 *Figure 8-4: FSM renovation to achieve sufficient fidelity for dynamic stability at 120kts, with the corresponding DS boundaries; 3kft*  
 2838 *result compared with flight test, and 10kft result with extrapolated renovation*

2839 In the above case, the renovations, or updates, were made using a single 'delta' derivative, augmenting the  
 2840 nonlinear FSM yaw damping with a 10% increase in  $N_r$ . A plausible physical explanation for this is that the wind  
 2841 tunnel tests to derive fuselage and empennage forces did not capture the interference/blockage effects  
 2842 correctly, both statically and dynamically. In addition, there are uncertainties regarding the modelling of the  
 2843 blockage effects on the tail rotor in the FSM. Uncertainty analysis could include varying interference modelling

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

2844 parameters, within the DoR range, to explore sensitivities, coupled with additional CFD analysis to compare with  
 2845 the wind tunnel test data.

2846 **8.3.2 Typical sources of FSM uncertainties**

2847 Within the rotorcraft FSM, there are several sources of potential mismatch that have featured in the limited  
 2848 public-domain references on simulation fidelity. Table 8-2 describes these as the ‘usual suspects’, but the list is  
 2849 far from exhaustive and can be modified or added to as experience is gained with the application of the RCbS  
 2850 process.

2851

2852

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

Usual Suspects	EpU or AIU	Issues and impact
Blade torsion dynamics	EpU	<ul style="list-style-type: none"> <li>Offsets between blade section cg, ac, tc give rise to couplings between flap, lag and (particularly) pitch/torsion</li> <li>Cambered sections have pitching moment as function of velocity (dynamic pressure) as well as incidence and M, causing torsion dynamics even in steady flight</li> <li>Change in 0/rev twist due to aerodynamic moment can require more or less collective in trim; impacts power</li> <li>2/rev Coriolis components in loads evidence for this effect</li> </ul>
Aircraft inertias	EpU but treated as AIU	<ul style="list-style-type: none"> <li>Usually not measured so estimated from mass distributions; considered to be unreliable, particularly for old types where no digital data are available</li> </ul>
Stick to blade calibrations	EpU but may vary from blade to blade and A/C to A/C so aspects of AIU also	<ul style="list-style-type: none"> <li>Calibrations usually made on the ground with auxiliary power unit (so actuation hydraulic pressure can be different from in-flight)</li> <li>Feedback of rotor torsion aerodynamic loads through pitch-links to swashplate in flight will distort relationships</li> </ul>
Delta3 Flap-pitch coupling	EpU	<ul style="list-style-type: none"> <li>Sometimes deliberately designed in (especially on tail rotor) but needs careful checking during calibration, so need flap measurements to be sure.</li> </ul>
Wake decay and contraction	EpU	<ul style="list-style-type: none"> <li>One of the most challenging aeromechanics prediction problems</li> <li>Typical finite-state dynamic wake model has several ‘tuning’ parameters to shape results but these need to be physically realistic</li> <li>Major impact on interference effects</li> </ul>
Hub retention – flap, lag and torsion	EpU	<ul style="list-style-type: none"> <li>Modelling an elastic blade with a rigid blade, the hub retention structure is very important and dominates the hub moment predictions</li> <li>Validation with blade tip and hub moment measurements can reveal how accurate the rigid blade approximation can be</li> </ul>
Fuselage blockage on tail, tail rotor and variations with incidence and sideslip	EpU	<ul style="list-style-type: none"> <li>Known to be a significant contribution to reducing dynamic stability in forward flight</li> <li>Variations with sideslip and incidence significant and has a dynamic component (hysteretic) gives rise to strong nonlinearities</li> </ul>
Radial distribution of rotor dynamic inflow	EpU but usually no measurements for validation	<ul style="list-style-type: none"> <li>Significant impact on performance since induced drag/power impacted by loss of bound circulation radially</li> <li>Variations during manoeuvres can impact dynamic response, particularly off-axis (e.g. Manoeuvre Wake Distortion)</li> <li>Strong impact in vortex ring state</li> </ul>

