Validation Criteria for Helicopter Real-time Simulation Models

Sketches from the Work of Garteur HC-AG12

Gareth D Padfield
The University of Liverpool, UK

Marilena Pavel
TU Delft, The Netherlands

Didier Casolaro
Eurocopter, France

German Roth
Eurocopter, Germany

Mario Hamers
DLR Braunschweig, Germany

Armin Taghizad
ONERA, Salon-de-Provence, France

This paper presents an overview of the work of GARTEUR Action Group HC-AG12 tasked with examining the process and criteria used in the validation of helicopter flight simulators. The paper assesses the strengths and weaknesses of the present standard for the qualification of helicopter synthetic training devices, JAR-STD-1H, with particular reference to the simulated flight model, and is composed of a number of 'sketches'. In the first, current industry experience of qualifying a helicopter flight simulator to the JAR-STD is presented, highlighting that, while the standard is comprehensive and challenging, improvements in the fidelity criteria and qualification procedures would be beneficial. Trying to answer the question - whether meeting JAR-STD standard will always guarantee a model sufficiently representative of the real world - the paper presents results from sensitivity studies into the suitability of the JAR tolerances. The work has shown that the tolerances are highly sensitive to the nature of the manoeuvre performed and the modelling errors introduced by the simulation model. Especially when trying to validate complex and long running manoeuvres, the errors introduced by modelling (such as deficiencies in the rotor model, engine model interaction from the rotor on fuselage, horizontal or vertical tail), the value of discretisation used in the control inputs from flight tests and the use of flight test data gathered in turbulent conditions, may create difficulties in meeting the requirements for a level D simulator. In addition, the simulator tolerances may introduce large inaccuracies in assessing the performance according to the ADS-33 handling qualities standard. For a Bo-105 helicopter it is shown that although a simulation model subscribes to JAR tolerances, the HQ ratings when compared to the flight test data may be quite different. The simulator errors originating from the tolerances may also, in some cases, accumulate while in other cases tend to cancel each other out. This may introduce problems when judging the safety of a new manoeuvre performed in the simulator with the risk of inducing negative transfer of training to pilots. Finally an approach to overall simulation system fidelity is described using an adaptive model of the coupled pilot-aircraft system.

Notation

A matrix of motion derivatives
a_1 longitudinal disc-tilt angle (a_1>0 for disc plane tilting forwards) [deg]
B matrix of control derivatives
C coeff. in the downwash at the horizontal tail (C=1.2) and vertical tail (C=0.7)
C_{Ds} helicopter drag coefficient [-]
C_l^{α} lift slope
$C_{T\,elem}$ rotor thrust coefficient calculated in blade-element theory [-]
$C_{T\,Glau}$ rotor thrust coefficient calculated in Glauert theory [-]
g gravitational acceleration [m/sec^2]
h vertical rotor hub position [m]
I_R moment of inertia of rotor and transmission system [kg m^2]
I_y helicopter moment of inertia about body y-axis [kg m^2]
$K_X, K_{\dot{X}}$ pilot range and velocity gains in the adaptive pilot model
K_1, K_2 coefficients in the power equation for optimally controlling the induced power after engine failure
K_3 droop constant indicating the reduction in steady-state rotor speed between autorotation and full power K_3=0.8 [-]
k_1, k_2 gains in the longitudinal cyclic pitch controller
m helicopter mass [kg]
n_z load factor [-]
p helicopter roll rate [rad/sec]
P_{eng} engine power (KW)
P_{AEO} power all engine operative
P_{OEI} power one engine inoperative
P_{req} power required
P_{pr} profile power
P_{par} parasite power
P_i induced power
P_m miscellaneous power
P_c climb power
P_{av} power available
P_{iav} induced power available to generate the inflow through the rotor after engine failure
P_{ireq} induced power required after engine failure

P_{iuse} induced power used after engine failure
q helicopter pitch rate [rad/sec]
q_{ref} reference (desired) pitch rate
r helicopter yaw rate [rad/sec]
R rotor radius [deg/sec]
t time [sec]
t_p engine time response t_p=0.5 sec
T rotor thrust $T = \rho(\Omega R)^2 \left(\pi R^2\right) C_{Telem}$
u horizontal body velocity [m/sec]
u vector of control variables
v lateral body velocity [m/sec]
$V_{ind,mean}$ medium induced velocity
w rate of descent [m/sec]
w_{des} desired touchdown speed after engine failure w_{des}=1.3 m/sec
x vector of state variables
α_c angle of attack in the rotor tip path plane [deg]
β thrust inclination angle
δ_x longitudinal cyclic stick (%)
δ_y lateral cyclic stick (%)
δ_p pedals (%)
δ_0 collective stick (%)
θ Euler pitch angle
θ blade pitch angle
θ_0 collective pitch
θ_{1s} longitudinal cyclic pitch (θ_{1s}>0 for stick forward)
θ_{ref} reference (desired) pitch angle
λ_c inflow ratio $\lambda_c = \frac{V}{\Omega R}\sin\alpha_c$
λ_I dynamic inflow coefficient
μ advance ratio
ρ air density [kg/m^3]
σ rotor solidity
τ time-constant of the dynamic inflow τ = 0.1 sec
ω_X, ζ_X natural frequency and relative damping in the adaptive pilot model
Ω rotor rotational speed
Ω_i idling speed

1. Introduction

Flight simulators have nowadays become indispensable tools for training, product development and research. Despite the advancement of modern technology, a flight simulator cannot perfectly represent the aircraft in all aspects: the mathematical model of the aircraft is never fully accurate, and the motion and visual systems have physical limitations that make the full representation of the sensation of flying always less than perfect. Regulatory authorities have established standards to be used by the manufacturers and operators of simulators, or more generally synthetic training devices, in the process of acceptance and certification of their products. For helicopters, the recognised European qualification standard is JAR-STD 1H [1], against which helicopter models have to be validated. This validation standard contains a large number of individual tests and associated criteria, many of which were defined based on FAA Advisory Circular AC 120-63 [2]. Such criteria are formulated by using "tolerances". Tolerances are defined as acceptable differences between the model results and flight test data. What is not clear is whether meeting this standard will always guarantee a model sufficiently representative of the real world that the simulator is fit for purpose; there is simply no supporting data or analysis to judge one way or the other.

GARTEUR (*Group for Aeronautical Research and Technology in Europe*) has engaged the rotorcraft industry and research laboratories on the topic of helicopter modelling for flight mechanics and handling qualities for a number of years (see for example [3] and [4]), with a focus chiefly on developing an improved understanding of the fidelity requirements for research, design and development. The most recent of these initiatives, GARTEUR HC Action Group - AG12, has re-focussed on real-time simulation models for flight simulators. The present paper presents an overview of the work performed by this Action Group. Sketches will be presented from recent industry experience of qualifying a flight simulator to the JAR-STD, alongside various sensitivity studies into the suitability of the JAR tolerances. AG-12 has tackled several questions related to JAR-STD, such as:

- what is the sensitivity of JAR-STD-1H fidelity to modelling errors?
- Are the JAR-STD-1H tolerances fine enough that they lead to only minor changes in handling qualities?
- If the physical models do not satisfy the tolerances, what tuning is acceptable and what is the tuning process?
- What is the effect of modelling fidelity on the overall pilot control strategy?

The paper is structured as follows:

- The 2nd section discusses the background to the tolerances prescribed by JAR-STD,
- The 3rd section gives a description of recent industry experience at Eurocopter on qualifying flight simulators to JAR-STD, revealing strong and weak points in JAR-STD-1H,
- The 4th section investigates the sensitivity of JAR-STD-1H fidelity to modelling errors when certifying a landing manoeuvre,
- The 5th section analyses the effects that the JAR tolerances may introduce in handling qualities investigations performed in the simulator,

- The 6th section gives an example of the errors that can be introduced by the simulator when testing new piloting strategies,
- The 7th section describes an approach to overall simulator fidelity using an adaptive pilot model,
- Finally, general conclusions and recommendations from the work of GARTEUR AG-12 are presented.

2. Background and origins of the tolerances prescribed by JAR-STD-1H

The intention to develop guidance for qualification of helicopter flight simulators became clear in late 1982 with the publication of a draft document by the Federal Aviation Administration (FAA) entitled "Guidance and Procedures for Helicopter Simulator and Visual System Evaluations" [5]. This document presented procedures, guidelines and criteria against which helicopter simulators could be qualified for use in training under Federal Aviation Regulation (FAR) 135.335 [6]. Later, in 1984, Ref 5 was improved and published as the first draft of the FAA Advisory Circular AC "Helicopter Simulator and Visual System Qualification", being exclusively dedicated to helicopter simulators [7]. Generally, this draft document was very similar to the FAA AC 120-40 "Airplane Simulator Qualification" document [8], as issued in 1984 for airplane simulator evaluation; containing the same basic policy and procedures as that for airplanes, with the appendices tailored to helicopters. Validation tests were divided distinctively into performance validation and handling qualities validation. In each case, validation parameters were identified and tolerances between simulator behaviour and flight measurements were assigned. There was no related background document to explain the basis or rationale for the various tolerances assumed in this first draft, but it is certain that these tolerances were based on the experience gained from both helicopter and fixed-wing test programmes. The FAA Advisory Circular AC draft as published in ref. [7] was further analysed by a working group and revised according to the many recommendations made [9]. The limitations on the tests imposed for flying at low speeds (<30 kts) and at altitudes less than 50ft had to be investigated, since the helicopter simulators operating at that time featured particular deficiencies in these flight regimes.

