ON THE VALIDATION OF HELICOPTER FLIGHT SIMULATORS OPERATING IN EMERGENCY PROCEDURES

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Abstract

Flight simulators have become indispensable tools for both training 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; 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 simulator manufacturers in the process of acceptance and certification of their simulators. For helicopters, the most widely recognized standard in Europe used for simulation qualification is JAR STD-1H [2]. This standard provides criteria for both the simulator model and for the major components of the simulator. Current experience of simulator manufacturers shows that 80% "fidelity" can be achieved with a physical model; the remaining 20% requires artificial tuning. However, while tuning can rectify problems in a specific flight condition, it may actually have an adverse effect on other parts of the flight envelope. The present paper addresses the deficiencies existing in the FAA/JAR criteria when applied to the engine failures emergency procedures. Such flight procedures are generally regarded as the most dangerous and difficult to model in the simulator. In this context, using a point-mass model (4-degree of freedom (dof) representing the 3-dof dynamics of a point-mass helicopter and the rotor rpm dynamics), the paper investigates the effects of simulator tolerances on new pilot strategies implemented in the case of a helicopter landing procedure with one engine inoperative (OEI). It is showed that in some cases the errors introduced in the simulation by the JAR-STD "tolerances" – defined as differences between the model and the flight test data – tend to accumulate and give a false impression of danger; in other cases these errors tend to cancel each other out and give a false impression of safety. This last case can be especially dangerous when using the simulator for designing new piloting strategies.

Notation

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]
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_i,k_v	coefficients used to compute the rotor induced velocity (see eq. (2))
m	helicopter mass [kg]
P_{eng}	engine power
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
R rotor radius [deg/sec]
t time
t_p engine time response t_p=0.5 sec
T rotor thrust
u horizontal body velocity [m/sec]
v lateral body velocity [m/sec]
v_i induced velocity [m/sec]
V_x,V_z helicopter velocities in an inertial system [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
β_{long} thrust inclination angle in the longitudinal plane
β_{lat} thrust inclination angle in the lateral plane
μ advance ratio
ρ air density [kg/m^3]
σ rotor solidity
Ω rotor rotational speed
Ω_i idling speed

1 Introduction

For helicopters, the most widely recognized standard for simulation qualification is the American FAA Advisory Circular AC 120 63 [1] which has been reworked in Europe into JAR STD-1H [2]. These standards provide criteria for the simulator model, for the motion system and for the visuals. Four levels of qualification exist in JAR-STD 1H (A, B, C and D), the highest level D allowing the replacement of most of the flight hours required for a type rating (or for recurrent training) by simulator hours. As concerning the criteria used for validating the simulator mathematical model, the actual JAR process implies the following stages:

- firstly, a physical model is developed with a required accuracy depending entirely on what the simulator is going to be used for;
- secondly, the model is implemented in the simulator and validated through a rigorous checking of the simulator's flying capabilities against specified "tolerances" - defined as differences between the model results and flight test data - and quantitative criteria formulated in the FAA/JAR standards;
- third, piloted evaluations of pre-defined test maneuvers are conducted, using aircrew familiar with the real aircraft;
- the results of the tests are compared with the flight tests database and the discrepancies identified by the pilots are corrected through a subjective "tuning" process where modifications are made to the model or simulator systems, with the intention of improving the general feeling of "realism".

A Level D training simulator is a "perfect" simulator and it is very difficult to achieve. To develop such a simulator many quantitative tests representing relevant maneuvers have to be run and then first compared to the JAR tolerances; then the tuned model is examined w.r.t. the subjective pilot opinions about the simulator behavior. In Europe, HELISIM - a joint venture involving helicopter industry (Eurocopter), simulator industry (Thalès Training&Simulation) and a military training specialist (Defense Conseil International) – is the first corporation in Europe qualifying simulators for Level D qualification. Since 2002 within HELISIM different Eurocopter helicopters (such as Super Puma MK1, Super Puma MKII, Dauphin DN 2, and recently EC155) have been successfully qualified to Level D. In their experience (see ref. [3]) two main categories of tasks have to be performed for qualification in JAR STD 1H:

- first category of tasks belongs to the so-called "static tests" (60 tests) aiming to demonstrate correct trim and performance;

- second category belongs to the so-called "dynamic tests" and aims to check the simulator handling qualities. In this category a set of 7 so-called trajectory tests are performed (landing OEI, rejected take-off OEI, autorotational landing etc.). These tests are not directly used for tuning but more for a globally check whether the model behaves like a real helicopter.

