Flight Training Simulator Fidelity Requirements to Address 'Rotorcraft Loss of Control In-flight'

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ABSTRACT

This paper examines the trends in rotorcraft accident statistics, particularly regarding Loss of Control In-flight accidents (LOC-I), with the aim of stimulating interest in new research relevant to this area. Despite recent safety initiatives, LOC-I rotorcraft accidents have been identified as a significant and growing contribution to accident rates. The fixed-wing commercial airline community faced a similar situation starting in the late 1990s and, through a coordinated international effort, developed a new training program to help reduce accident rates. Lessons learned from the fixed-wing work are presented to highlight the need for improved rotorcraft modeling tools to reduce rotorcraft accidents through higher-quality, simulator-based training programs. The findings from previous and ongoing rotorcraft modeling and simulation research are presented, and areas for further research are identified. A proposal is made in the paper for a workshop to bring together the key rotorcraft stakeholders to develop future steps in tackling rotorcraft LOC-I accidents.

NOTATION

ASID	Additive System IDentification
AG	Action Group
CAST	Commercial Aviation Safety Team
CS	Certification Specification
EAP	Emergency and Abnormal Procedures
EHSAT	European Helicopter Safety Analysis Team
EHSEST	European Helicopter Safety Team
EPAS	European Plan for Aviation Safety
FFS	Full Flight Simulator
FNPT	Flight and Navigational Procedures Trainer
FSG	Flight Simulation Group
FSTD	Flight Simulation Training Device
FTD	Flight Training Device
HQ	Handling Qualities
H-SE	Helicopter Safety Enhancement
ICATEE	International Committee for Aviation Training in Extended Envelopes
IHST	International Helicopter Safety Team
IR	Intervention Recommendations
LOC	Loss of Control (including ground events)
LOC-I	Loss of Control In-flight
LTRE	Loss of Tail Rotor Effectiveness
MCC	Multi-Crew Cooperation
NTSB	National Transportation Safety Board
OEI	One Engine Inoperative
OMCT	Objective Motion Cueing Test
SD	Spatial Disorientation
SID	System IDentification
SME	Subject Matter Expert
SPS	Standard Problem Sets
SWR	Stepwise Regression
UPRT	Upset Prevention and Recovery Training
USHST	US Helicopter Safety Team
USJHSAT	US Joint Helicopter Safety Analysis Team

INTRODUCTION

The safety of rotorcraft operations has been a major area of concern for the past few decades. Several initiatives have been introduced to reduce accident numbers and rates through improved designs, operational procedures, training and reinforcement of a safety culture in operators. In his 2006 Alexander Nikolsky Lecture, “No Accidents – That’s the Objective” (Ref. 1), Franklin Harris cited his analysis of over 10,000 accidents statistics in the period 1964 – 2005, (derived from his previous NASA report (Ref. 2)), identifying a number of concerning trends. As shown in Figure 1, whilst there was a downward trend in the number of accidents per year over the period, the roughly linear trend suggested that, at the current rate it will be 2060 before the numerator of any accident statistics would become “*zero*”. Within the data shown, several observed “*spikes*” were attributed to the introduction of new aircraft types into the fleet, which serves as a word of caution for the current drive to develop new eVTOL aircraft. Careful consideration of the design, handling qualities (HQs) and operation of new vehicles should be central to any new rotorcraft development. This need to improve vehicle design, producing vehicles with improved handling qualities to the point “*where pilot errors, in any shape or form attributable to deficient flight characteristics, are things of the past*” was a key message from Padfield’s 2012 Alexander Nikolsky lecture (Ref. 3).