It is obvious that twenty years ago helicopter simulator development lagged that for airplanes and this was also the case for helicopter simulator qualification standards. Since then, continued efforts have been made by the simulator manufacturers to improve the capability available to helicopter training organisations. Through test programs and capitalising on industry experience, efforts were focused on adapting and revising continuously Ref 8 in order to identify and quantify the deficiencies observed in helicopter simulators. This resulted in 1994 with a 'baseline' document dedicated exclusively to the qualification of helicopter simulators – FAA Advisory Circular AC 120-63 "Helicopter Simulator Qualification" [2] – providing "*an acceptable means… for qualifying helicopter simulators to be used in training programs ….*".

In the meanwhile, during 1990 and 1991 a working group representing the international flight simulation community [10] and sponsored by the Royal Aeronautical Society, attempted to harmonize different flight simulator standards existing worldwide (Europe and America) and to establish commonly recognized standards for the qualification of flight simulators. These new standards are referred to as the Joint Aviation Requirements (JAR) and have been recognized by the Civil Aviation Authorities of the European countries as an acceptable basis for showing compliance with their national airworthiness codes. For airplanes, the commonly recognized standard for qualification of flight simulators is the so-called JAR-STD 1A [11]. This standard was developed first by reviewing the validation tests and the tolerances imposed in the FAA Advisory Circular 120-40B [12] and then by developing a coherent methodology for compliance. For helicopters, the commonly recognized standard for qualification of flight simulators is JAR-STD 1H [1] and was developed, in essence, from the FAA AC 120-63 [2]. JAR-STD 1H is still under development, with the philosophy that "*JAR-STD 1H should be applied in practice and the lessons learned embodied in future amendments*".

It is a goal of GARTEUR group HC/AG-12, to contribute to the international effort that focuses on improving the JAR-STD 1H criteria existing for helicopter simulator qualification.

3. Current experience on qualifying flight simulators in JAR-STD 1H

This first sketch is drawn from the recent experience at Eurocopter with the qualification of the HELISIM facility [13] to Level D standard. Four levels of qualification exist in JAR-STD 1H (A, B, C and D), the highest being level D that allows the replacement of most of the flight hours required for a type rating, or for recurrent training, by simulator hours. Zero flight type rating in a simulator, allowed with a level D qualification, is only possible if the pilot feels that the simulator is highly representative of real flight. It is often 'emphasised' by Authorities during the qualification phase that a level D training simulator must be "perfect". Level D qualification depends on quantitative tests with tolerances on

parameters defined and subjective pilot opinion about the behaviour of the simulator in relevant manoeuvres. Quantitative tests can be classed in three main categories:

1. performance tests,
2. handling qualities tests,
3. trajectory tests (inc. approach, landing and take off), this last category demonstrating the behaviour of the simulator over a wide flight envelope.

As flight test data is the raw material of tuning the flight model, the flight testing needs to be considered very carefully. Consistency of flight data with the requirements of the qualification standards has to be verified, to be able to associate each requirement with a portion of a flight. Additionally, verifying the consistency of the measured parameters is a task of outstanding importance which will govern all of the tuning process. JAR requirement tolerances are so fine that they must truly represent the difference between flight data and simulation, and not to be absorbed by differences of the measurements between two different flights. Software packages used by Eurocopter's Flight Test Centre have been used and enhanced for this task which has to be accomplished within a very short time window. Indeed, asking for new data is only realistic if the helicopter is still available and the measurement equipment still on board.

A ten hour flight test campaign (even more for helicopters for which several aerodynamic configurations have to be simulated) is the minimum necessary to ensure that all the required tests for JAR-STD 1H level D qualification are covered. Such an amount of data cannot be managed without dedicated processing and analysis software. Furthermore, several individual engineers will use these data at the same time and all the files have to be made secure; software coming up to these expectations has been developed and linked to the test database, to facilitate the analysis of these data in a safe environment.

The tuning process. State-of-the-art flight models give a good estimation of the real helicopter if all the parameters required for each test are correctly set. However, Level D certification requirements are so demanding that some parameters and some parts of mathematical models have generally to be improved. This is the primary task - tuning data sets and mathematical models to bring the model as close as possible to the final level required. Once this is achieved, the adjustment process takes over from model tuning in order to refine the model for all the parameters and for all of the required tests. Experience suggests that even if it is not explicitly asked for in JAR-STD 1H, all the parameters for each test will be monitored by the Authorities. Throughout the tuning process, quantitative criteria defined by standard tolerances on checked parameters and pilot subjective remarks are taken into account. Figure 1 summarises the 'global tuning' process.

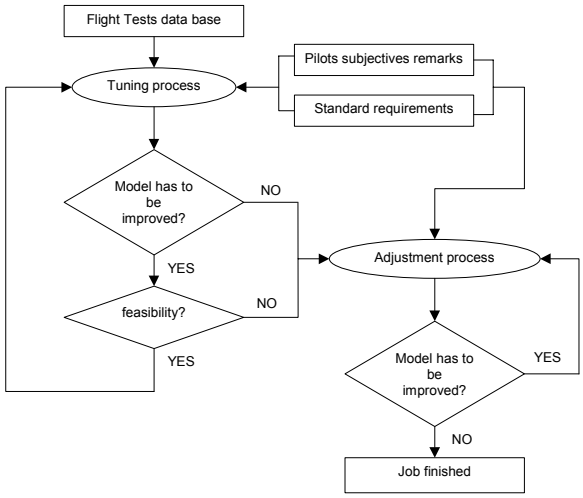


Figure 1 Global tuning process

The initial phase of the process, described as "Physical tuning", focuses on corrections that directly change model data based on physical reasoning. These corrections can be applied to data sets, for example, to modify an aerodynamic coefficient, or within the mathematical model to improve the influence of a phenomenon where modelling was insufficiently accurate. This process provides a flight model which can be very close to the final level required. For example, at the end of physical tuning, about 80 % of the trim tests are typically in accordance with JAR-STD 1H requirements. Final adjustment takes over from this tuning process when adjusting physical parameters no longer gives improvements to the match.

Even if measurement consistency is ensured in the upstream pre-process, some minor differences may still appear from one flight to another; this consistency is estimated in a range of acceptable values. The result is a slight scattering of measurement for the whole flight envelope to which have to be added measurement errors and the lack of precision for some parameters such as wind speed and direction. All of this makes it is very difficult even for a perfect mathematical model to stay as close to measurement as demanded by standard. Furthermore, all the physical phenomena involved in helicopter dynamics cannot be fully represented in a mathematical model; therefore, numerical methods must be used to enhance model accuracy and remain in accordance both with quantitative tests and pilot opinion. The corrections brought by this process are marginal,

since the major part of the task has been accomplished through the physical tuning process, but it is essential to meet all the required tolerances in accordance with the requirements

Figures 2-4 show an example of comparisons between simulation and flight for the AS365 N2; the input is a lateral cyclic pulse from a mid-speed flight condition, applied at about 26 secs and brought back to trim at 28 secs. Fig 2 shows the comparison before tuning, Figure 3 after physical tuning and Figure 4 after adjustment and final tuning. The plots show pitch, roll and sideslip angles and pitch, roll and yaw rates.

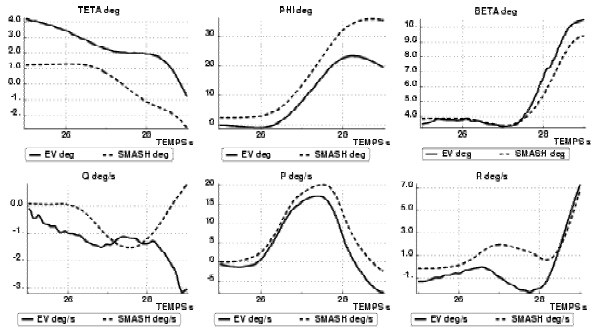


Figure 2 AS365 N2 – Typical result before any tuning

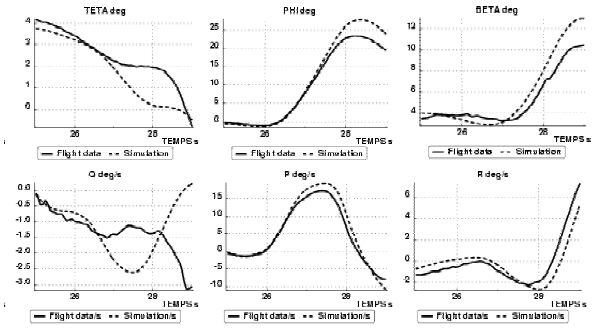


Figure 3 AS365 N2 – Typical result after physical tuning

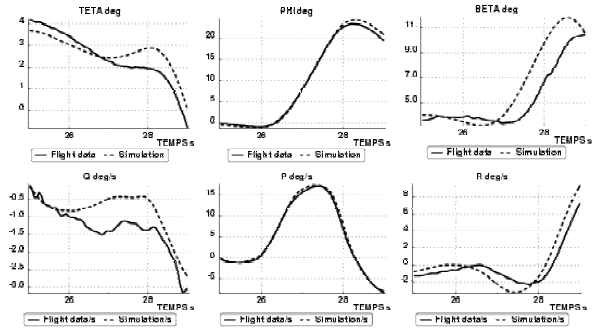


Figure 4 AS365 N2 – Typical result after adjustment and final tuning

Figure 4 shows results that meet the JAR requirements and, without going into details of how this was accomplished, it is interesting to highlight some important effects. Initially (Fig 2), the error in roll attitude is about 50% after only 2 seconds, largely due to a more rapid build up in roll rate in the simulation. The aircraft appears to yaw initially to starboard in the simulation and to port in flight. The flight data shows an initial nose up pitch attitude of 4 degrees, decreasing at about 1 deg/sec (out of trim), while the simulation is trimmed steady at 1 deg nose up attitude. The build up in positive sideslip is slightly stronger in flight, increasing from 4 degrees initially to 10 degrees after only 3 secs. The physical tuning process (Fig 3) has changed the initial conditions in the simulation (no longer in trim, hence more correctly reflecting flight) and achieved a much closer match for the roll and yaw motion. The simulated sideslip now increases to about 13 degs. In the final adjustment (Fig 4) the close match for roll and yaw motions has been achieved partly at the expense of the sideslip behaviour, which is not a checked state in the JAR-STD 1H process. The measurement of sideslip is notoriously difficult however and the result might be interpreted as a correction to the flight measurement. However, additional measurements could be made to check the sideslip response to cyclic, including simple steady heading sideslip which would provide the relationship between lateral cyclic and roll angle as a function of sideslip, thus providing substantiation of both the physical tuning and adjustment processes. The ratio of roll to sideslip during turning manoeuvres is an important handling qualities parameter, for which criteria exits (e.g. ADS-33E-PRF [14]). If the ratio and phasing (during the Dutch roll mode) are different in the simulator compared with flight, there is the potential for pilots to experience different motion cues, although they may not be aware of the source of the difference. In the present sketch this feature is highlighted as one potential area where the JAR-STD 1H requirements may be inadequate for capturing true fidelity.