The present paper will address the area of trajectory tests, namely landing with one engine inoperative (OEI). Recent work of GARTEUR Action Group AC-HG-12 [4] has highlighted the need for more substantiation of the criteria and qualification of the dynamic tests category. In this sense, it was demonstrated that flight simulator tolerances are highly sensitive to control strategy chosen for tuning the pilot in the loop model. The reference concludes that care should be taken in practicing new procedures in the flight simulators without ever actually flying them. For the fixed wing aircraft, reference [10] underlined as well the fact that changing the OEI procedure in the simulator may induce errors and false impressions in piloting strategies. Reference [5] showed that the tolerances may introduce further errors in the simulator's handling qualities.

2 Definition of the Problem

2.1 FAA requirements for forced landing in OEI

Engine failures are critical operations of concern especially when they happen in the flight phases of take off or landing. To be able to deal safely with an engine failure, JAA and FAA both established regulations (see refs. [6], [7]) dealing with helicopters operating in such emergency cases. According to these standards a helicopter may be certified in Category A or Category B. A Category A helicopter (multiengine) must offer the performance needed to guarantee that, in case of a failure, the flight can continue safely. Category B (for single or multiple engine helicopter) requires that a safe landing be possible in the event that one or all engines become inoperative, and therefore there is no requirement for continued flight capability.

Category A qualification means therefore a more severe safety guarantee for a multiengine helicopter because it implies the ability of the helicopter to continue the flight with OEI, enhancing such helicopters to operate in areas where no emergency sites are available. Fig. 1 from [8] sketches the landing procedure to (a) a clear heliport and (b) an elevated helipad. Similar to fixed-wing aircraft, during landing, the pilot must: 1) continue the landing (CL) if the engine fails after the helicopter has passed the landing decision point (LDP) or 2) the pilot may either continue or balk the landing (BL) if an engine failure occurs at or before reaching the LDP. In confined helipads it is required that the helicopter land back to the original take off point.

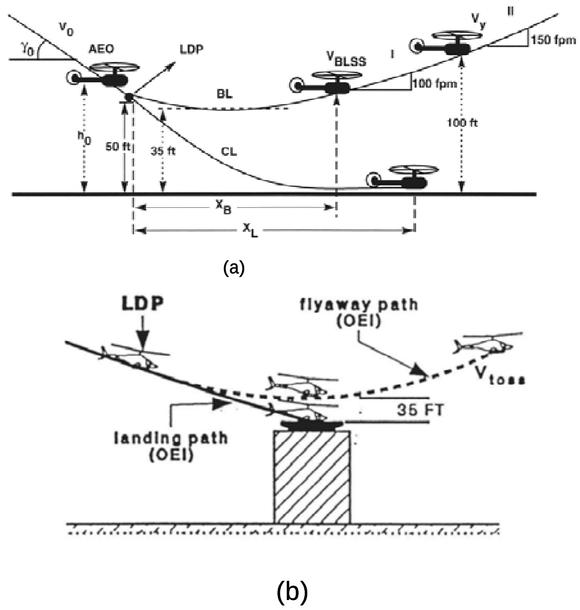

Fig. 1 Continuous and Balked landing

To be able to perform a safe landing after engine failure, certain combinations of height and forward speed should be avoided in the height-velocity diagram shown in Fig. 2 (example of a Hughes 500 helicopter from ref. [9]). The shape and size of the regions in the (V,h) diagram are dependant on parameters such as gross weight, ambient conditions and piloting procedures.

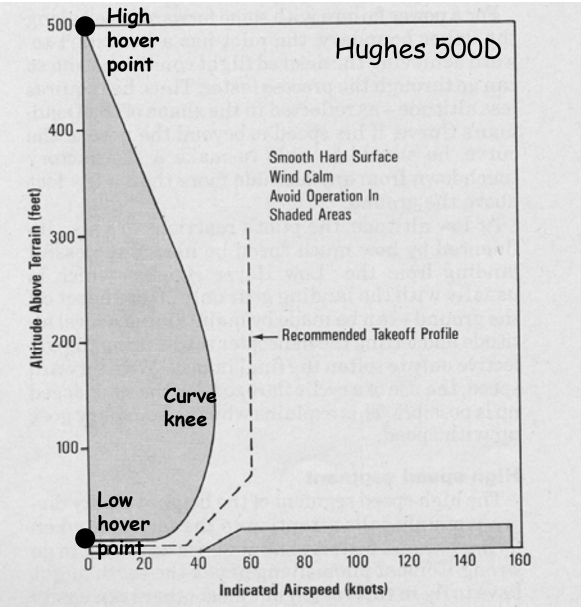

Fig. 2 Height-velocity diagram

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 practicing such tests is therefore critically important.