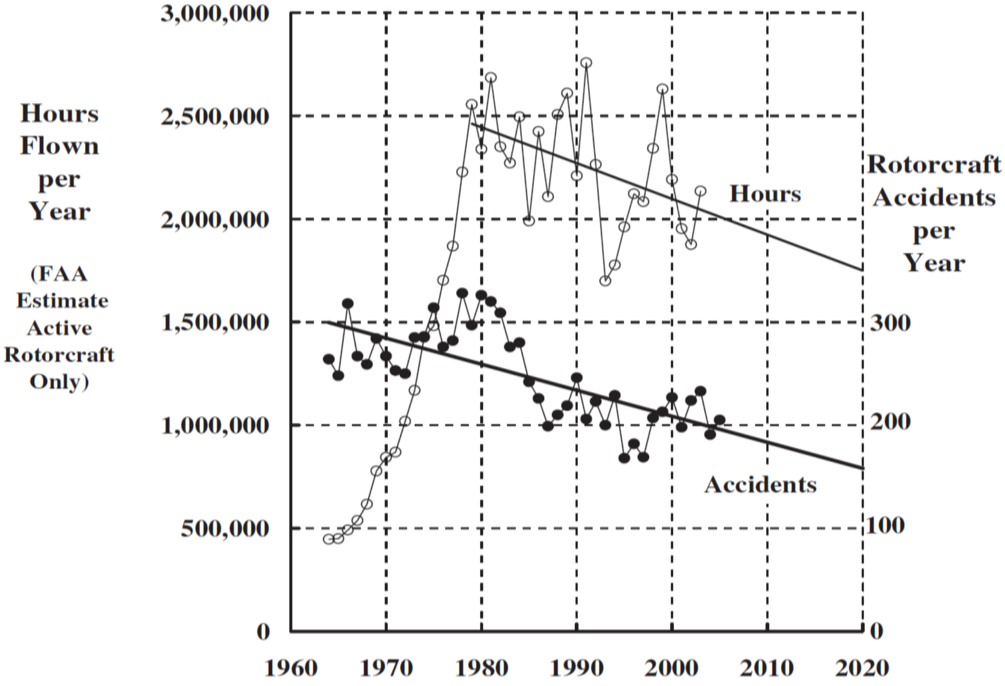


Figure 1. Hours flown and accidents per year (Ref. 2).

In his analysis, Harris also drew attention to a range of HQs issues e.g. poor autorotational performance and the susceptibility of the loss of directional control in the current fleet. He identified an undesirable trend that Loss of Control In-flight (LOC-I) related accidents had doubled as a percentage in the period analyzed, as shown in Figure 2, accounting for 12% of commercial and 32% of general aviation accidents. Harris made several recommendations to improve rotorcraft safety including continuing to review the accidents statistics, encourage academia to be more involved with research to improve rotorcraft safety, and to “*beg, borrow or steal a copy of NASA/TM-2000-209597*” (Ref. 2) to better understand where gains in safety can be achieved.

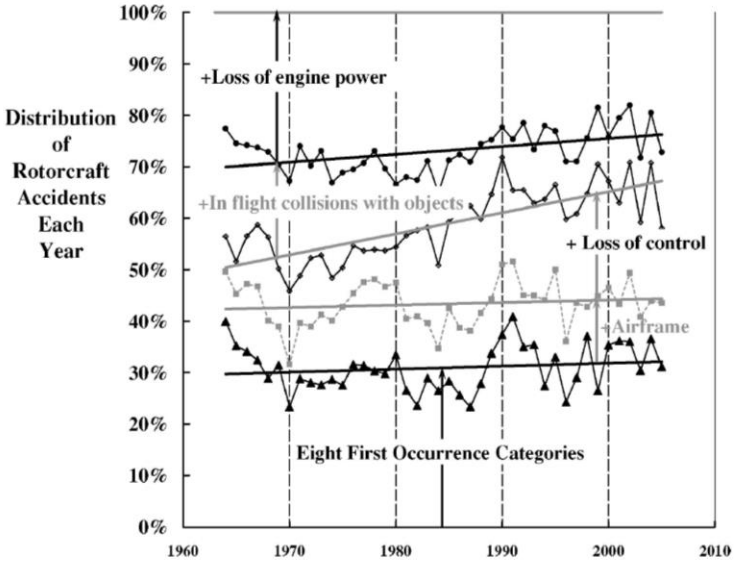


Figure 2. Illustration of the increase of LOC accidents (Ref. 2).

Following on from Harris' work, the need to reduce accident rates was the focus of the International Helicopter Safety Team (IHST). Formed in 2005 to address factors affecting the "*unacceptable*" helicopter accident rate, the IHST's mission was to facilitate an 80% reduction in accident rates by 2016. Its strategy for tackling accident rates was based on the data-driven approach used by the Commercial Aviation Safety Team (CAST) formed in 1997. Figure 3 shows the change in the accident rates following the start of the IHST initiative.

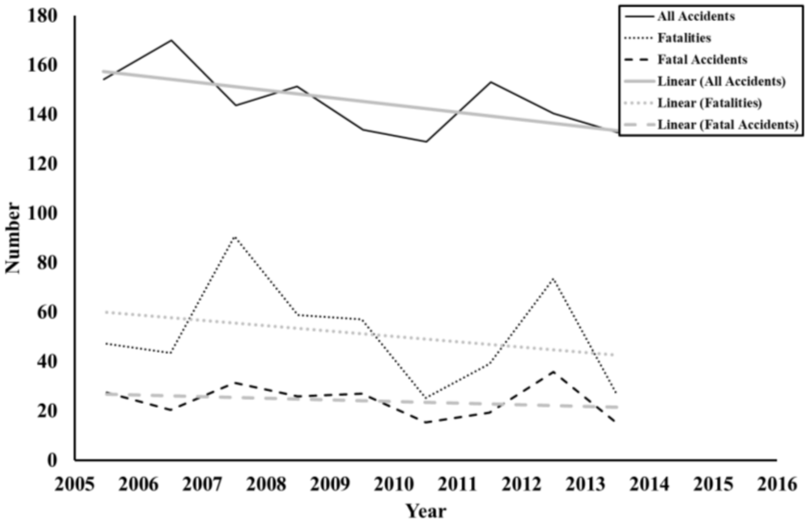


Figure 3. Accident rate trends following IHST initiative (Ref. 4).

