ROTORCRAFT FLIGHT SIMULATION TO SUPPORT AIRCRAFT CERTIFICATION: METHODOLOGIES TO EVALUATE THE UNCERTAINTIES ON A TILTROTOR MODEL

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Abstract

The present work proposes methodologies used to assess the uncertainties for a tiltrotor model flying at low speed with the objective of providing a mid-fidelity flight mechanics numerical model that could be used for preliminary analysis in view of a Certification by Simulation campaign. The proposed technique was conceived to comply with the guidelines for rotorcraft certification by simulation developed by project RoCS. Numeric uncertainty is assessed first considering all possible sources of numerical error and identifying those who have the largest impact on the output of interest. Calibrations and uncertainty quantification analyses are performed using Dakota, an open-source toolkit which provides an interface between different simulation codes. As the first step, sensitivity analysis is performed to gain a better understanding of model parameters and their effect on the system response. Sensitivity indexes are calculated using a Variance Based Decomposition (VBD) technique which summarizes how the uncertainty in the model output can be apportioned to the uncertainty of the individual input variables. Then a calibration under uncertainty is performed using Bayesian Calibration approach. In Bayes Calibration prior distributions of input variables are updated through experimental data, in order to derive posterior distributions which are more likely to reproduce the observed data. Prior uniform distributions have been assumed for all the parameters, with a Gaussian-type Likelihood function implemented by Dakota, whereas reference test uncertainties were treated all as epistemic.

1 Notation

CbS	Certification by Simulation
CG	Center of Gravity
FM	Flight Mechanics
HIGE	Hovering In Ground Effect
HOGE	Hovering Out of Ground Effect
IFR	Instrument Flight Rules
LHD	Leonardo Helicopters Division
LOD	Level Of Detail
PB	Physics Based
SA	Sensitivity Analysis
UQ	Uncertainty Quantification
VVPM	Viscous Vortex Particle Method

2 Introduction

A newly developed aircraft must be certified before entering service by demonstrating compliance with the safety requirements set by certification authorities. Both the structure of the certification process and the means to demonstrate compliance with the regulations must be reached with agreement between the manufacturer, or more generally the applicant, and the authority. The compliance demonstration is usually performed through flight and ground tests which are usually the lengthiest and most expensive part of the certification process. Moreover, certain compliance flight tests could pose safety issues, such as those related to flight control systems or engine failures. To reduce the scope of flight test activities, and thus reduce the cost and time consumption, and lower the potential risk, advanced analysis-based methods of compliance, such as flight simulation, are being explored. For instance, Leonardo Helicopters used simulation in the certification of the engine-off landings for the AW189 [1], and tail rotor loss of effectiveness for the AW169 [2]. Both EASA's CS-27 and CS-29 Subpart B define the term "analysis-based" methods of compliance as "calculations" in the clause of "tests upon a rotorcraft of the type for which certification is requested, or by calculations based on, and equal in accuracy to, the results of testing" [3], [4]. Federal Aviation Administration

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(FAA) Advisory Circular AC-29.21(a) states “calculation” includes flight simulation [5]. FAA’s AC 25-7D §3.1.2.6 defines the general principles under which flight simulation may be proposed as an acceptable alternative to flight testing for large aeroplanes [6]. With the increase in the fidelity of physics-based rotorcraft flight simulation models, it is foreseeable that the usage of flight simulation to replace flight testing through a virtual-engineering process will become more dominant, as the industry pursues efficiency, low cost, increased safety, and low energy consumption [7]. The team of the European CleanSky2 funded project, Rotorcraft Certification by Simulation (RoCS), has the aim to explore the possibilities, limitations, and guidelines for best practices for the application of flight simulation to demonstrate compliance with the airworthiness regulations related to helicopters and tiltrotors [8]. Under the framework of the RoCS project, preliminary Guidance for the application of (rotorcraft) flight modelling and simulation has been developed in support of certification for compliance with standards CS-27/29, PART B (Flight) and other flight-related aspects (e.g. CS-29, Appendix B, Airworthiness Criteria for Helicopter Instrument Flight) [9].

This paper will present the application of the developed guidelines to the case of tiltrotor, i.e. a novel configuration for whom there is a limited experience in the certification processes that can lead in some cases to a lack of appropriate Accepted Means of Compliance with the consequent additional necessity to exploit the capabilities of simulation to assess more thoroughly potential risks associated with certification flight tests. This paper in particular will concentrate on the uncertainty analysis that is required by the guidelines to assess the credibility of the simulation model [10].