Usual Suspects	EpU or AIU	Issues and impact
Measurements of $V$ , $\alpha$ and $\beta$ conversion to $u$ , $v$ and $w$	AIU and EpU	<ul style="list-style-type: none"> <li>• Problem in low speed but also higher speeds</li> <li>• Impact of rotor wake can be significant and won't be captured in, e.g., wind tunnel calibrations</li> <li>• <math>V</math>, <math>\alpha</math> and <math>\beta</math> vary at different points of the aircraft but usually measured at a single point, ahead of the nose on a boom</li> </ul>
Kinematic consistency	EpU and AIU	<ul style="list-style-type: none"> <li>• Crucial to undertake analysis to ensure that the measurements of re-constructed states <math>u</math>, <math>v</math>, <math>w</math>, <math>p</math>, <math>q</math>, <math>r</math> and <math>\theta</math>, <math>\phi</math>, <math>\psi</math> form a consistent set that satisfy the 6DoF equations</li> <li>• Scale factor and bias errors are common for accelerations, angular rates and air-data measurements and can vary from flight to flight</li> </ul>
Main rotor wake interference on tail rotor	EpU	<ul style="list-style-type: none"> <li>• Can have major impact on yaw control in low speed manoeuvres with certain wind azimuth conditions; difficult to predict correctly without some form of vortex wake model</li> </ul>
Tail rotor vortex ring state (VRS)	EpU	<ul style="list-style-type: none"> <li>• Evident with winds from port side (anti-clockwise main rotor); requires significant corrections to tail rotor dynamic inflow model to predict the adverse effects of VRS</li> </ul>
Dynamic stall	EpU	<ul style="list-style-type: none"> <li>• Can impact the performance and flight stability particularly for flight at high Mach number (forward speed, altitude)</li> <li>• Complex phenomena that triggers local unsteady rotor blade lift and pitching moment changes; stall characteristics quite different from quasi-steady stall and involve hysteresis</li> </ul>
Yawed flow and reversed flow effects	EpU	<ul style="list-style-type: none"> <li>• Complex nonlinear 3-dimensional effects that require aero data tables for sections that include large incidence and sideslip</li> <li>• Can lead to changes in aircraft flight behaviour at higher airspeeds</li> </ul>

2853

## 2854 8.4 CONCLUDING REMARKS

2855 This Guidance suggests that Credibility Assessment should be contained within the final Certification activity of  
2856 the RCbS process. As such, the way results are presented to certification authorities needs to be documented  
2857 in the PMP, the subject of the next Section. It is acknowledged that the initial publication of these guidelines is  
2858 far from complete or comprehensive in this regard. As with other elements of the RCbS process, the guidelines  
2859 emphasise early-adopter practice to be shared community-wide to maximise the capturing of lessons-learned  
2860 as the guidelines evolve.

## 2861 8.5 SUMMARY: PHASE 3

2862 To summarise, activities in Phase 3, Credibility assessment and certification, include:

- 2863 i. RCbS certification tests performed for relevant ACRs
- 2864 ii. uncertainty characterisation undertaken throughout the domain of prediction,
- 2865 iii. credibility analysis and assessments undertaken on the results of i. and ii.,
- 2866 iv. results assembled and presented to certification authorities to make case for certification,
- 2867 v. based on the feedback from Phases 2 and 3, the Requirements Specification is updated to
- 2868 constitute a formal element of the case for RCbS for the selected ACRs.
- 2869 **vi.** Outputs; updated RCbS Requirements Specification and Type/Supplemental-Type Certificate
- 2870 documentation.

## 2871 9 PROCESS DOCUMENTATION; THE PROJECT MANAGEMENT PLAN, CONTROLLED 2872 DEVELOPMENT AND CONFIGURATION & DATA MANAGEMENT

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### 2873 9.1 INTRODUCTION

2874 This Section addresses what might be described as the administrative aspects of the RCbS process and  
2875 application. Sometimes, and mistakenly, considered as 'second order' to the main development and creative  
2876 activities, these aspects are, in this Guidance, put forward as equally critical to achieving success. Although there  
2877 are currently no formal standards for the qualification of the tools and data of the RCbS process, this situation  
2878 may change as the experience builds. In such a scenario, methods, data management, standards and practices  
2879 adopted will need to be fully documented to establish an applicant's credibility, while providing evidence of such  
2880 for certification authorities. This Guidance therefore recommends a fully transparent and comprehensive  
2881 approach to developing the PMP, the controlled development of the FSM, FS and FTMS and the associated  
2882 configuration/data management; described as Phase 0 of the RCbS process.