The flight model can be tuned using an off-line version of the model which will later be integrated into the simulator. After this integration has been accomplished, subjective tests are made in the real simulator environment. The real challenge at this stage is to keep all the required quantitative tests in accordance with requirements, while at the same time, resolving all of the unrealistic behaviour highlighted by the pilot during pilot in the loop assessment. Although monitored during the whole process, the model accuracy for take off and landing manoeuvres is fully optimized during the tuning process. These tests can be further optimized using control position adjustments. JAR-STD 1H allows 10 % tolerance for control position in order to demonstrate the

behaviour of the simulator for a wide flight envelope (such manoeuvres cover speed range from 0 to 70 knots forwards and vertical speed from –1000 ft/min to 1000 ft/min). Other tests can also be considered even if JAR-STD 1H does not define tolerances on control positions. Small adjustments, within the measurement accuracy, can be used to improve the results.

4. Sensitivity of JAR-STD fidelity to modelling errors

JAR-STD requires a whole database of complex manoeuvres such as take-off (all engines and one engine inoperative), autorotation, landing (all engines and one engine inoperative) etc. to be flown in order to validate the simulator model. In this sketch the CBM model (Common Baseline model) developed during the previous GARTEUR AG-06 and AG-09 exercises (see refs. [3] and [4]), is used. Much attention was given during these exercises to determine the minimum required model for a good prediction of helicopter flying qualities. The model developed in GARTEUR AG-09 corresponded to the non-linear enhanced model (CBM_{enh}) featuring:

- Main rotor with three blade degrees of freedom (flap, lead-lag, torsion) based on equivalent system techniques,
- Stiff blades for tail rotor (no DOF),
- Pitt/Peters dynamic inflow model with corrections to momentum theory to improve power prediction,
- Empirical ground effect model based on BK117 and TIGER test results,
- Engine and landing gear model,
- Adapted downwash interaction model (downwash = C *$V_{ind,mean}$) for fuselage (C=1.2), horizontal tail (C=1.2) and vertical tail (C=0.7) aerodynamic interactions.

However, the previous GARTEUR exercises tested the CBM model fidelity only for simple step and 3211 inputs on the controls. The present investigation has concentrated on a more complex manoeuvre, i.e. the landing (all engines) manoeuvre, investigating how modelling errors influence the fidelity level obtained in the simulation. The landing manoeuvre is structured in five phases and limited to an overall duration of 50 sec: 1) Level flight at 80 kts in North direction; 2) Level turn up to 30 deg bank angle for a heading change of about 35 deg; 3) Descent at a rate of about 600 ft/min; 4) Deceleration during descent to hover 5) Touch down.

4.1 Sensitivity of landing manoeuvre to discretised control inputs from test data

Consider first the landing manoeuvre flown with the 'test data' generated by the simulation according to the block diagram in Fig. 5 using ideal conditions for landing (i.e. ideal sensors, no wind or gusts).

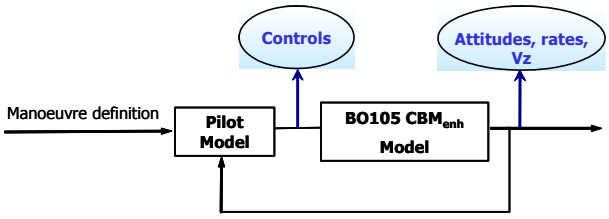


Figure 5 Simulation diagram for flying a landing manoeuvre

The pilot model in this diagram is derived from a code developed within the RESPECT project [15] - Rotorcraft Efficient and Safe Procedures for Critical Trajectories (a research program partially funded by the European Commission (CEC DG12, 4th PCRD)). The model requires the definition of forward speed or pitch attitude, vertical speed, bank angle or heading in tabulated form in the time domain. For each phase the appropriate combination of controllers can be chosen among a set of speed, attitude, torque and altitude controllers.

The CBM model uses a 1ms frame time for simulation. The controls and the usual simulation output parameters are extracted in ASCII files obtained in tabulated form normally using time steps of 10ms (100Hz).

The first exercise is to check whether the tolerances defined by JAR-STD in the landing manoeuvre can be met with the CBM_{enh} model using a standard replay technique. This means that the simulation with the Bo-105 CBM_{enh} model was re-run using the controls extracted from the reference case without any controller. Discretisation levels for the controls of 333Hz, 100Hz and 50Hz were tested. The tabulated controls with an accuracy of five digits are interpolated linearly to calculate the missing data points necessary for a simulation frame time of 1ms.

Figure 6 shows the attitude deviations from the reference landing. It can be seen that, even in these ideal conditions, the simulation starts to diverge from the test case after about 15 secs, especially in yaw, so that in the final phase the JAR limits for all attitudes are exceeded.

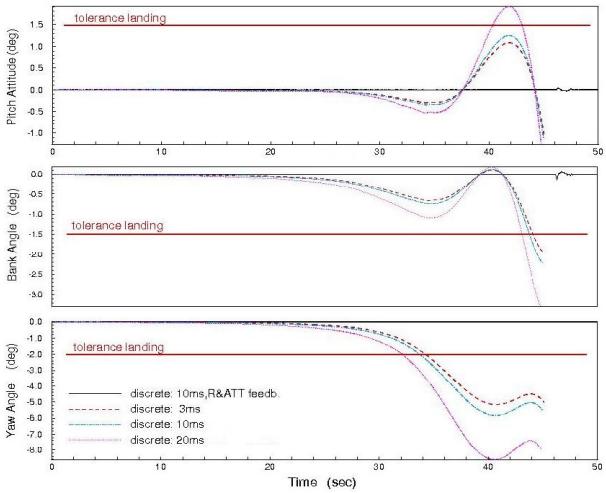


Figure 6 Effects of discretised control inputs on flying the landing manoeuvre

This behaviour is mainly a consequence of the small torque deviations (<0.2%) generated by the engine model due to the interpolated main and tail rotor collective inputs. This effect is amplified when using an engine model with high gains in the feed-forward loop for collective control.

The above problem can be solved by including a controller using rate and attitude feedback for pitch, roll and yaw axes. Figure 7 presents the new simulation diagram used to fly the landing manoeuvre.

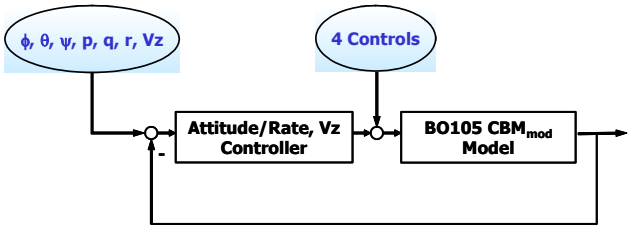


Figure 7 Simulation diagram to be used for validation of landing manoeuvre

The attitude controller used in Fig. 7 was introduced to reduce the deviations of the CBM model and is given by simple proportional-derivative (PD) controller, for example in pitch:

$$\Delta\theta_{1s} = k_1\left(\theta_{ref} - \theta\right) + k_2\left(q_{ref} - q\right) \qquad (1)$$

Using similar PD controllers for all three axes reduces the deviations when flying the CBM to negligible values. The corrective control inputs generated by the controller are smaller than 0.02 deg. The gains used in (1) should be high in order to reduce the size of the error. However, increasing the gain increases the tendency for oscillations in the controlled variables. In practice, a compromise is necessary where gains are made as large as possible without producing unacceptable oscillations.

4.2 Sensitivity of landing manoeuvre to modelling the main rotor, tail rotor and engine dynamics

Next, the CBM_{enh} model is modified in the sense that the main rotor blade torsion degree of freedom (dof) is 'frozen' and at a tail rotor blade flap dof is added to investigate the effects of these dynamics on performing the landing manoeuvre. Figure 8 presents the simulation results for 4 cases: 1) modified configuration tested without vertical speed feedback (only rate and attitude feedback); 2) modified configuration tested with vertical speed feedback and rate and attitude feedback; 3) modified configuration with vertical speed feedback in which the sample time is modified from 10ms to 20ms (to check if the modification in discretisation has a negative impact), and 4) initial configuration in which the rotor speed dynamics are modified by including a different engine model.