3 Research Objective

The topic of RCbS becomes of special interest when it is aimed at the exploration of flight characteristics of not yet completely explored unconventional configurations, which are expected to be widespread in the near future. The design and certification of a new conventional machine presents a lot of advantages for an OEM , among which:

- huge database of historical information;
- flight test data of older models for comparison;
- data about product of the same category from competitors;
- availability of a structured set of CS and guidelines to rely on;
- infrastructure for building and testing;
- test pilot reduced workload and time for training and familiarization on the new machine;
- configuration under consideration already known to the certifying authorities;
- etc. . . .

Figure 1: The NextGen tiltrotor developed by Leonardo in CleanSky2.

Clearly, when a completely new configuration is meant to be studied, all the above benefits lose some of their effects, like in the case of Tiltrotors of wich an example is presented in the picture of Figure 1]. Tiltrotors are designed to take off and land as a helicopter, and perform cruise flight as a fixed-wing aircraft. The classical counter-rotating proprotors placed at wing tips are typically 3–bladed. Rotor assemblies, including engines sometimes, are mounted on rotating nacelles at wing tips, to allow the conversion from helicopter to airplane modes. In aeroplane mode, the lift is produced by the wings. The control authority around the yaw axis is performed via differential control of the rotors. in the case of OEI, the other engine can provide power to both proprotors thanks to a common driveshaft. The large variability of flight characteristics among the different configurations of this rotorcraft generated by different nacelle angles requires a full fly-by-wire system which controls the flaperons mounted on the wings, rotor blade orientation and elevator angles. The engines are controlled by a FADEC. The aim of the research was to assess the level of fidelity of the tiltrotor models already available and to extend its effectiveness by improving the correlation between the numerical model and the experimental results that were gathered during past flight test campaigns. The main effort was focused on the generation of a numerical model dedicated to performing CbS for hover and low-speed controllability, with some activity dedicated to the acknowledgement of the power-off envelope, in compliance with EASA Certification Specifications. The work presented here describes only a part of the topics touched by the study of uncertainty quantification and aims at presenting the way RoCS guidelines were applied to the real case scenario of the tiltrotor in hover out of ground effect.

4 Overview of Rotorcraft Certification by Simulation Process

The Guidance follows a requirements-based approach and is presented in the form of a structured process for Rotorcraft Certification by Simulation (RCbS), as shown in Figure