2.2 Rotorcraft model

A point-mass simulation model was developed including {u, v, w, Ω} as degrees of freedom. This model was obtained by extending the 2-dof model of ref. [8] and adding the rotor speed and lateral motion as additional degrees of freedom. The following assumptions are made: aerodynamic forces and moments are calculated using actuator disc theory; the fuselage is modeled with linear aerodynamics; 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:

$$\begin{cases} m\dot{u} = T\sin\beta_{long}\cos\beta_{lat} - D_f\cos\gamma + \\ mg\sin\theta \\ m\dot{v} = T\sin\beta_{lat} + mg\cos\theta\sin\phi \\ m\dot{w} = -T\cos\beta_{long}\cos\beta_{lat} - D_f\sin\gamma + \\ mg\cos\theta\cos\phi \\ \dot{\Omega} = \dfrac{1}{I_R}\left\{ \begin{matrix} -K_3(\Omega-\Omega_i) - 2\sigma\times \\ \left(\dfrac{C_{Ds}}{8}(1+4.7\mu^2) - C_T\lambda\right) \end{matrix} \right\} \end{cases} \tag{1}$$

where the induced velocity is calculated combining the impulse theory and blade element theory:

$$\frac{\bar{v}_i}{k_i}\cdot\left[\frac{\bar{V}_x^{\,2}}{k_v^{\,2}} + \left(\frac{1}{k_v^{\,2}} - \frac{1}{k_i^{\,2}}\right)\cdot\bar{V}_z^{\,2} + \frac{(\bar{V}_z+\bar{v}_i)^2}{k_i^{\,2}}\right]^{\frac{1}{2}} = 1 \tag{2}$$

with $k_v = k_i = (5/4)^{1/4}$.

Assume that the helicopter is approaching with a constant glide path γ_0 = 6 deg having a velocity V_0 = 35 kts at h_0 = 100 ft 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_{long} longitudinally and β_{lat} laterally as represented in Fig. 3 ($\beta_{long} > 0$ for tip-path-plane tilted backwards; $\beta_{lat} > 0$ for tip-path-plane tilted to the right) and thus controlling the energy stored in the rotor.

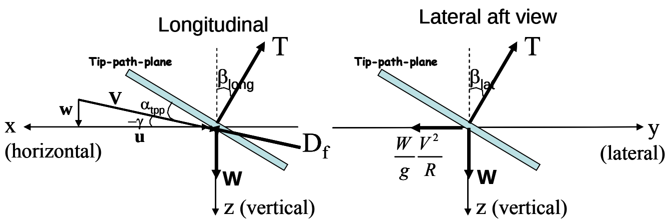

Fig. 3 Controlling the thrust angle longitudinal and lateral

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 single 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. As in autorotation, the pilot has to lower the collective in order to maintain rpm and then immediately use aft cyclic and tilt back the thrust vector in order to allow the air to flow up through the rotor and so increase the rotor rpm. As the rpm starts increasing, energy will be stored in the rotor, so that the pilot could start gliding (in principle) at a constant airspeed, "keeping an eye" on the rpm to not get too high (if the rpm gets too high the pilot must increase collective pitch and thus transform kinetic rotational energy into potential energy). Then, before landing, the pilot must initiate the flare by using aft cyclic. The rotational kinetic energy stored in the rotor may be in this way used to tilt the thrust back in the cyclic flare and reduce the forward speed and the rate of descent so that the landing gear can cope with the touchdown, finally accomplished by using the collective to cushion the landing.