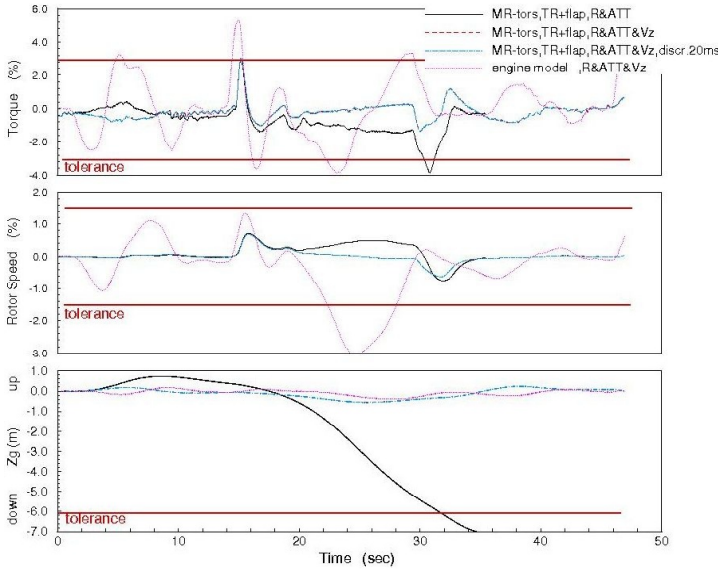


Figure 8 Sensitivity of landing manoeuvre to modelling main rotor, tail rotor and engine dynamics

It can be seen from Fig. 8 that modifying the main rotor model has a significant effect on the vertical speed and hence altitude profile during the landing manoeuvre. The helicopter reaches the ground about 10 sec too early exceeding the limits for torque and altitude. A vertical speed feedback is therefore added to compensate for this effect. When using this improved simulation model, the increased sample time within the input data shows no negative impact. As expected, deficiencies in the engine model may cause an exceedance of the torque and rotor speed tolerances, whereas the basic flight dynamics, especially the pitch and roll response, are less influenced.

4.3 Sensitivity of landing manoeuvre to inflow modelling

To explore the impact of inflow modelling on fidelity level, the following modifications are made to the initial CBM model:

- Payne/Glauert inflow instead of Pitt/Peters
- Increased pitch/roll coupling by wake distortion factor K_r=1.5 (reference case K_r=0)
- Ground effect model frozen
- All aerodynamic interactions set to zero

Figure 9 presents the results of the simulations when these modifications are implemented in the CBM. It can be seen that the effect of inflow modelling is most obvious at low speeds in the final part of the manoeuvre, due to the variations in longitudinal distribution of induced velocity in the different models. The wake distortion factor modifies the influence of pitch and roll rates on the distribution of induced velocity at the rotor disc. It is therefore most influential when the level turn at the beginning of the manoeuvre is initiated or ended. Incorrect ground effect, as well as interaction models, may cause an exceedance of torque tolerance also in the low speed range, when close to the ground.

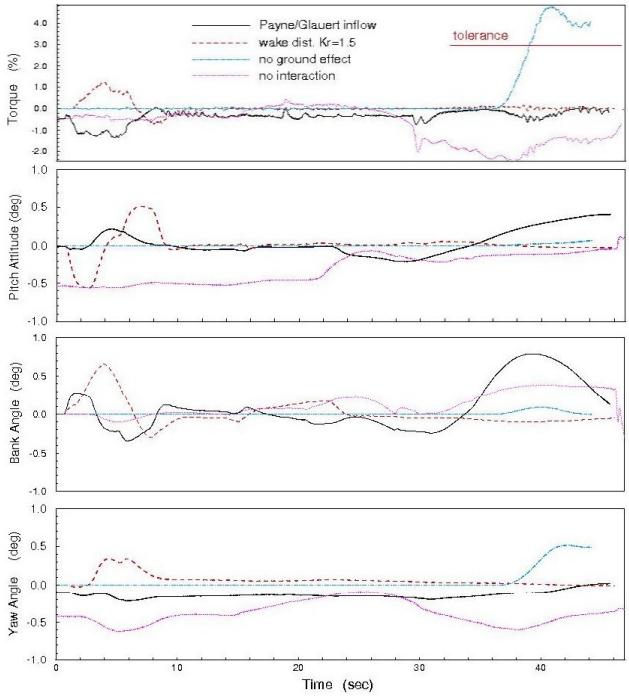


Figure 9 Sensitivity of landing manoeuvre to inflow modelling

4.4 Sensitivity of landing manoeuvre to wind and turbulence

The validation process for a model dedicated to a level D simulator is complicated due to the lack of exact wind and gust information during flight test. Figure 10 shows the effect of a constant wind of 5kts from a northerly direction, with and without a moderate turbulence generated by the Dryden model. For the simulation a controller with rate, attitude and vertical speed feedback was used and the helicopter was initially trimmed at an IAS=80kts. This results in an initial ground speed 5kts lower compared to the case without wind.

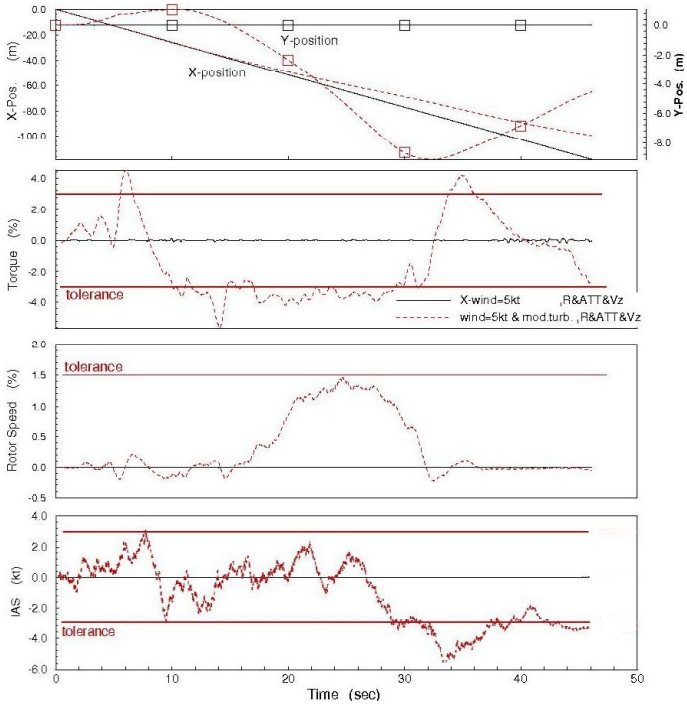


Figure 10 Sensitivity of landing manoeuvre to wind and turbulence

It can be seen from Fig. 10 that the only significant deviation caused by a constant wind, using the prescribed controller, is in the position signal. The offset in x-position divided by the simulation time gives an almost exact estimation of the wind component. However, differences appear if turbulence is applied. Depending on the horizontal and vertical wind variations, the indicated airspeed, torque and rotor speed now exceed the JAR limits. Although the controls remain within the specified limits, they will often not show the right trend as the controller compensates for the gusts to hold the attitude, for example. This might be an item of concern and complaint by the certification authorities.

The purpose of this exercise was to investigate JAR-STD fidelity when flying a complex manoeuvre and to determine its sensitivity to modelling errors. Concerning the discretisation and the limited accuracy (number of digits) of control inputs from flight test, it is concluded that this could prevent a successful re-simulation of complex and long running manoeuvres, unless an attitude controller is included in the simulation loop. For the validation of a landing manoeuvre the feedback of vertical speed or altitude seems to be mandatory to cancel model deficiencies in vertical axis. The attitude/vertical speed feedback

method will not correct position errors, although specific position tolerances are not currently defined in JAR-STD 1H.

The effects of modelling changes can be summarized as follows:

a) The aerodynamic interactions from the rotor onto the fuselage, horizontal and vertical tail influence especially speed, torque and position,
b) Deficiencies in the rotor, engine or ground effect models may cause an exceedance of rotor speed and/or torque tolerances,
c) The choice of the inflow and pitch/roll coupling model has a moderate effect on controls and attitudes.

If the flight tests used for the validation of a simulation model are performed in turbulent conditions, it is almost impossible to meet the requirements for a level D simulator.

5. Sensitivity analysis of ADS-33 handling qualities criteria to simulator tolerances

This sketch investigates the effect that the tolerances, as prescribed by JAR-STD, have on handling qualities evaluations performed according to the ADS-33 criteria. One of the most common tests prescribed by JAR-STD to check the simulator for low airspeed handling qualities, compares responses to step control inputs performed in the longitudinal, lateral, directional and vertical axes. Table 1 shows the acceptable tolerances for the parameters involved in the longitudinal and lateral step control tests.

Table 1 Tolerances prescribed by JAR-STD for handling qualities validation

Step control Manoeuvre	Tolerances (parameters)
Longitudinal	± 10% or ± 2°/sec pitch rate; ± 10% or ± 1.5° pitch attitude
Lateral	± 10% or ± 3°/sec roll rate; ± 10% or ± 3° roll attitude

The simulation model used in the current activity is the Bo-105 generic model used at DLR [16] and featuring a linear frequency-domain identification model. In the time domain the helicopter dynamics are represented by the linear vector differential equation:

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t) \qquad (2)$$

where x represents the vector of state variables x^T={u, v, w, p, q, r, Θ, Φ, Ψ, $\dot{p}$, $\dot{q}$, $\dot{r}$ }, u represents the vector of control variables u = {δ_x, δ_y, δ_p, δ_0}, and the coefficients in the state matrix A and control matrix B are the stability and control derivatives.

This model was used to perform a sensitivity analysis to the tolerances prescribed by JAR-STD as given in Table 1. In this sense, for example, flying a longitudinal input of 5% with the model and implementing in the model the maximum upper (+10%) and lower (–10%) deviations in the pitch rate resulted in "JAR-STD boundaries" plotted for the pitch rate response as seen in Fig. 11.

Next, consider that the same step input is flown not by implementing the tolerances in the model but by varying each element in the matrix A and B so that the pitch rate response reaches the JAR-STD response boundaries for maximum deviation. In this way, one can determine the maximum possible variation of each element of the matrix A and B that can be considered in the model that continues to satisfy the JAR-STD standard. For example, for the element A(4,11), representing the derivative of the roll acceleration w.r.t pitch acceleration, a maximum variation between -3,9 < A(4,11) < 4,3 (value in the initial model is 0) was found that can be used without exceeding the JAR-STD boundaries imposed on pitch and roll rate. This 'derivative' encapsulates a variety of un-modelled moments on the helicopter components. Figures 11a and 11b present the on and off-axis responses to longitudinal and lateral step inputs for the model with A(4,11) = 4.3. It can be seen that the response reaches the upper JAR boundary imposed in the pitch rate after 5 sec without exceeding this boundary.