2883 As highlighted in the Executive Summary, the Phase 0 development of the PMP should address, for each selected  
2884 ACR,

- 2885 i. Resources and timescales,
- 2886 ii. Dependencies and constraints,
- 2887 iii. Risks and mitigations,
- 2888 iv. Process control, documentation, configuration and data management,
- 2889 v. Preparation for documenting the RCbS certification case.

2890 The first three bullets are standard in project management; as is the fourth, but because of the potential  
2891 evolution of requirements and configurations in RCbS, perhaps has added importance. It should also satisfy the  
2892 dual purpose of providing comprehensive documentation of the applicant's RCbS process, and how it is  
2893 managed, for the benefit of both the applicant and the certification authority. The process control and materiel  
2894 management will underpin any required 'qualification' of flight simulation models and flight simulators for use  
2895 in RCbS. Applicants shall therefore formalise a controlled development and configuration/data management  
2896 process, mirroring the phases described in this Guidance. This includes the systematic documentation of all  
2897 relevant information necessary to enable the authority to understand the methodologies used, the underlying  
2898 assumptions and limitations involved in Phase 2 developments, and to assess the validity of the simulation  
2899 results and consequent credibility analysis in Phase 3.

2900 The emphasis on creating a requirements-based framework for developing and validating, in parallel with pre-  
2901 certification flight testing (Section 7), facilitates such a formalised approach. The requirements for the FSM and  
2902 FS and their V&V, as well as a documented narrative on how the requirements have been met, or not, must be  
2903 captured in a configuration/data management process.

2904 The formal practice of (FSM/FS) configuration/data management facilitates appropriate representations with  
2905 respect to the expected certification configuration(s), traceability of the results, and repeatability for future  
2906 analyses and tests. The requirement for configuration/data management extends to the simulator hardware,  
2907 even if generic subsystems are used (e.g. reconfigurable control loading system). Deviations from the expected  
2908 certification configuration should be documented and justified. Records of the relevant information and data  
2909 shall be retained as, e.g. Part 21.A.55 requirements [39].

2910 Items to be addressed in the RCbS configuration/data management documentation are:

- 2911 a) FSM/FS requirements specification, including how different variants are to be used and relate to one
- 2912 another
- 2913 b) Data structures and related sources and uncertainties
- 2914 c) V&V process and results, including model tuning/updating
- 2915 d) Definition and rationale/justification for the four domains (DoV, DoP, DoE, DoR)
- 2916 e) Problems relating to FSM and FS, e.g. configuration data and physics modelling
- 2917 f) Interpolation, extrapolation and similarity
- 2918 g) Experience and expertise being applied to RCbS by the applicant
- 2919 h) Documentation and record keeping processes

2920 Known problems, as referred to under e), would typically include deficiencies, process deviations and errors in  
2921 definition or implementation of the FS & FSM. These problems and their impact and/or mitigation should be  
2922 documented and communicated in dedicated Problem Reports.

2923 As described in Sections 5 and 6, it is acknowledged that several versions of the FSM and FS are likely to be used  
2924 in the RCbS process, addressing different Influence-Predictability combinations. It is recommended that a  
2925 common framework for the different variants is used, that forms a core in the configuration management. The  
2926 documentation of the V&V process includes details on the relevance and robustness of the selected metrics, and  
2927 the model-updating methods that have been or will be applied. The overall documentation shall also include a  
2928 description of the flight simulation model and the simulator hardware. As noted in Sections 5 and 6, the  
2929 components of the model and simulator can be described in terms of the requirements that the component is  
2930 serving, addressing functions, modes of operation, data structures, inputs and outputs, constraints and  
2931 interfaces with other components.

2932 The configuration/data management documentation covers a wide range of topics, in many ways mirroring the  
2933 structure of this Guidance material. The early adopters of the use of M&S in support of certification will have  
2934 the opportunity to shape the development of this approach, identify the critical issues, and highlight strengths  
2935 and weaknesses of different methods.