Assuming 1) a time response of the engine, t_p=0.5 sec and 2) that the engine power from the moment of failure decreases linearly in the first few seconds of failure, the engine power before and after the failure moment can be calculated as:

at $t<t_p$

$$P_{eng}(t) = \frac{P_{AEO}}{2} + \frac{(P_{OEI} - P_{AEO}/2)}{t_p} \cdot t \qquad (3)$$

at $t \geq t_p$

$$P_{eng}(t) = P_{OEI} \qquad (4)$$

The power available is then:

$$P_{av} = \frac{1}{\eta} P_{eng}(t) - P_{req} \qquad (5)$$

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.

$$P_{req} = P_{pr} + P_{par} + P_{i\,req} + P_m + P_c \qquad (6)$$

Profile power can be easily calculated using the Bennet approximation:

$$P_{pr} = \frac{\sigma \cdot \overline{C}_{D_{bl}}}{8} \rho (\Omega R)^3 \pi R^2 (1 + 4.65 \cdot \mu^2) \qquad (7)$$

where $\overline{C}_{D_{bl}}$ is the mean profile drag coefficient. The parasite power is calculated assuming the fuselage as an equivalent flat plate area:

$$P_{par} = \sum (C_{D\,s}) \frac{1}{2} \rho V^3 \qquad (8)$$

where $\sum (C_{D\,s})$ is the fuselage parasite drag area and is determined experimentally. Calculating at every moment the induced velocity v_i passing through the rotor by using the helicopter equations of motion (1) gives the induced power as:

$$P_{iOGE} = kTv_i \tag{9}$$

where k is a constant accounting for the non-uniform distribution of the induced velocity along the rotor, k=1.2. Including a ground effect term in the form of a coefficient $f_g = 1 - \frac{1}{16 \cdot (H_r + h)}$, where H_r is the rotor hub height when the helicopter is on the ground, the induced power required to induce the inflow through the rotor becomes:

$$\overline{P}_{ireq} = f_g \cdot \overline{P}_{iOGE} \tag{10}$$

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

$$P_{iav} = P_{av} - P_{ireq} = \frac{1}{\eta} P_{eng}(t) - \begin{pmatrix} P_{pr} + P_{par} \\ + P_m + P_c \end{pmatrix} \tag{11}$$

The difference between the P_{iav} and P_{ireq} is the induced power that can be stored in the rotor in the form of rotational energy. However, this power will be not continuously stored in the rotor but, rather, only a quantity $P_{i\ use}$ will be used so that sometimes energy is stored in the rotor ($P_{iav} - P_{iuse}$>0) and sometimes it is dissipated, $P_{iav} - P_{iuse}$<0, taking care that $P_{iuse} - P_{ireq}$>0 in order to maintain the required thrust for a soft descend. For controlling the power used $P_{i\ use}$ the condition to arrive at the ground with minimum vertical and horizontal velocity was imposed and a optimal law was searched for controlling the power. The law for controlling optimally $P_{i\ use}$ (and thus β_{long} in the longitudinal plane) was found after some numerical trials as:

$$P_{iuse} = P_{iav} - K_1(P_{ireq} - P_{iav})K_2 \tag{12}$$

where K_1=0.25 and

$$K_2 = \begin{cases} 1.1\min\left(\left[16(w - w_{des})^2 + 1\right]^5,\ \ 5\right) & if\ \ w > w_{des} \\ \min\left(\left[16(w - w_{des})^2 + 1\right]^3,\ \ 4\right) & if\ \ w \le w_{des} \end{cases} \tag{13}$$

and w_{des}= 1.3 m/s was imposed as a suitable desired touchdown speed.

First, the paper will analyze the effects of controlling the longitudinal thrust angle β_{long} (designated in the followings simply β). Combining (12) with (1) 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 the solution of controlling β_{long} as presented in Fig. 4.

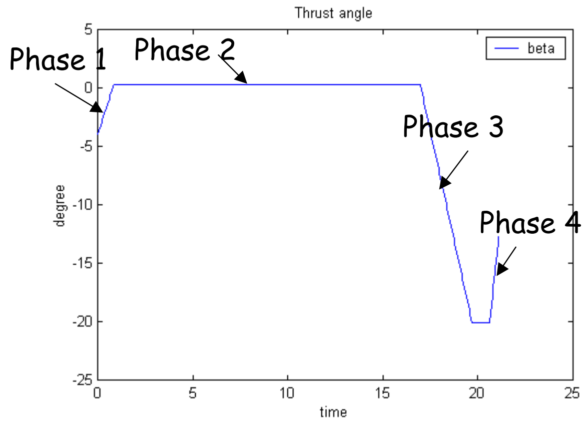

Fig. 4 Controlling the thrust angle for OEI-CL maneuver

From Fig. 4, 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. Second, 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 tilting back β at a constant rate of $\left(\frac{d\beta}{dt}\right)_2$ = –22 deg/sec until β_{long} reaches –20 deg. In the final phase, at a point h < 0.8m, β is increased for touching down.