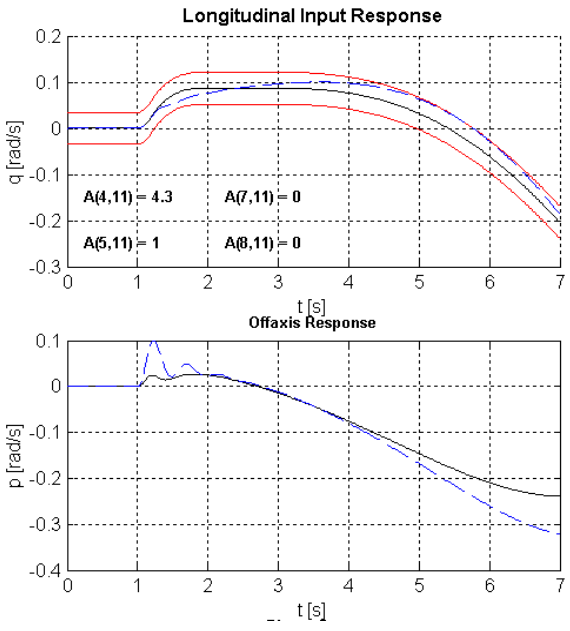


Figure 11a Response to longitudinal cyclic input; comparison of baseline Bo105 with modified model

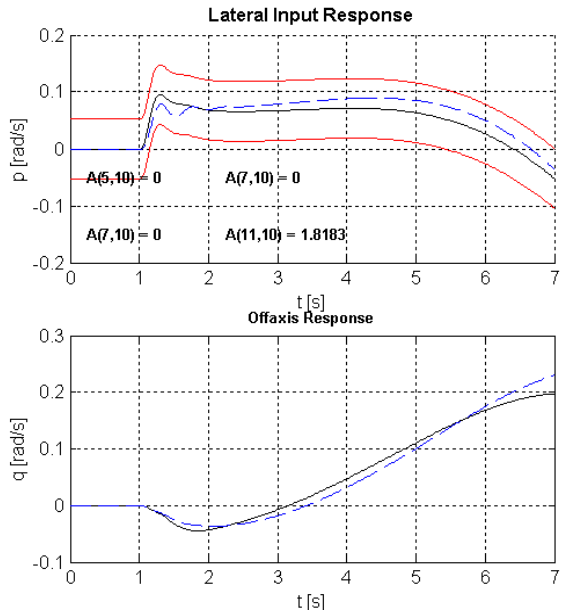


Figure 11b Response to lateral cyclic input; comparison of baseline Bo105 with modified model

Using this approach, the effect of tolerances on handling qualities can now be examined. Three criteria from ADS-33 were chosen to be analysed, i.e. the bandwidth criterion, attitude quickness criterion and cross coupling criterion. The bandwidth criterion pertains to any closed-loop tracking task and measures the point from where, by increasing the disturbance frequency, there is an increasing risk of closed-loop pilot/aircraft system instability. The attitude quickness criterion pertains to the aircraft agility and measures the helicopter's capability for achieving rapid, precise attitude changes when performing a moderate amplitude manoeuvres. The cross-coupling criterion measures the inherent roll-pitch-roll couplings characteristics.

Consider first the bandwidth criterion and assume that the element A(11,10) in matrix A is varied within the JAR boundaries (this element gives the variation in the pitch acceleration due to roll acceleration change). In the bandwidth criterion ADS-33 defines boundaries for the phase delay as a function of the bandwidth frequency (see ref. [14]). Figure 12 presents the results obtained when the simulation model is excited by 5% step inputs in longitudinal and lateral cyclic pitch and the element A(11,10) is continuously varied between its minimum and maximum JAR-STD boundary values. Looking at this figure one can see that flying with the simulation model at low values of A(11,10) – although valid for JAR-STD - results in a degradation of HQs from Level 1 performance to Level 2 performance for pitch axis manoeuvres and from Level 1 to Level 3 performance for roll axis manoeuvres.

Continuing this theme, consider the attitude quickness criterion and, as above, step inputs in pitch and roll cyclic when the element A(11,10) is varied. Figure 13 presents the ADS-33 (pitch and roll) attitude quickness boundaries parameters as a function of attitude changes. It can be seen that while increasing the value of A(11,10) results in an improvement in HQ performance in the pitch axis (meeting Level 1 HQs), there is a consequent degradation in HQs from Level 1 to Level 3 in the roll axis.

Finally, consider the ADS-33 cross-coupling criterion represented in the frequency domain as roll/pitch rate coupling as a function of the pitch/roll coupling and the variation of the element A(11,10) between the lower and upper JAR-STD boundaries. Figure 13 presents the points obtained with the simulation model showing that Level 2 and 3 performance is achieved when varying A(11,10).

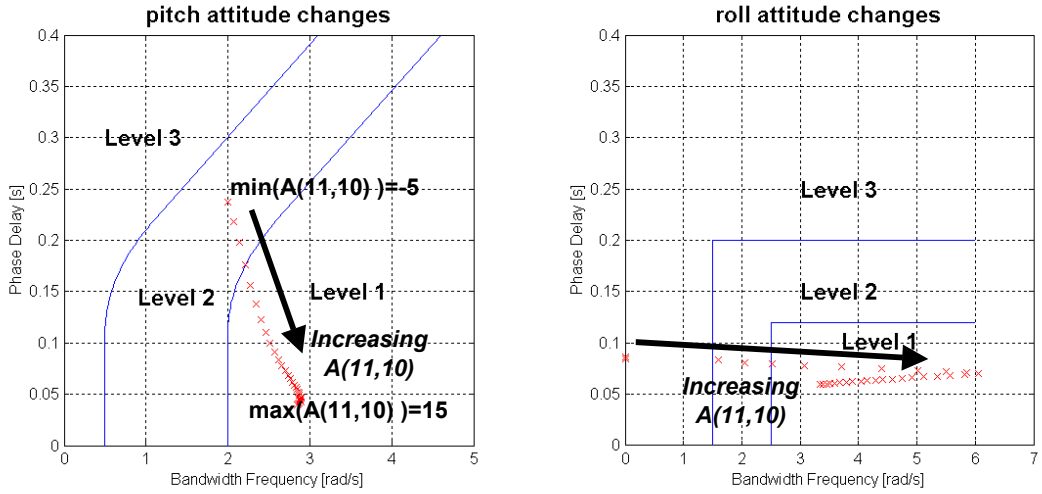


Figure 12 Bandwidth criterion for step inputs applied to simulation models obtained varying A(11,10) between upper and lower JAR limits

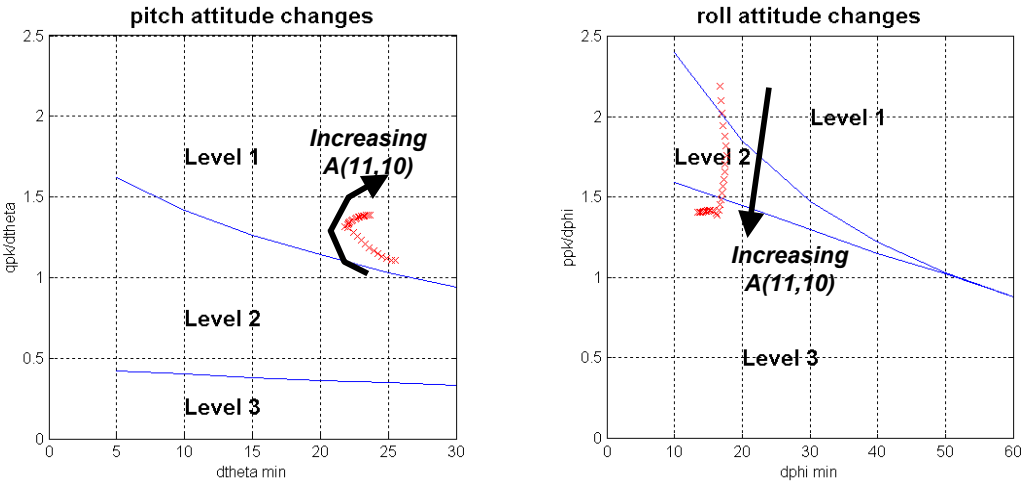


Figure 13 Attitude quickness criterion for inputs applied to simulation models obtained varying A(11,10) between upper and lower JAR limits

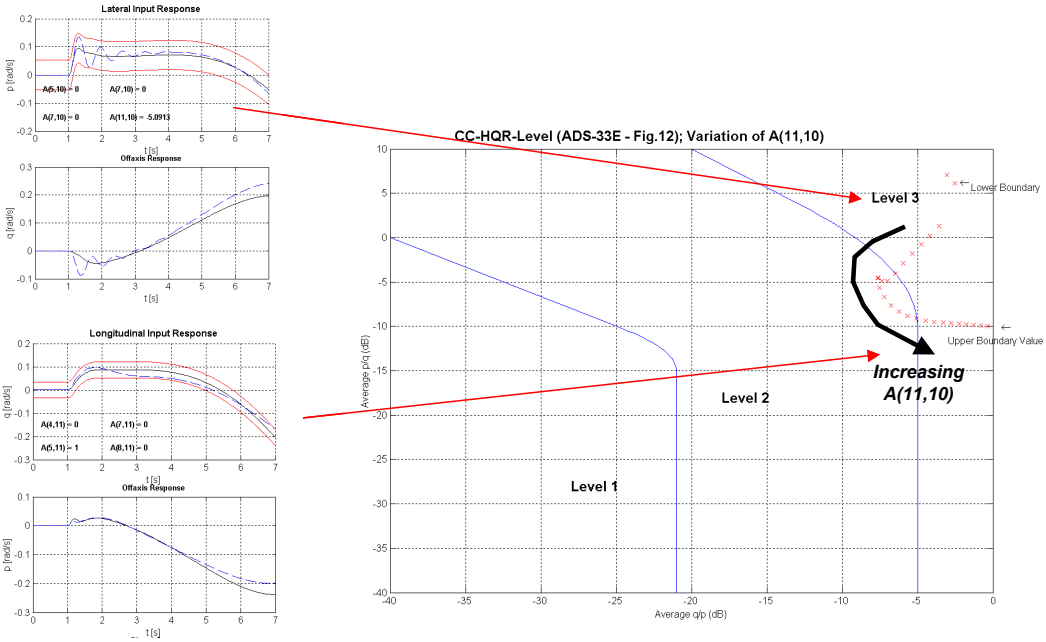


Figure 14 Cross-coupling criterion for step inputs applied to simulation models obtained varying A(11,10) between upper and lower JAR limits

The main conclusion that can be drawn is that although the simulation models used may comply with JAR-STD, handling qualities evaluations obtained using these models are very sensitive to tolerances and show large variation in performance measured with ADS-33 criteria. It might be expected that pilots would perceive such differences in HQs which calls into question the validity of the JAR tolerances. The cases shown are not necessarily worst cases of course and one can imagine variations in multiple elements in the A and B matrix giving even larger HQ changes.