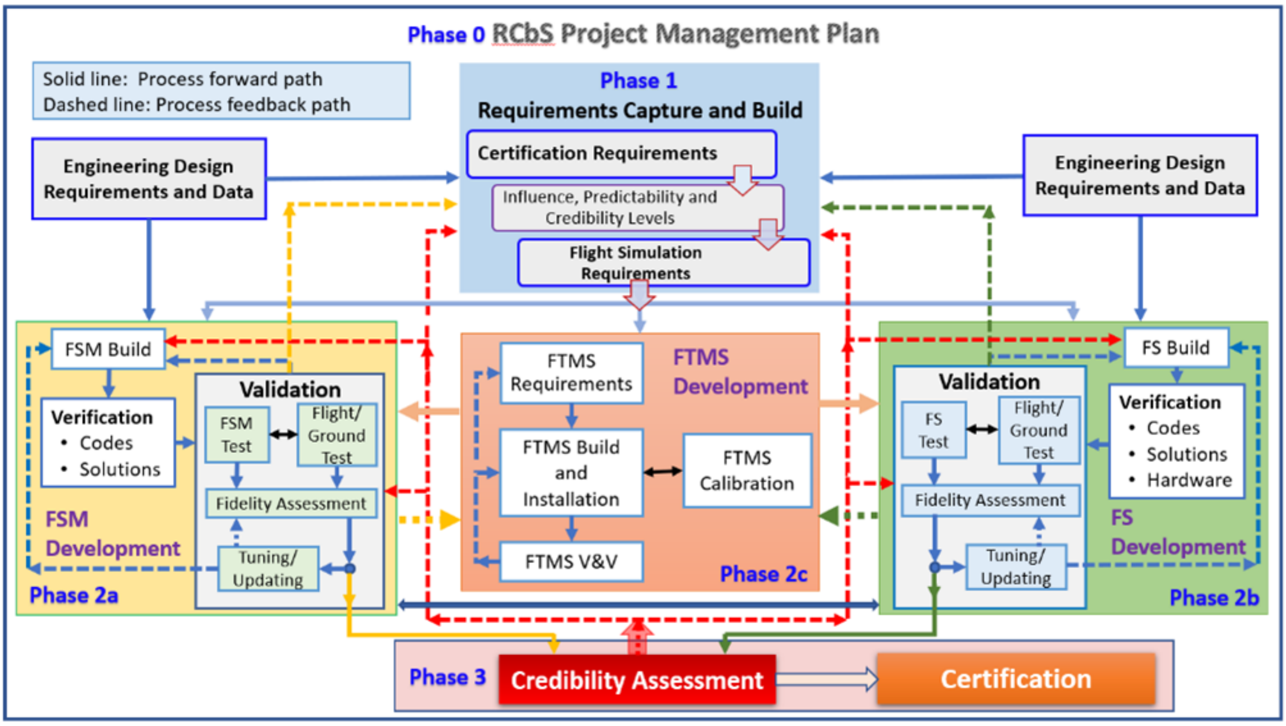

Figure 2: Block scheme of the Rotorcraft Certification by Simulation Process.

2. The process is organized into three main phases:
   - Phase 1 the requirements-capture phase, intended to understand the problem under consideration and determine the objectives of the analysis in terms of desired outcomes and required accuracy.
   - Phase 2 of model development where the flight simulation model (FSM, 2a), flight simulator (FS, 2b) and Flight Test Measurement System (FTMS, 2c) are created and validated.
   - Credibility assessment and certification.

It starts with the selection of 'applicable certification requirements' (ACRs) for the application of RCbS, with judgements on a matrix of factors of Influence (how the RCbS process will be applied), Predictability (extent of interpolation/extrapolation), and Credibility (confidence in results), in line with a comprehensive description of the assembly of flight simulation requirements (see Ref. [10]). Credibility is an assessment of confidence in using the model to perform certification tasks. Confidence is an elusive concept, but for RCbS it must be reinforced by quantitative analysis of the uncertainties in predictions and test data. The relationship between confidence and Uncertainty is established through the Confidence Ration (CR) illustrated in Figure 3. If we call M the margin, or the generalised 'distance', between the performance requirement (e.g. control limit, touch-down velocity or the damping of an oscillation) and the FSM prediction, and U the uncertainty in the prediction, a generalised Confidence Ratio can be defined as

$$CR = \frac{M}{U}. \tag{1}$$

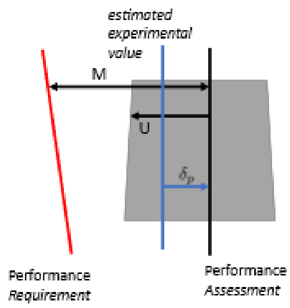

Figure 3: Confidence ratio relating a performance margin to uncertainty.

An intuitive result of this simple expression is that the smaller the margin to the performance limit, then the lower should be the uncertainty. Credibility relates to the relative size of U and M, and from a safety perspective it seems appropriate to define a minimum acceptable CR for the credibility-safety trade-off. In fact, this has been defined in the Guidelines [10] through the matrix shown in Figure **??**, where the symbols L, M, H, and VH refer to higher values of minimum confidence ratio required to perform certification analysis.

The uncertainty of a flight simulation model is typically composed of three parts: the uncertainties due to numerical errors u_{num}, those associated with experimental errors u_r, and those due to uncertainty in the input parameters u_{inp}. u_{num} can be estimated through the solution verification, while the experimental uncertainty should be determined within the Flight test campaign development and cal-

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)

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

ibrations. Uncertainty due to input parameters should be implemented through the usage of Uncertainty Quantification methods using knowledge of the uncertainty of input data provided at the initial stages of RCbS from the design department, supplemented with expert insights on the type of modelling included in the FSM.

5 Model and methods

The models used for the tiltrotor were developed using Flightlab [13], state of the art multibody software tool. Modelling activity was carried out using a component-based, physics-based approach. The model was conceived for time domain use, to better grasp the physics under each element represented. All the simulation activity was carried out mainly under a flight mechanics (FM) framework (rigid fuselage and rotors, finite state inflow and blade element aerodynamics). Various models were implemented, aimed at representing the real machine at different levels of complexity. The reason for the generation of a library of models resided, besides the need for comparison, in the necessity of having both mid-fidelity and real-time, pilot-in-the-loop models to prepare the ground for performing the assessment of the handling qualities of the machine at the simulator in the future iterations of the research. The major modifications are interesting in particular the variation of the wake models applied to the rotor and the study of the mutual interference between rotors and aerodynamic surfaces. As a first step, already available FM models were investigated in-depth, and their components were improved where necessary by using the same techniques adopted in the traditional company workflow. This initial effort was made with the objective of familiarizing with the already available and structured process of model definition and validation and having a clear idea of how to harmonize LHD standards with the technique introduced by CbS philosophy with as little disruption as possible. For what concerns the definition of the procedure, putting the tiltrotor model under the lens for the purpose of developing optimization and uncertainty analysis techniques was a fundamental exercise to understand the flaws and critical aspects that could be met when facing CbS activity for a complex, unconventional rotary wing vehicle. The next phase involved the choice of a model that could be enough representative of the real machine, without being too much detailed or too poorly descriptive. Once it was identified, RoCS guidelines were introduced. The flight condition to be analyzed was chosen, together with the corresponding CS. Predictability level matrices were defined for the CS/model pair, followed by the choice of the most critical parameters from the point of view of uncertainty quantification, extracted via engineering judgement and sensitivity analysis. The model was then analyzed from a statistical perspective to quantify the influence of uncertainty with respect to purely deterministic model analysis.