## 2936 9.2 RESOURCING THE RCbS PROCESS

2937 It is recognised that building a capability able to fully embrace virtual engineering in certification, as summarised  
2938 in Figure 2-1, and expanded on throughout this guidance, will take time and dedicated resources. The emphasis  
2939 on 'dedicated' is part of a recommendation of these guidelines, to ensure that sufficient time is allowed to grow  
2940 capabilities without the constraints and pressures of current programs. The technical capabilities will include the  
2941 disciplines of flight dynamics and control and associated multi-body dynamic modelling,  
2942 aerodynamics/structural dynamics and associated numerical modelling, flight simulation and associated flight  
2943 simulator technologies, system identification methods and applications, flight and wind tunnel testing and  
2944 measurement techniques etc. Of course, these technical capabilities will exist in various depth levels within a  
2945 modern rotorcraft industry and be applied throughout the life cycle of numerous 'projects' concurrently. A major  
2946 challenge is to establish what is required to achieve 'sufficient' fidelity and credibility in the company's flight  
2947 simulation models, flight simulators and flight test measurement systems, to make a significant impact on  
2948 certification costs, timescales and safety. Developing a profound understanding of what is meant by sufficient  
2949 and credible, is part of this challenge.

2950 Such a challenge can be approached by first applying the RCbS process at various I-P levels, and for specific ACRs,  
2951 to existing, certified, products taking advantage of existing flight test databases. This would also provide  
2952 opportunities to train new engineers in the exercising of the RCbS phases. In this way, the existing 'operational'  
2953 capabilities can be drawn on, providing a framework for the RCbS process development; also extant capabilities  
2954 can be improved as new methods, focused on the certification application, are developed. As the process

2955 matures to the point where it is applied to a new application, a question that might arise is ‘how deep should  
2956 the RCbS capability be’? Because of the importance of the V&V processes in Phase 2, a strong argument could  
2957 be made for at least duplex in each discipline. This would enable a progressive and independent checking of any  
2958 analysis and the results of simulation. This duality would also extend to the simulation tools adopted in the  
2959 process, e.g. CFD codes, flight models, SysID techniques. The dedicated RCbS team will also face a significant  
2960 challenge when faced with using ‘existing’ flight test data, usually captured for unrelated purposes. It is  
2961 suggested that dedicated test programs in support of RCbS capability development will also be required to  
2962 ensure that validation and fidelity assessment processes can be productively exercised and refined.

2963 Early applications are likely to be modest in their aims, but it is strongly recommended that the long-term  
2964 aspiration to achieve the I-P full credit goals define the backbone of the capability development. We elaborate  
2965 on these aspects later, in Section 11 of the Guidance.

2966

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## 2967 10 GUIDANCE FOR SPECIFIC ACRs WITHIN THE CERTIFICATION SPECIFICATIONS

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### 2968 10.1 INTRODUCTION

2969

### 2970 10.2 CONTROLLABILITY AND MANOEUVRABILITY: LOW-SPEED

2971 Applicable sections: §29.143(c-d)

2972 ...important to emphasise here the importance of hi-fi aerodynamics derived from, e.g. CFD results, in the FSM  
2973 and challenges of how to turn these into real-time data-maps that provide the pilot with realistic effects in the  
2974 FS

### 2975 10.3 VFR/IFR DYNAMIC STABILITY

2976 Applicable sections: §29.181, App. B §VI

2977 ...

### 2978 10.4 CATEGORY A TAKE-OFF AND LANDING

2979 Applicable sections: §29.49, §29.53-62, §29.67, §29.77-81, §29.85, §29.141(b), §29.143(e)

2980 ...

### 2981 10.5 SAS FAILURES

2982 Applicable sections: ...

### 2983 10.6 POWER-OFF LANDING

2984 Applicable sections: ...

2985

## 2986 11 WHAT NEXT? ROUTES TO THE ADOPTION OF RCbS

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### 2987 11.1 INTRODUCTION

2988 Here, in this final Section of the Guidance, the RoCS team outline some potential routes forward, and how the  
2989 first steps along these might be taken, for early adopters of the RCbS process. In Section 9, 'resourcing the  
2990 process' was discussed and a key point was made that, "*early applications are likely to be modest in their aims,*