6. Sensitivity analysis of a one-engine inoperative landing manoeuvre to simulator tolerances

The use of fixed-wing simulators for testing new complex scenarios and procedures has given rise to some recent controversy. For example, one such case refers to the testing of an engine failure during take-off. The Federal Aviation Administration (FAA) strongly recommends that the pilot should land straight ahead in such a case, and under no circumstance should they attempt to turn back and land on the departure runway. This recommendation is very strong, but if the failure altitude is 300-1000ft, the FAA advice is then arguable. In some cases it may be safer to

turn and glide back to the runway. Tests with such manoeuvres have been carried out using a flight simulator to determine the optimum conditions for returning to the departure runway; results showed that, with minimal training, over 90% of pilots with more than 100 hours of flight time were able to successfully complete the manoeuvre. However, references [17] and [18] report analysis of these results that show errors can be introduced by simulators showed. The references conclude that care should be taken in validating such new procedures in flight simulators without ever actually flying them, because sometimes the simulator errors, originating from the tolerances existing between simulated and measured parameters, can accumulate and may induce negative transfer of training to pilots. Clearly, practicing new procedures in a simulator without ever actually flying them is a risky process and must be carefully done.

The present sketch describes a sensitivity study to one-engine inoperative (OEI) landings with a helicopter showing the effects of simulator tolerances on testing new piloting strategies. In general, forced landings correspond to the event of an inadvertent one engine failure occurring when the helicopter is in the final approach phase of a landing. To be able to deal safely with an engine failure, the FAA established regulations [19] dealing with such emergency cases. Figure 15 (from ref. [20]) presents a typical landing procedure to a clear heliport in the case of an engine failure for category-A certification, which applies to (large) multi-engine helicopters. Similar to fixed-wing aircraft, during landing, the pilot must: 1) continue the landing when in the so-called “continuous landing CL” region, if an engine fails after the helicopter has passed the Landing Decision Point (LDP) or 2) the pilot may balk or continue the landing, in the so-called “balked landing (BL)” region, if an engine failure occurs at or before reaching the LDP.

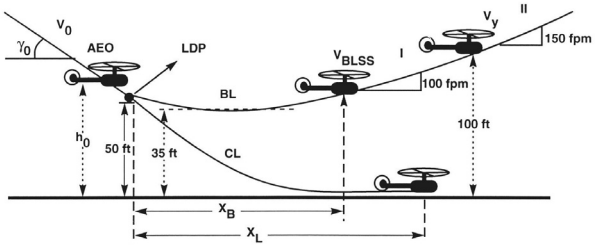


Figure 15 Engine failure procedures for a helicopter during approach and landing at a clear heliport [19]

To be able to perform a safe landing after engine failure, certain combinations of height and forward speed should be avoided. The shape and size of the regions in the (V,h) space – under the so-called Avoid-curve – are dependant on parameters such as gross weight, ambient conditions and piloting procedures. Increasing weight and density altitude both expand the unsafe region.

The current certification process for OEI helicopter operations involves extensive tests requiring the pilot to simulate engine failures at increasingly critical conditions. Such tests are of course dangerous and should ideally be performed using ground-based simulators. This would give the pilot the opportunity to develop optimal strategies and procedures for landing in such emergency situations. The fidelity of the flight simulator for practising such tests is therefore critically important.

In the following, a sensitivity analysis to simulator tolerances is carried out using a model of the Sikorsky UH-60A helicopter, a single rotor helicopter powered by two turboshaft engines, landing in an OEI condition at an altitude situated under the LDP. A (computer) piloted four degree-of-freedom (4-dof) simulation model was developed including {u, w, q, Ω} as degrees of freedom. This model was obtained by simplifying the 6-dof model of ref. [21] and adding the rotor speed as a new degree of freedom. The following assumptions are made: aerodynamic forces and moments are calculated using the blade element theory; the fuselage is modelled with linear aerodynamics; a quasi-steady dynamic inflow was included with a time constant τ of value 0.1; the rotor is vertically above the helicopter centre of mass at a distance h; the blade is rectangular, there are no tip losses, and the blade mass distribution is uniform with the mass centre and aerodynamic centre located on the quarter chord line.

The simplified equations of motion describing the helicopter motion in an inertial body-axis system of reference are:

$$\begin{cases} \dot{u} = -g\sin\theta - \dfrac{\rho}{2}\dfrac{C_{Ds}}{m}u\sqrt{u^2+w^2} - \\ \quad \dfrac{T}{m}\sin(a_1-\theta_{1s}) - qw \\ \dot{w} = g\cos\theta - \dfrac{\rho}{2}\dfrac{C_{Ds}}{m}w\sqrt{u^2+w^2} - \\ \quad \dfrac{T}{m}\cos(a_1-\theta_{1s}) + qu \\ \dot{q} = \dfrac{T}{I_y}h\sin(a_1-\theta_{1s}) \\ \dot{\theta} = q \\ \dot{\Omega} = \dfrac{1}{I_R}\left\{\begin{array}{l} -K_3(\Omega-\Omega_i) - 2\sigma\times \\ \left(\dfrac{C_{Ds}}{8}(1+4.7\mu^2) - C_{T\,elem}\lambda\right) \end{array}\right\} \\ \dot{\lambda}_i = \dfrac{1}{\tau}(C_{T\,elem} - C_{T\,Glau}) \end{cases} \quad (3)$$

where the rotor thrust coefficient in blade-element theory is given by,

$$C_{Telem} = \frac{\sigma C_l^{\alpha}}{2}\left[\frac{\theta_0}{3}\left(1+\frac{3}{2}\mu^2\right) + \frac{\lambda_c - \lambda_i}{2}\right] \quad (4)$$

and in Glauert theory by,

$$C_{TGlau} = 2\lambda_i\sqrt{\left(\frac{V}{\Omega R}\cos(\alpha_c - a_1)\right)^2 + \left(\frac{V}{\Omega R}\sin(\alpha_c - a_1) + \lambda_i\right)^2} \quad (5)$$

Assume that the helicopter is approaching with a constant glide path γ_0 = 6deg having a velocity V_0 = 35 kts at h_0 = 100ft and a constant deceleration of 0.075g's, when one engine fails at h = 25ft above the ground. The optimal trajectory is equivalent to controlling the thrust inclination angle β as represented in Fig. 16 ($\beta > 0$ for thrust tilted forward) and thus controlling the energy stored in the rotor.

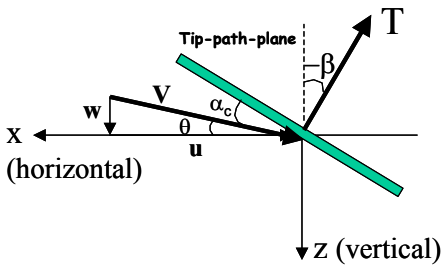


Figure 16 Controlling the thrust angle β

In an OEI condition, the pilot may store energy in the rotor by using the rotor rotational energy source in addition to the usual kinetic and potential energy of the aircraft. The procedure to be followed after the engine failure is similar to a total engine failure, with the exception that there is some torque available from the remaining engine, so the use of the collective and pedals will be different.

The engine power from the moment of failure decreases linearly in the first few seconds of failure for $t < t_p$ where t_p is the time response of the engine, t_p=0.5 sec:

$$P_{eng}(t) = P_{AEO} + \frac{\left(P_{OEI} - P_{AEO}\right)}{t_p}\cdot t \quad (6)$$

and, after this, for $t \geq t_p$,

$$P_{eng}(t) = P_{OEI} \quad (7)$$

The power available can be now calculated as:

$$P_{av} = \frac{1}{\eta}P_{eng}(t) - P_{req} \quad (8)$$

where η = 0.85 is the engine efficiency and the power required P_{req} is a summation of profile power P_{pr} (i.e. the power required to overcome the drag due to the friction of the blades), parasite power P_{par} (i.e. the power required to overcome the drag of the fuselage), induced power P_i (i.e. the power required to induce the velocity through the rotor), miscellaneous power P_m (i.e. the power needed for the tailrotor, gearboxes, hydraulic pumps, generators) and the climb power P_c. For a further description of these powers the reader is referred to ref [21].