5.1 Levels of Detail

Several variations were investigated, each one with its peculiar characteristics, to establish an optimal level of detail (LOD) to concentrate on the application of the guidelines-based exercise. The focus of the model investigation was based on sorting different levels of aerodynamic subcomponents and their mutual interaction. The choice was made because historically, in FM-based models, the only way to improve correlation with experimental results resides in the appropriate tuning of aerodynamic-based elements. For HIGE, HOGE and low speed in general, wake behaviour is very difficult to predict, and often there is the need to add empirical corrections that are not directly originated from the real physics of the problem. One of the tasks carried on during the tiltrotor model development and optimization campaign involved an extensive study of the aerodynamics of the tiltrotor to provide an adequate representation of the wake. This study included the use of the Viscous Vortex Particle Method (VVPM) [15]. The results obtained were promising, but the complexity of such a numerical layout for SA and UQ would have increased of an unacceptable amount the time scale for the analysis. However, VVPM results have been used within RoCS project to assess the overall representativeness of classic aerodynamic models, namely BEM theory coupled with finite state inflow, compared to higher fidelity solutions (Figure 5).

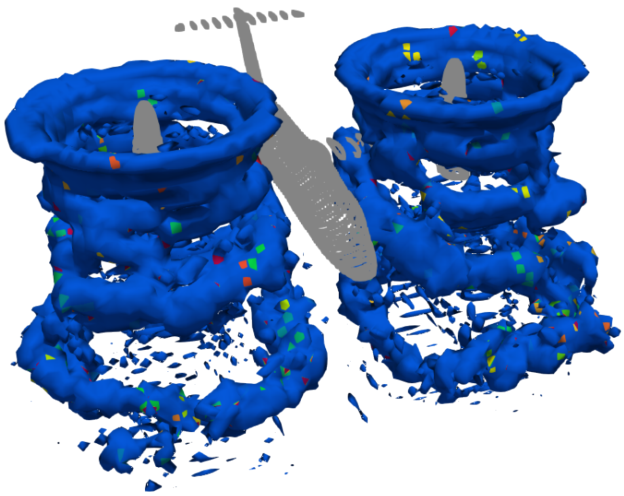

Figure 5: VVPM Tiltrotor Model.

6 Analysis Within RoCS Framework

The analysis of model fidelity was carried out under the following hypotheses:

- model was considered at an initial development stage, due to the lack of dedicated flight test data aimed at the identification of specific parameters,
- numerical simulation was required to familiarize with the rotorcraft configuration and to identify the most critical parameters to be investigated,
- for the flight condition tested (HOGE) some extrapolation might have been performed on the model for initial prediction of the flight characteristics, such as the behaviour at different atmospheric conditions.

In addition to these conditions, even if no certification credit would have been required at this preliminary modelling stage, it would be extremely useful to identify the effect of model optimization in terms of compliance with the CS relative to the flight condition studied. Being the main objective of the Certification by Simulation, the effort made to keep up with the required compliance to CS even from the preliminary phases of model development provides important added value to the next iterations of the numerical representation, where the higher LODs will increment the complexity of the analysis.

6.1 Predictability Level Matrices

Using the RoCS approach, the model was then associated with the predictability level matrices (see 4), both in terms of expected influence levels (I) and predictability levels (P), concerning the certification specifications compliance that could be influenced by model representativity at the present level of detail. Being the Tiltrotor to be certified (at least partially at low speed) under CS29 [4] some of the requirements the model was called to comply with were identified, e.g. as:

- CS29.49 - Performance at minimum operating speed for de-risking (**I1**) in domain of validation (**P2**),
- CS29.87 - Height-velocity envelope, for partial credit (**I3**) in domain of validation (**P2**) and
- CS29.341 - Gust loads, for partial credit (**I3**), in the domain of prediction (**P1**);

The concept of Domains applied in RoCS could be found in Ref. [10], and it is graphically summarized in Figure 6, whereas a complete description of them and of the influence levels is reported in Tables 1,2 of Appendix A. The definition of the predictability level matrices for the CS under investigation allowed for the identification of the target conditions with respect to which the model must minimize model error.