3 Sensitivity of landing maneuver to tolerances

3.1 Initial strategy

Next, a sensitivity analysis is performed consisting of varying the flight parameters with the tolerances specified in the JAR-STD regulation. Table 1 shows the acceptable tolerances for the parameters involved in the OEI landing test [1].

Table 1: Tolerances prescribed by JAR-STD for handling qualities validation [2]

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 maneuver 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 maneuver, these deviations being attributed to the flight simulator tolerances. From the tolerances as given in Table 1 it can be demonstrated 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 standard.

Implementing the extreme cases 2 and 3 in the equations of motion (1), the footprint (x,h) of the helicopter as it approaches the landing can be plotted. Fig. 5 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.

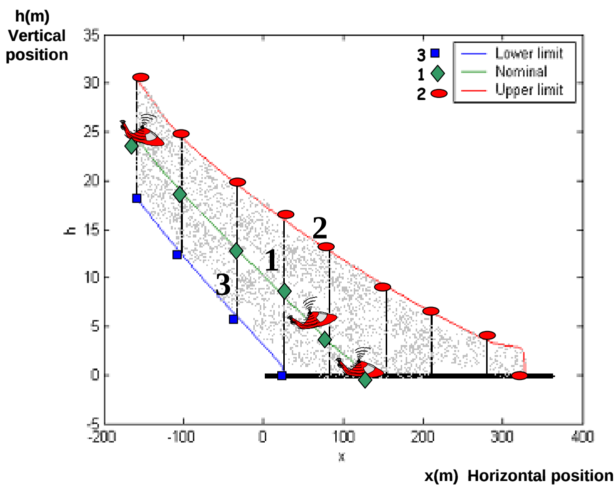

Fig. 5 The helicopter footprint including the sensitivity of tolerances

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}= 4.5 m/sec. This region is converted into Fig. 6 for the touchdown points.

H_{decel}=3.8m;

$$\left(\frac{d\beta}{dt}\right)_1 = 0.3\,\mathrm{deg/sec};\ \left(\frac{d\beta}{dt}\right)_2 = -22\,\mathrm{deg/sec}$$

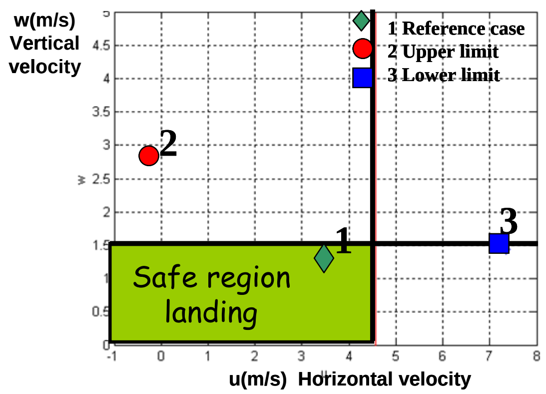

Fig. 6 Sensitivity of the touchdown point to JAR tolerances

From Fig. 6, 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.

3.2 Changing the altitude where the flare is initialized

Consider next a change in the strategy when executing the OEI-CL maneuver, in that the pilot decides to change the height h= 3.8m at which the flare maneuver is initiated, still following the same β law defined by Fig. 4.