2991 *but it is strongly recommended that the long-term aspiration to achieve the I-P full credit goals define the*  
2992 *backbone of the capability development.”* This is reinforced here because, while there may be opportunities for  
2993 short term success, the ‘quick-wins’ as they are sometimes described, the more extensive benefits from RCbS,  
2994 the full vision, can only be realised by building a strong foundation and comprehensive framework as put forward  
2995 in this Guidance. Any route forward must be safe (risks quantified and pitfalls avoidable), reliable (well defined  
2996 with uncertainties quantified), ambitious (acknowledging the challenges) and ultimately affordable (clear  
2997 returns on investment). Milestones along the route need to reflect growth in capability in harmony with success  
2998 in application. The RoCS team stress these points in view of the strategic role that CbS will play during the  
2999 evolution of virtual engineering within the aviation industry.

3000 So, the Guidance advocates small steps in the pursuance of big goals, with examples described below.

## 3001 11.2 WHAT NEXT FOR EARLY APPLICATIONS?

3002 Some suggestions for early adopters of RCbS to pick up on are listed below.

- 3003 a) Study and understand the RCbS process set out in this Guidance, particularly the value of the iterative  
3004 pathways between phases,
- 3005 b) Undertake a thorough assessment, a calibration/valuation, of your existing FSM/FS/FTMS capabilities,  
3006 in terms of both models and facilities and human skills and experience; calibrations referred to above  
3007 could relate to the use of both interpolation and extrapolation, and draw on existing test data,
- 3008 c) Build capability around cases, by selecting ACRs that enable the full RCbS process to be exercised, albeit  
3009 at reduced levels; include uncertainty quantification in this capability development,
- 3010 d) As recommended in Section 9, apply the RCbS process at various I-P levels, and for specific ACRs, to  
3011 existing, certified, products; exercising extrapolation in such cases could be particularly valuable, pinning  
3012 the corners of the DoP using certified flight test points,
- 3013 e) For any application (e.g. from c) or d)) assess carefully the levels of uncertainty of your M&S predictions  
3014 to provide users of these results an indication of the credibility levels,
- 3015 f) Consider the potential utility of flight test data for M&S validation purposes as a standard part of  
3016 development/envelope expansion flight test preparation activities,
- 3017 g) Scope out what a ‘fully-operational’ RCbS team might look like; how it might fit into the Company  
3018 structure and how capabilities can be sustained for the long term,
- 3019 h) Train your engineering team to develop and report certification-ready M&S results with a section in the  
3020 report dedicated to evidence that support the credibility of the results,
- 3021 i) Consider how your applications might need to comply with ‘industry-wide’ standards and the  
3022 importance of knowledge-sharing in this context; the Guidance has been specific in its recommendation  
3023 that early-adopters are pro-active in sharing good practice throughout the community,
- 3024 j) Seek support from relevant certification authorities who also need to develop a deep understanding of  
3025 the RCbS process,

3026 In Section 9, we briefly touched on the types of skills and experience that would be required in a RoCS team.  
3027 Technical capabilities will feature large, but other skills and experience will also be important. Individuals whose  
3028 strength is in finishing a task, deciding when enough is enough, or writing the PMP, or designing/conducting the  
3029 flight trials, won’t be the same people who write the CFD codes or UQ algorithms or try to make sense of the  
3030 results of validation or credibility. The RCbS team will have strength in breadth and depth, and to be fully  
3031 effective, will need to operate as a team, across multiple disciplines and departments, with heightened  
3032 awareness of important synergies and the need to adopt a systems-engineering discipline.

3033 As these guidelines are being written, it is evident that they are being considered, wholly or in part, by others  
3034 whose focus is not on the CS-27/29 requirements, including players in the emerging eVTOL industry. This is  
3035 welcomed by the RoCS team, who are, in principle, available to advise on how the process might be adopted or  
3036 adapted to these applications during the remaining tenure of the project (30<sup>th</sup> November 2023).

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# Preliminary guidelines for the rotorcraft certification by simulation process: update no. 1, March 2023

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2023-03

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Padfield GD, van't Hoff S, Lu L, et al., (2023) Preliminary guidelines for the rotorcraft certification by simulation process: update no. 1, March 2023. Milan: Rotorcraft Certification by Simulation (RoCS)  
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