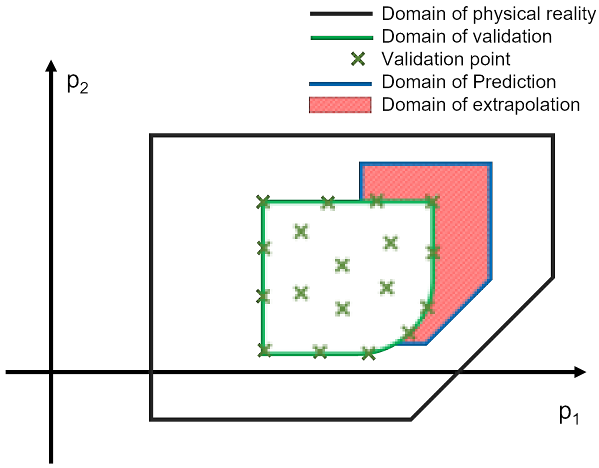

Figure 6: The Domains Concept in RcBS.

7 Assessment of the uncertainty due to numerical errors

According to the framework set by RoCS guidelines, an investigation of the uncertainty associated to numerical approximations was carried out. The assessment involved a set of fidelity metrics evaluated at trim in low speed OGE flight conditions at several azimuths. Numerical approximation uncertainties were classified and combined according to the state-of-the-art procedure summarized in [16]. Tolerances associated to both trim equations and time marching scheme were considered to estimate the iteration error. Concerning the discretization error, several model discretization parameters were contemplated (including the step for time integration, blade and fixed lifting surfaces aerodynamic segments, dynamic inflow and interference model states [17]). Round-off error was neglected.

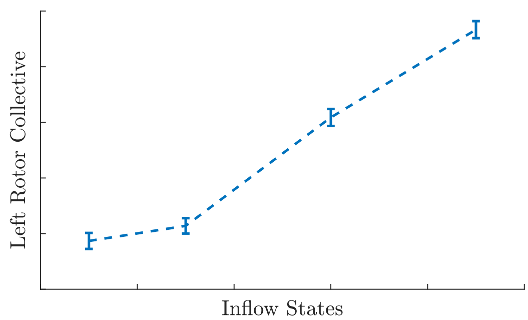

Figure 7: Left rotor collective variability due to inflow states truncation and other discretization parameters.

As a result of the estimation procedure, a chart like the one reported in Figure 7 was obtained for every fidelity metric in each flight condition. In such chart, the variability of the metric (left rotor collective in this instance) with respect to the number of inflow and interference states can be appreciated. In addition, the error bar on each point represents the combination of all the remaining numerical error estimates,

due to iteration error as time step and aerodynamic segments discretization. This effective numerical uncertainty decomposition comes in handy to isolate the inflow error behavior and, therefore, to draw several observations.
First of all, Figure 7 highlights the magnitude difference between the uncertainty associated to inflow discretization (dotted line) and the uncertainty due to the remaining parameters involved (error bar amplitude). Thus, for this model and considering the typical flight simulation execution time constraints imposed by industrial applications, the numerical error due to inflow and interference states truncation is dominant. Secondly, while the uncertainties owed to trim equation tolerances, aerodynamic segments and time step converge to zero as the discretization improves, the same behavior was not observed for the examined inflow states samples. Therefore, the numerical error due to inflow states truncation was not confidently assessed either. As a consequence, accounting for this uncertainty as part of the model error is likely to be more reasonable.

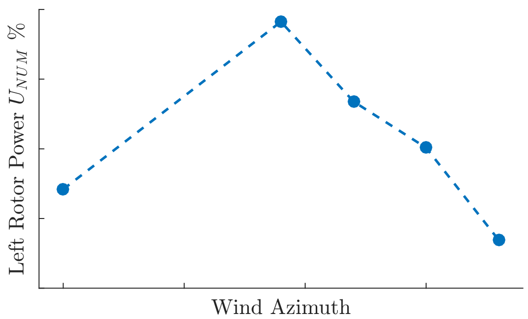

Figure 8: Left rotor shaft power uncertainty due to numerical approximation.