Hdecel=4.82m;

$$\left(\frac{d\beta}{dt}\right)_1 = 0.3\,\mathrm{deg/sec};\ \left(\frac{d\beta}{dt}\right)_2 = -22\,\mathrm{deg/sec}$$

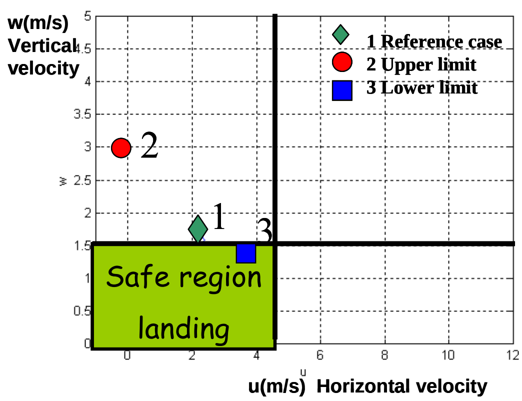

Fig. 7 Flaring at higher altitude

Hdecel=3.3m;

$$\left(\frac{d\beta}{dt}\right)_1 = 0.3\,\mathrm{deg/sec};\ \left(\frac{d\beta}{dt}\right)_2 = -22\,\mathrm{deg/sec}$$

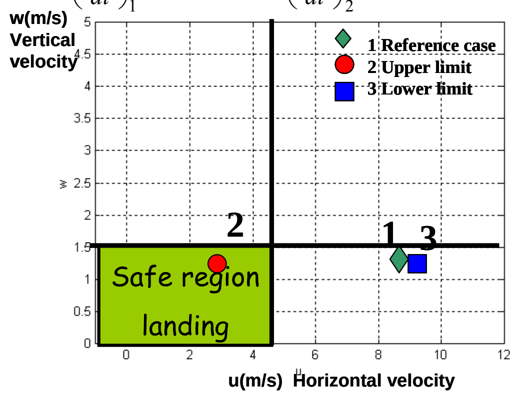

Fig. 8 Flaring at lower altitude

Fig. 7 and Fig. 8 present safety region plots for two new cases: when the flare is initiated at a height h= 4.82m (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. From these figures it can be concluded that changing the piloting initial altitude where the flare is initialized (change of piloting strategy) gives, for some cases, a false impression of safety in the simulator (see point 3 in Fig. 7 corresponding to the lower limit in tolerances and point 2 in Fig. 8 corresponding to the upper limit in tolerances).

3.3 Changing the pilot quickness in reacting to the engine failure

Consider next a change in the strategy when executing the OEI-CL maneuver, in that the pilot decides to apply a new strategy in controlling β now in the initial phase of landing. Fig. 9 and Fig. 10 present safety region plots for two cases: when the flare is initiated at the same initial height h=3.8 m but the pilot is reacting more promptly to the engine failure and starts decreasing quicker the power required $\left(\frac{d\beta}{dt}\right)_1$ = 0.36 deg/sec and when the pilot starts reacting slower in the initial phase of engine failure and starts decreasing later the power required $\left(\frac{d\beta}{dt}\right)_1$ = 0.24 deg/sec.

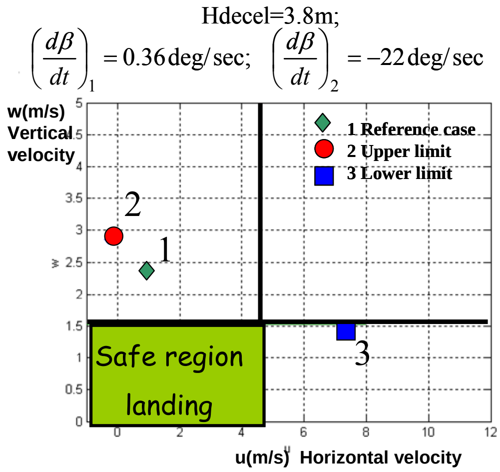

Fig. 9 Pilot reacting slower to the engine failure ($\left(\frac{d\beta}{dt}\right)_1$ is decreasing)

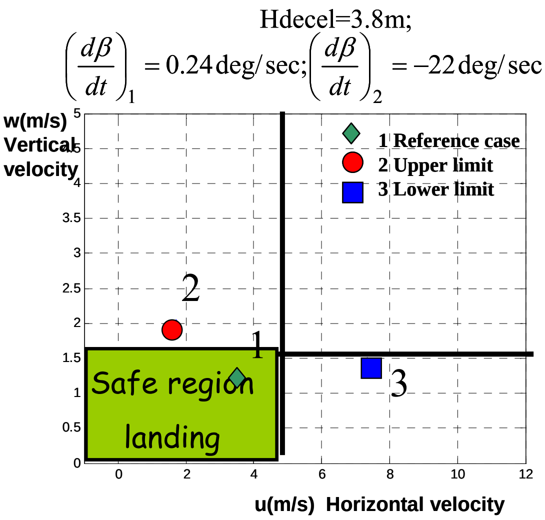

Fig. 10 Pilot reacting slower to the engine failure ($\left(\frac{d\beta}{dt}\right)_1$ is increasing)

From these figures it can be concluded that, when the pilot reacts slower in the simulator he/she may get the impression in the simulator that they will touch down outside the safety region which is actually a false impression.