After one engine fails, the induced power available to generate the inflow during the OEI manoeuvre becomes:

$$P_{iav} = P_{av} - P_{ireq} = \frac{1}{\eta}P_{eng}(t) - \left(\begin{array}{l} P_{pr} + P_{par} \\ + P_m + P_c \end{array}\right) \quad (9)$$

The difference between the P_{iav} and P_{ireq} is the total induced power that can be stored in the rotor in the form of rotational energy. However, we assume that only a proportion P_{iuse} will be used so that sometimes energy is stored ($P_{iav} - P_{iuse} > 0$) and sometimes energy is dispersed ($P_{iav} - P_{iuse} < 0$). During the landing, $P_{iuse} - P_{ireq} > 0$, in order to preserve the thrust for a soft touch down. To control $P_{i\,use}$ optimally, the vertical and horizontal velocity at touch down is minimised, as described

in Ref. 22. The law for controlling $P_{i\ use}$ optimally (and thus β) is developed from [23] and given by:

$$P_{iuse} = P_{iav} - K_1(P_{ireq} - P_{iav})K_2 \qquad (10)$$

where K_1=0.25 and,

$$K_2 = \begin{Bmatrix} 1.1\min\left(\left[16(w-w_{des})^2+1\right]^5, 5\right) & if\ w > w_{des} \\ \min\left(\left[16(w-w_{des})^2+1\right]^3, 4\right) & if\ w \le w_{des} \end{Bmatrix} \qquad (11)$$

and w_{des}=1.3 m/s is the desired touchdown speed. Combining (10) with the equations of motion (3) and including the limits for the rotor rotational speed, i.e. $\Omega_{min} \le \Omega_{nom} \le \Omega_{max}$, Ω_{min} = 91% Ω_{nom}, Ω_{max} = 110% Ω_{nom}, leads to a solution of controlling β as presented in Fig. 17.

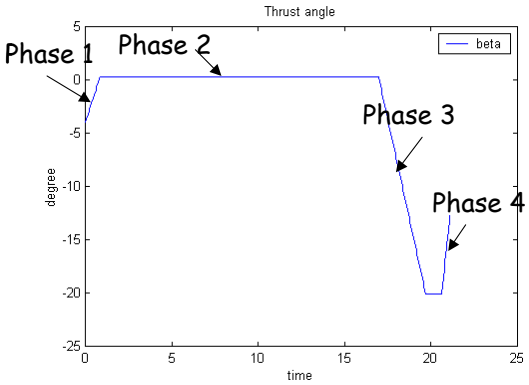


Figure 17 Optimally controlling the thrust angle for OEI-CL manoeuvre

From Fig 17, one can see four phases that the pilot has to follow in controlling the thrust angle: first a small increase in β for decreasing power required which was optimally chosen at a constant rate $\left(\frac{d\beta}{dt}\right)_1$ = 0.3 deg/sec until β reaches 0.8 deg. Then, phase 2 corresponds to β kept constant until the aircraft is 3.8 m above the ground when phase 3, the flare, is initiated by suddenly tilting back β at a constant rate of $\left(\frac{d\beta}{dt}\right)_2$ = –22 deg/sec until β reaches –20 deg. In the final phase, at a point h < 0.8m, β is increased for touching down. Figure 18 presents the variation in rotor speed, helicopter velocity components u,w and height h throughout the manoeuvre.

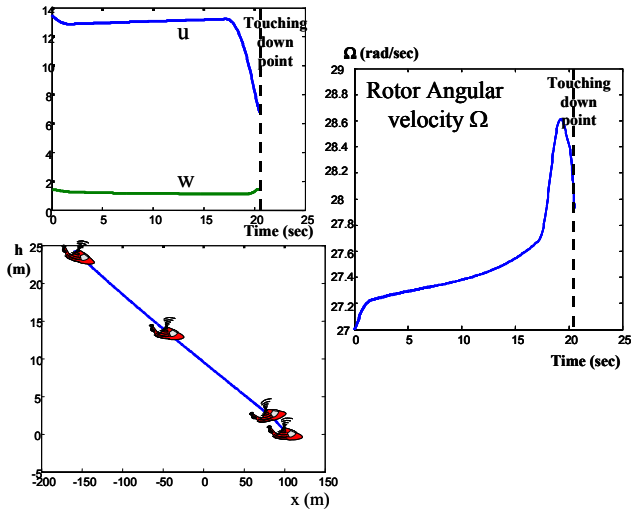


Figure 18 Optimal trajectory for OEI-CL manoeuvre

A sensitivity analysis is now performed, varying the flight parameters with the tolerances specified in the JAR-STD regulation. Table 2 shows the acceptable tolerances for the parameters in the OEI landing test.

Table 2 Flight simulator tolerances in OEI landing from JAR-STD

Parameter	**Tolerance**
Airspeed	± 3 kts
Altitude	± 20 ft
Rotor speed	±1.5 %
Pitch attitude	±1.5 %
Torque	± 3 %
Bank attitude	± 1.5 deg
Heading	± 2 deg
Longitudinal control position	± 10 %
Lateral control position	± 10 %
Directional control position	± 10 %
Collective control position	± 10 %

To determine the sensitivity of the CL manoeuvre to the simulator tolerances, one has to consider that deviations of ±20ft in height, ±3kts airspeed, ±1.5% pitch, ±10% collective and ±10% longitudinal cyclic have to be added through all the segments of the CL manoeuvre; these deviations being attributed to the flight simulator error tolerances. Looking at the tolerances given in Table 2, it can be shown that, from all possible combinations, there are 3 failure cases (3 combinations) that have to be studied to determine the magnitude of the sensitivity. These cases are:

- case 1, or the reference case, where no tolerances were applied to the flight dynamics equations,
- case 2, or the upper limit in touchdown location, given by +20ft in height, -3kts in

velocity, and +1.5% in pitch attitude, +10% collective,

- case 3, or the lower limit in touchdown location, given by -20ft in height, +3kts in velocity, and –1.5% in pitch attitude, -10% collective as specified in JAR-STD 1H.

Implementing the extreme cases 2 and 3 in the equations of motion (3), the footprint (x,h) of the helicopter as it approaches the landing can be plotted. Figure 19 shows these results. The touchdown point varies from 30m to 320m, producing an error of 290 m. An error of 290 m may be not so critical when landing on a clear heliport but is obviously important when landing on an elevated helipad.

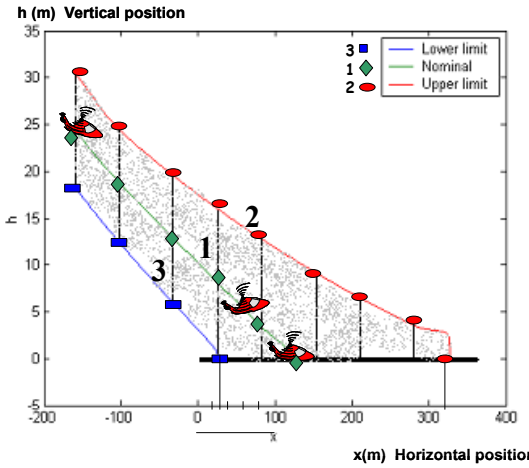


Figure 19 Sensitivity of tolerances on the footprint for a helicopter in OEI-CL

Consider a "safety region" as the region where the OEI-CL landing can be regarded as safely performed. This region is defined as the region where the points of touchdown are imposed to be within the following limits: vertical velocity w does not exceed w_{max}=1.5 m/sec and the horizontal velocity u does not exceed u_{max}=4.5m/sec. Figure 19 is converted into Figure 20 for the touchdown points.

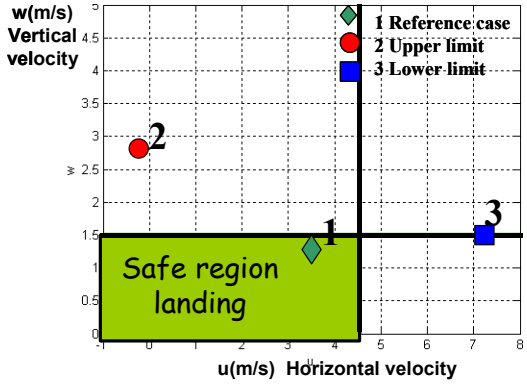


Figure 20 Sensitivity of the touchdown point to performance tolerances

From Fig 20, it can be seen that the errors introduced by the tolerances accumulate and move the touchdown points for both upper and lower limit cases outside the safety region.

Consider next a change in the strategy when executing the OEI-CL manoeuvre, in that the pilot decides to change the height at which the flare manoeuvre is initiated, still following the same β law. Figures 21 and 22 present the safety region plots for two new cases: when the flare is initiated at a height h=4.8m (this means that the pilot stores more energy in the rotor before landing) and when the flare is initiated at a height of 3.3m.

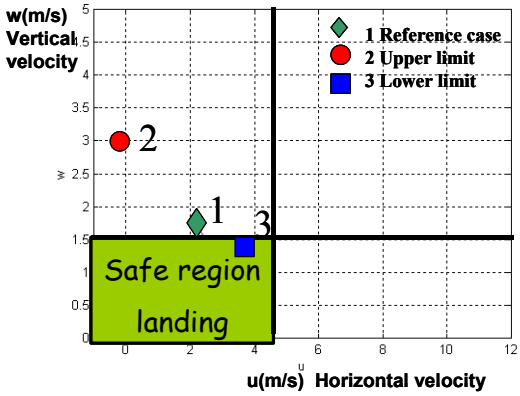


Figure 21 Sensitivity of the touchdown point to tolerances when flaring at a higher altitude

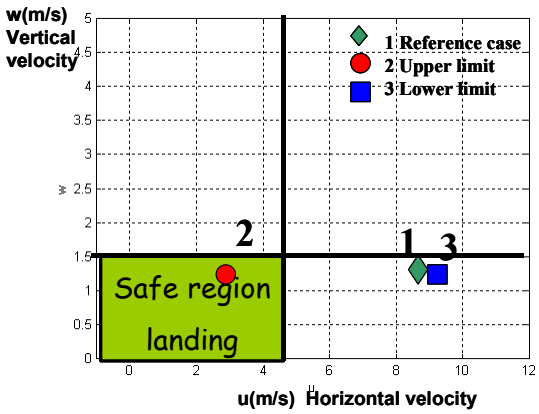


Figure 22 Sensitivity of the touchdown point to tolerances when flaring at a lower altitude

From these figures it can be concluded that, when changing the piloting strategy, the simulator can, for some cases, give a false impression of safety (see point 3 in Fig. 21 corresponding to the lower limit in tolerances and point 2 in Fig. 22 corresponding to the upper limit in tolerances).