The results clearly highlight that the Peters-He inflow model [21] does not show a monotonic reduction of the error with the increase of the number of states. Consequently, it seems that the availability of an experimental charaterization of this aspect is needed to correctly calibrate the numerical models. This could be generated either through an experimental assessment or through the availability of more reliable (and robust) numerical models, e.g. mid-fidelity simulation tools (see Ref. [22]) or CFD analysis of the flow field. In any case a significant level of uncertainty should be associated to models due to this modelling element to ensure the appropriate reduction of risks.

Eventually, building on the aforementioned considerations (which extend to all the metrics involved in this study), the numerical approximation uncertainty was retrieved as a function of the wind azimuth (Figure 8). Such information may then be exploited as a fundamental piece of information for model bias error estimation, according to RoCS guidelines.

8 Assessment of the uncertainty due to input

8.1 Critical Parameters and Target Parameters

After the definition of the predictability level matrices and the corresponding targets, an extensive sensitivity analysis was carried out to identify the most critical parameters to be used as tuning factors for the model optimization. After the selection of these fields of practical interest, based on qualitative considerations and engineering experience, the most influential input parameters were chosen quantitatively through a numerical sensitivity analysis approach. This was carried out by computing sensitivity indices through Variance-Based Decomposition (VBD) technique, which summarizes how uncertainties in model outputs can be linked to uncertainties of single input variables. VBD is a technique that allows to identify the global senstivity to a parameter, as opposed to the local sensitivity identified through local partial derivatives and often identified through finite difference approximation. The VBD assesses the relative influence of parameters over the entire input space identifying the general trend of the ouptut under consideration of all values of the considered input including the evaluation of the inter-dependency among several factors (see [19] for more information).

For the flight condition considered, the most critical parameters extracted from SA were the position of the CG and the rotorcraft's total mass. Regarding the target parameters, for HOGE the flight test data to be taken as reference were:

- Torque and/or Power: indicative of a correct prediction of performance;
- Collective pitch: useful to read potential compliance effect of the kinematic chain at the different configurations flight test were carried out;
- Flapping angles: indicative of the correct orientation of the rotor disk in the model.

The choice of targets was based on educated guess historical knowledge and engineering judgement.

8.2 Sensitivity Analysis and Uncertainty Quantification

Sensitivity analysis was performed in the areas in the vicinity of the corner points of the flight envelope. This meant that only a limited number (i.e. the most critical) HOGE flights were chosen among the ones available in LHD flight test database. The reduced amount of reference flight test data was done to minimize the already high amount of time required by the Dakota–Flightlab coupled routine [11]. SA an UQ were applied on Flightlab models by using the coupling technique shown in Figure 9. This metodology is generalized and can be used for any type of iterative analysis

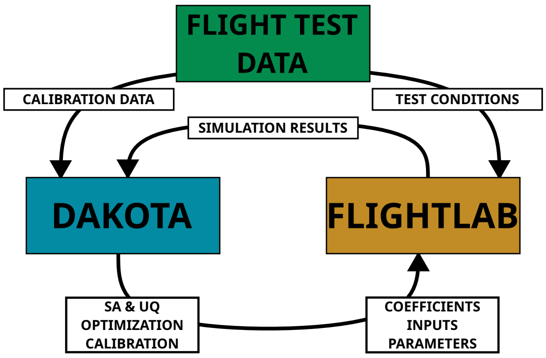

Figure 9: Schematic description of the Dakota-Flightlab coupling technique.

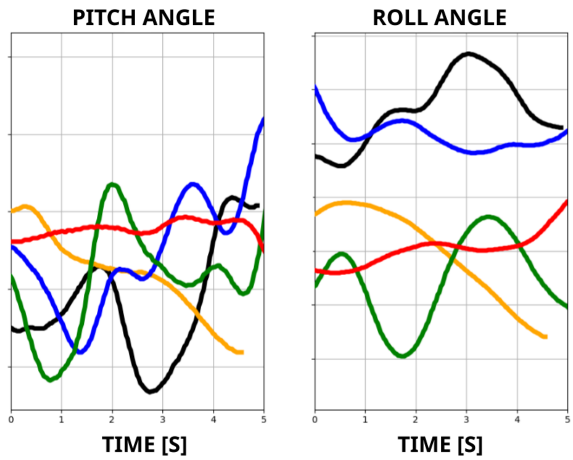

Figure 10: Variability encountered during HOGE flight test trimmed conditions. Each colour refers to a single flight test.

involving Dakota and any kind of model. A part of flight test data is used to set the calibration reference data for Dakota, while another subset of experimental results is applied as test conditions and input parameters for the Flightlab model. During the coupled loop, the simulation results coming from the numerical rotorcraft solver are processed by Dakota, which compares them with the calibration data, process them using the desired method and proposes a new set of calibration and uncertain input parameters to the Flightlab model. The result is a physic-based calibrated model joined with the availability of the input uncertainty that can be used to perform a UQ analysus and provide the $u_i np$ value. A more detailed description of the approach used here can be found in Ref. [20].