3.4 Changing the pilot quickness in performing the final phase of flare

Consider next a change in the strategy when executing the OEI-CL maneuver, in that the pilot decides to apply a new strategy in controlling β_{long} in the final phase of the flare.

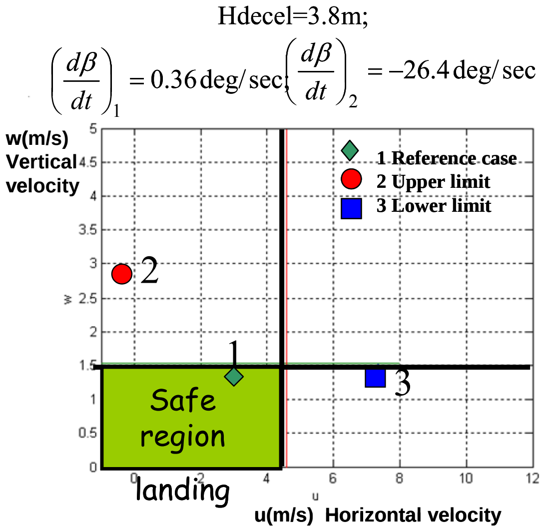

Fig. 11 Flaring more aggressively

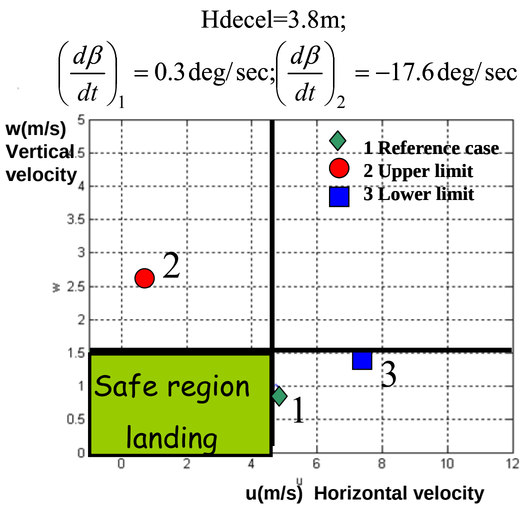

Fig. 12 Flaring less aggressively

Fig. 11 and Fig. 12 present safety region plots for two new cases: the flare is initiated at the same initial height h=3.8m but now the final flare is performed first more aggressively with a change in β at a rate $\left(\frac{d\beta}{dt}\right)_2$ = - 26.4 deg/sec and then less aggressively by changing β in the final phase at a rate $\left(\frac{d\beta}{dt}\right)_2 = -17.6$ deg/sec. From these figures it can be concluded that, while performing more aggressively gives the pilot the impression of being outside the safety region at the extreme of the tolerances, reducing the aggressiveness in executing the maneuver moves all the touchdown points outside the safety regions.

4. Conclusions

Concluding, the exercise of the paper was to analyze the effects of simulator tolerances on the pilot simulations. It has been demonstrated that flight simulator tolerances are highly sensitive on the nature of the maneuver performed. In this sense, a strategy has been first defined for controlling optimally the tilting of the thrust vector when performing the one engine inoperative continuous landing (OEI-CL) with helicopter. This strategy was implemented in a simulator considering also the simulator errors introduced by JAR tolerances. Next, the strategy in performing the OEI-CL maneuver was changed by changing 1) the altitude where the pilot decide to perform the flare; 2) the pilot quickness in initiating the flare 3) the pilot quickness in controlling the thrust vector in the last phase of flare. The paper demonstrated that the most "dangerous" change in the OEI strategy in the simulator is related to the altitude where the flare is initiated (equivalent to the decision of pilot to store more or less energy in the rotor). In this sense, deciding to initiate the flare at a higher and respectively lower altitude results in false impression of safety using a model tuned in the lower tolerances limits and respectively upper tolerances limits. Deciding to flare more aggressively in the last phase of flare or to react slower to the engine failure gives in the simulator a false impression of increased danger.

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