Concluding this sketch, this preliminary study has shown that for helicopters, as with fixed-wing aircraft, flight simulator tolerances are highly sensitive to how the manoeuvre is flown. In some cases the errors introduced by tolerances tend to accumulate and give a false impression of danger, while in other cases the errors tend to cancel each other out and give a false impression of safety.

This last case can be especially dangerous when judging the performance of a new procedure without ever actually flying it in reality.

7. Sensitivity of an adaptive pilot model to simulation fidelity

In this final sketch, results from the development of criteria for simulation system fidelity using an adaptive model of the pilot-aircraft system are presented. The theoretical framework to the approach is described in Refs [24] and [25] and is based on the notion that the aircraft motion control is divided into guidance and stabilisation components. Provided the attitude 'tracking' elements of manoeuvres are limited in extent, the guidance control can be approximated by a second order system with variable parameters. As an example consider the re-positioning manoeuvre shown in Fig. 23, often described as the acceleration-deceleration or dash-quickstop mission task element.

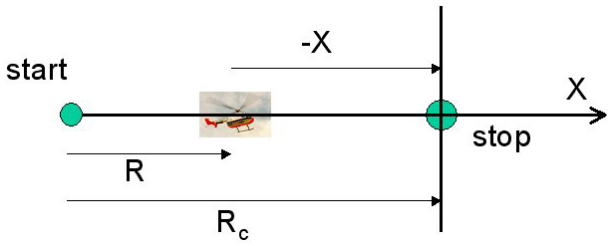


Figure 23 Horizontal re-positioning manoeuvre

It is assumed that the horizontal force is proportional to the pitch attitude (thrust vector tilt) so that the commanded acceleration and attitude are equivalent. The pilot motion control action is then approximated by a proportional-derivative feedback on distance to stop X, giving a coupled pilot-aircraft model in the 2nd order differential form,

$$\frac{d^2X}{dt^2}+2\zeta_X\omega_X\frac{dX}{dt}+\omega_X{}^2X=0, \qquad X(0)=-R_c \tag{12}$$

where the natural frequency (ω_X) and relative damping (ζ_X) are related to the pilot rate and position feedback gains by the forms,

$$K_{\dot{X}}\approx\frac{2\zeta_R\omega_R}{g} \quad K_X\approx\frac{\omega_R{}^2}{g} \tag{13}$$

The variations in the model parameters during a manoeuvre reflect the closed-loop pilot control strategy, reflecting a pilot's ability to use the available simulation cues and also the basic guidance dynamics of the simulation model. The level of equivalence of identified model parameters, derived from simulation and flight test, then reflects the fidelity level of the simulator. The model used in the study is the FLIGHTLAB Bo105, operating on The University of Liverpool's HELIFLIGHT simulation facility [26]. Figure 24 shows a comparison of the ADS-33 attitude quickness measured in simulation and flight test. The simulator open-loop test points (derived from pilot applied pulse inputs) are about 40% higher than measured in flight (DLR test points) although the closed loop points extracted from the attitude changes during an accel-decel manoeuvre are very similar; not surprising as the pilot is flying to the same manoeuvre performance standard (see Table 3. The use of such handling qualities parameters as fidelity measures is regarded as an important supplement to the JAR-STD 1H criteria, especially in the light of the results presented in Section 5 of this paper.

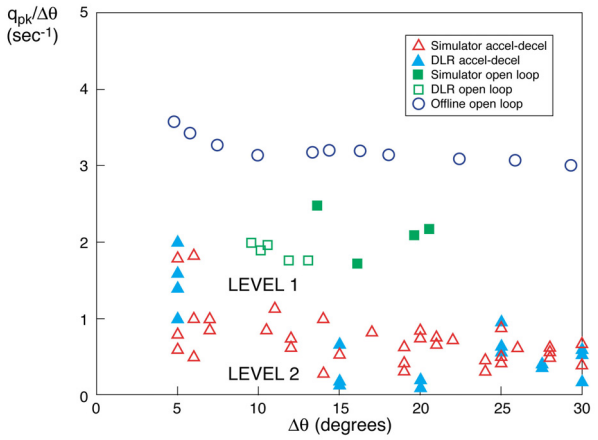


Figure 24 Pitch attitude quickness for the Bo105; flight vs simulation

The accel-decel re-positioning manoeuvres were flown on the HELIFLIGHT simulation facility with the performance standards given in Table 3.

Table 3 Performance standards for the accel-decel manoeuvre

	desired	adequate
Height	< 50ft(~ 15m)	< 70ft(~ 21m)
Heading	±10 deg	± 20 deg
Pitch angle	12 deg up, 15 deg down	7 deg up, 10 deg down

Typical results for the pilot gains, averaged over six runs are shown in Figs 25 and 26. The relatively low gains early in the manoeuvre reflect the rather open-loop nature of the acceleration phase. As the pitch reversal is approached, both gains increase, subsiding again in the deceleration before increasing again during the stopping phase. Gain strengths of nearly

0.25deg/ft and 1deg/ft/sec are predicted as the helicopter comes to a stop, giving rise to an increasing 'braking' action, modulated by the K_x spring which draws the helicopter to the final hover point.

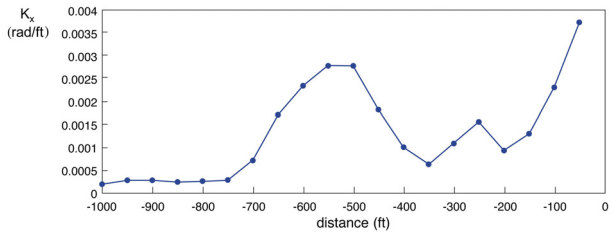


Figure 25 Variation of positional gain with distance to go

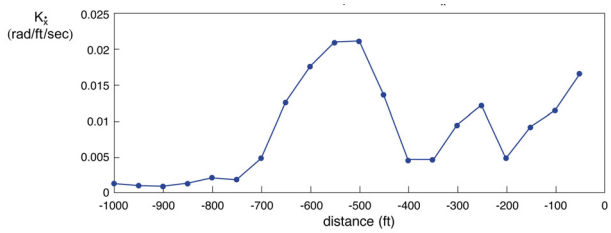


Figure 26 Variation of velocity gain with distance to go

The gain portraits in Figs 25 and 26 are measures of motion control strategy and workload and the continuing research on this theme aims to establish the sensitivity of these measures to simulation cues – motion, visual, flight modelling. Ref [25] also develops the theory for extending the adaptive model to include the stabilisation function. In the ongoing research, comparisons will be made with flight test data for the Bo105 flying accel-decels and other manoeuvres, aimed at developing robust, physically meaningful measures of overall system fidelity.

8. Conclusions and Recommendations

The present paper has presented a review of key aspects of the work of GARTEUR Action Group AG-12, tasked to examine the process and criteria used in the validation of helicopter simulators. Selected results from the work of the AG-12 have been presented dealing with JAR-STD 1H criteria for validating the helicopter simulator's model. A literature review on the source of tolerances and criteria used by JAR-STD 1H has revealed that these criteria have been largely drawn from the criteria developed for the qualification of fixed-wing flight simulators. Therefore, the appropriateness of helicopter tolerances and criteria used by JAR-STD to civil or military missions or to manoeuvres performed at the limits of helicopter capabilities should be questioned.

Initial industry experience with JAR-STD 1H has been generally positive but has required the development of a comprehensive model (physical) tuning and (non-physical) adjustment process. The physical tuning can achieve a fit, in a general sense, within 80% of the JAR tolerances. The adjustment process is more challenging and can lead to distortions in the model behaviour in areas not checked by the JAR criteria.

With regard to the tolerances prescribed by JAR-STD, the AG activities have highlighted that:

a) the tolerances are highly sensitive to the nature of the manoeuvre performed and the errors in the simulation model. When validating complex and long running manoeuvres, the errors introduced by modelling (such as deficiencies in the rotor model, engine model interaction from the rotor on fuselage, horizontal or vertical tail), the value of discretisation used in the control inputs from flight tests or the use of flight test data coming from tests performed in turbulent conditions, can be very high, making the task of meeting the level D requirements extremely difficult.
b) the current JAR tolerances can introduce large inaccuracies in assessing the handling qualities according to the ADS-33 standard. The GARTEUR sketch demonstrated that although a simulation model subscribes to JAR tolerances, the HQs when compared to the flight test data can be very different. This will be particularly important when considering borderline Level 1/2 aircraft.
c) errors originating from the tolerances existing between simulated and measured tolerances may in some cases tend to accumulate while in other cases tend to cancel each other out. This may introduce problems when judging the safety of a new manoeuvre performed in the simulator and there is the potential for inducing negative transfer of training to pilots.

The use of the (ADS-33) HQ metrics and manoeuvres as a supplement to JAR-STD 1H would provide a more substantiated framework for model response fidelity. The adaptive pilot model sketch showed how pilot (model) gains varied across an ADS-33 accel-decel manoeuvre. This approach has the potential for defining system level fidelity criteria, for both the JAR and ADS manoeuvres, modelling pilot control strategy and quantifying the sensitivity of system fidelity to the cues presented by simulation sub-systems.

JAR-STD 1H is a comprehensive and challenging standard with only limited experience to date of its application. The sensitivity analyses conducted by the GARTEUR AG have highlighted the need for more substantiation of the criteria and qualification procedures.

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