For the flight conditions under evaluation, SA to identify as most critical parameter CG position and mass values was performed by Dakota by performing random hypercube sampling [18] [11]. UQ was carried out on the same flights. For UQ, time histories of the flights were collected and minimum, maximum and mean value of the target parameter ranges were extracted. The variability of the targets was not directly and quantitatively relatable to any specific cause, such as errors in the sensors readings, machine perturbation from trim conditions due to environmental results or pilot's undesired control input. To give an idea, Figure 10 shows the variability of roll and pitch angles encountered in HOGE in 5 seconds of flight. A proper trim condition cannot be clearly identified, and a pure deterministic approach to isolate steady flight would introduce an high degree of uncertainty in the numerical results produced with the models. Therefore, target parameters were considered having an epistemic[1] uncertainty. For what concerns critical input parameters, they have been considered as statistical input variables. Given the epistemic nature of the parameters the initial distributions have been taken as interval distributions, interpreted as uniform probability distribution in the range under consideration. These interval were characterized by a mean value extracted from flight test data and a standard deviation which came from the an engineering judgement assumption that an uncertainty in the measure of mass and CG position of $\pm 5\%$. The information about real uncertainty levels coming from sensors and flight data measures to carry on a systematic statistical analysis were not directly available and, in many cases, they were the result of educated guesses or based on historical data gathering provided by flight test experts. However, in the framework of certification by simulation this level of information may not be sufficient to build a procedure solid enough to be accepted by the certification authorities.

[1] Epistemic (aka sistematic) uncertainty: due to things one could in principle know but does not in practice. This may be because a measurement is not accurate, because the model neglects certain effects, or because particular data have been deliberately hidden.

Using a Bayesian Calibration (see [20]), calibrated input variable uncertainties have been identified as Normal Gaussian distributions shown in Figure 12. Bayesian calibration methods take prior information on parameter values (in the form of prior distributions) and observational data (e.g. from experiments) and infer posterior distributions on the parameter values. When the computational simulation is then executed with samples from the posterior parameter distributions, the results that are produced are consistent with the experimental data Ref. [20].

Figure 11 shows an example of the longitudinal flight envelope of the machine. The red squares are the corner points, analyzed points' nominal values are the green circles. the error bars are representative of the uncertainty range in the input parameters considered in the study. The uncertainties associated to the parameters introduce the statistical framework to the analysis. Latin Hypercube sampling was carried out with a relevant amount of weight and balance combinations to guarantee a suitable variability of the input combinations driven by uniform uncertainty distributions.

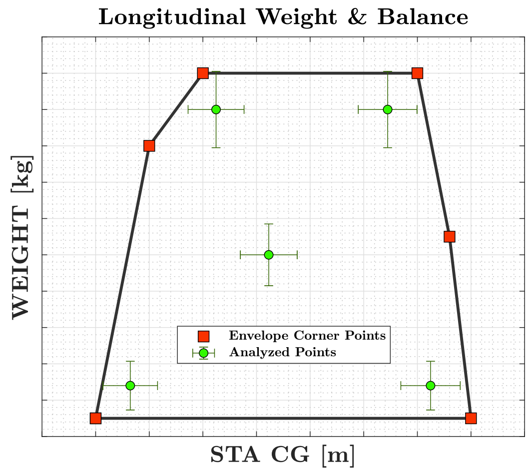

Figure 11: An example of Longitudinal Weight & Balance Envelope.

8.3 Results and considerations

A summary of the results obtained is shown in Figure 13, where torque for one of the rotor output prediction is compared. The black range represents the variability identified looking at the experimental output. The green dot is the result of the computation obtained considered the nominal value of the parameters, that is outside the range of cases that would be obtained using the variability of the input parameters considered. However the use of statistical input variables identified through the Bayesan Calibration allowed to obtain from the numerical model a statistical distribution of the output that is more representative of the experimental results, improving the correlation with flight test data. If the traditional model, based on purely deterministic input, seems to be not representative of the real rotorcraft, the one based on the statistical considerations discussed above shows, in term of distribution, a good matching with the epistemic results obtained with flight test data.

From the results obtained it is possible to draw the following considerations:

- In order to consider a model valid it is not sufficient to take into account only deterministic conditions
- Statistical description may give significance even to a simple model, apparently not sufficient to describe with enough accuracy the experimental results
- For the cases here analyzed, the model showed, under probability distribution assumptions, good correlation compared to the epistemic uncertain experimental data
- A statistical model, under some conditions, can be used to anticipate certification requirements even at the early stages of development, for de-risking purposes and/or for extrapolation.

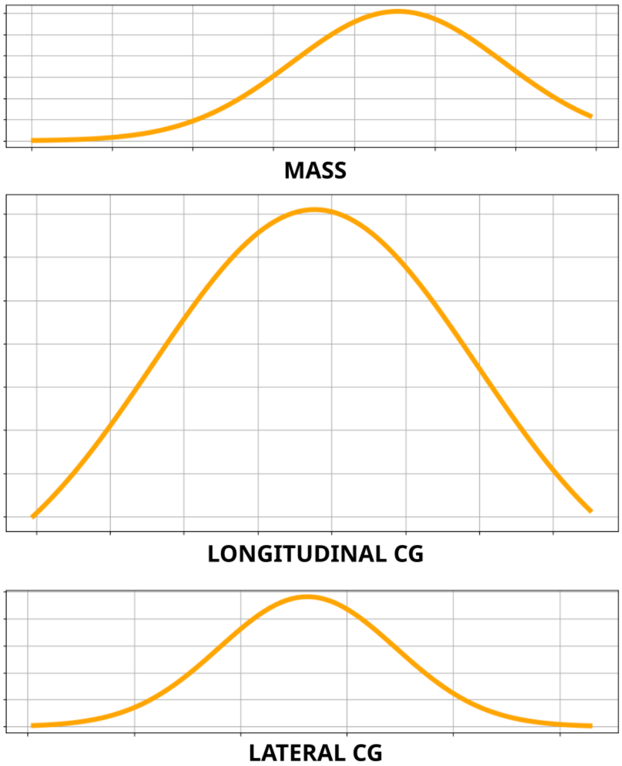

Figure 12: Critical input variable are considered as statistical quantities. The vertical axis contains the probability density while the abscissa is related to the values of the quantity of interest.

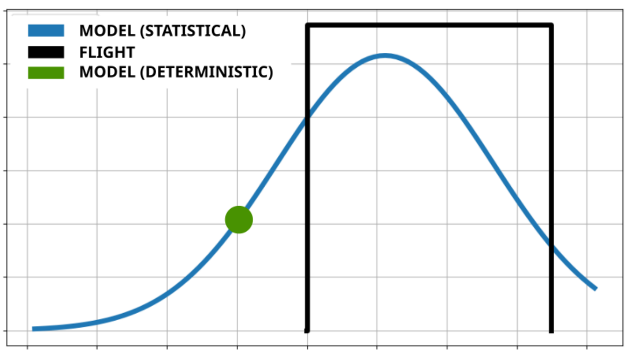

Figure 13: Comparison between deterministic model results, statistical model and epistemic flight test data.

- Significant improvement in the correlation may be obtained by performing Bayesian calibration on the flight test data to refine the definition of input distributions.

9 Conclusions

The paper presented some simple examples applied to a tiltrotor of procedures to identify the numeric and input uncertainties to be then used for the credibility assessment of a model used for Certification by Simulation. The paper showed that by using available software, e.g. Dakota, together with some engineering judgment it is possible to easily set up a framework that allows for the characterization of these types of errors in simulation models. The simple exercise performed showed that the level of uncertainty that could be introduced may be significant, especially if there are no flight test data specifically developed for the model validation. This may lead to the necessity to use safety factors, that may hider the possibility to proficiently use the certification by simulation approaches. While calibration of physical model can, and should be used, as shown here, the process must be done in a way that accounts the effect of calibration in the evaluation of the uncertainty, so that a stronger calibration always results in a larger uncertainty.

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A Influence Levels and Domains

Domain	Description
1. Domain of Prediction (DoP)	Tthe 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. 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 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.
3. 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’.
4. 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, e.g. activity in the DoE include high (safety) risk failure cases and static/dynamic stability assessment at extreme atmospheric or aircraft loading conditions.

Table 1: RoCS domains, from Section 3.2 of Ref. [10].

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. No certification credit is obtained.
II Critical Point Analysis	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.
IV Full Credit	Supplementary flight tests will need to be performed to obtain full credit. This category is for cases where certification flight tests for a specific ACR are replaced by simulation.

Table 2: RoCS influence levels, as described in Section 3.2 of Ref. [10].