Whilst there has been a decrease in the total number of accidents during the IHST activities (over 20% achieved by 2016) this has not met the target that was set. The trend for the number of fatal accidents appears almost flat suggesting that a "zero-accident" year might not occur until after 2040.

To understand the main causal factors of accidents, the US Joint Helicopter Safety Analysis Team (USJHAT) completed a review of 523 U.S. helicopter accidents from 2006 to 2011. The review identified that loss of control (LOC) was the main factor in 217 (41%) of the accidents (Ref. 5) as shown in Figure 4. LOC occurrences, which include ground events, are defined when the pilot loses control due to improper handling of the aircraft e.g. due to poor performance management or improperly responding to an onboard emergency, rather than due to a structural or mechanically-initiated problem.

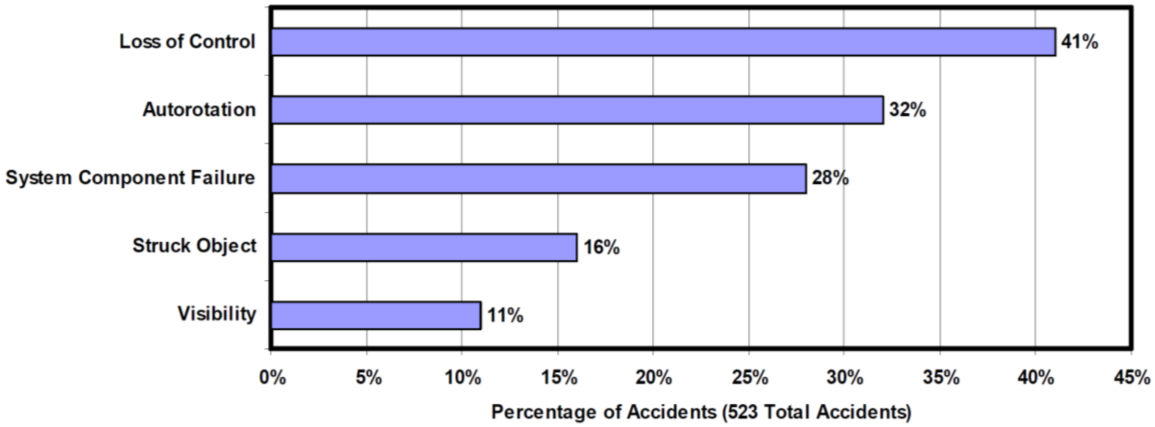


Figure 4. Top five occurrence categories in USJHAT study (Ref. 5).

It is evident from these statistics that further work is required to reduce LOC accidents and improve safety. Lessons learned from other aviation safety initiatives could help with this process. For example, CAST's work led to a reduction in the fatality risk for commercial aviation in the United States by 83% from 1998 to 2008, and the LOC-I problem was tackled through an international collaborative effort (International Committee for Aviation Training in Extended Envelopes (ICATEE)) to successfully address the problem.

The aim of this paper is to examine the key success factors, and lessons learned, from the ICATEE activity, and to stimulate new research collaborations to reduce rotorcraft LOC-I accidents. The next section describes the ICATEE activity and how it led to the development of a new Upset Prevention and Recovery Training (UPRT) program. UPRT uses training simulators to support the total training requirement, to address fixed-wing LOC-I accident rates. A review of rotorcraft safety initiatives follows this, identifying where some of the rotorcraft modeling and simulation challenges exist. A review of current rotorcraft flight-model fidelity and motion fidelity research is then presented. The paper is drawn to a close with a discussion on future research challenges together with potential next steps for initiating a new rotorcraft safety activity and some concluding remarks.

LESSONS LEARNED FROM THE FIXED-WING WORLD

Lambregts et al. (Ref. 6) undertook a review of fixed-wing upset accidents over a 15-year period (1993 – 2007) using, in part, the annual commercial airline accident statistics report produced by Boeing (Ref. 7). At this time, an aircraft upset was defined as any event with:

- Pitch exceeding +25/-10 degrees,
- Bank angle exceeding ±45 degrees, or
- Inappropriate airspeed

Lambregts et al. challenged this definition, citing the Armavia Flight 967 accident at Sochi where the aircraft had a pitch attitude of only -5 degrees, well within the limits above, but due to the low altitude of the aircraft it was not in a "normal" condition. (ICATEE subsequently redefined an upset as an "*unintended deviation from the desired flight path*"). Ref. 6 also indicated that upset/LOC accidents are not problems confined to general aviation or military fighters, they also happened to transport airplanes in scheduled service. Furthermore, LOC-I accidents were reported as "*not a problem of yesteryear*" (see Figure 5). Their analysis of the statistics highlighted the need for research to solve the root causes of this problem; stall was subsequently identified as the main causal factor leading to LOC-I accidents (see Figure 6). Based on their analysis, the need for new regulations and training programs was identified to improve flight safety. This would require a coordinated approach to address prevention of such upsets and recovery from them.

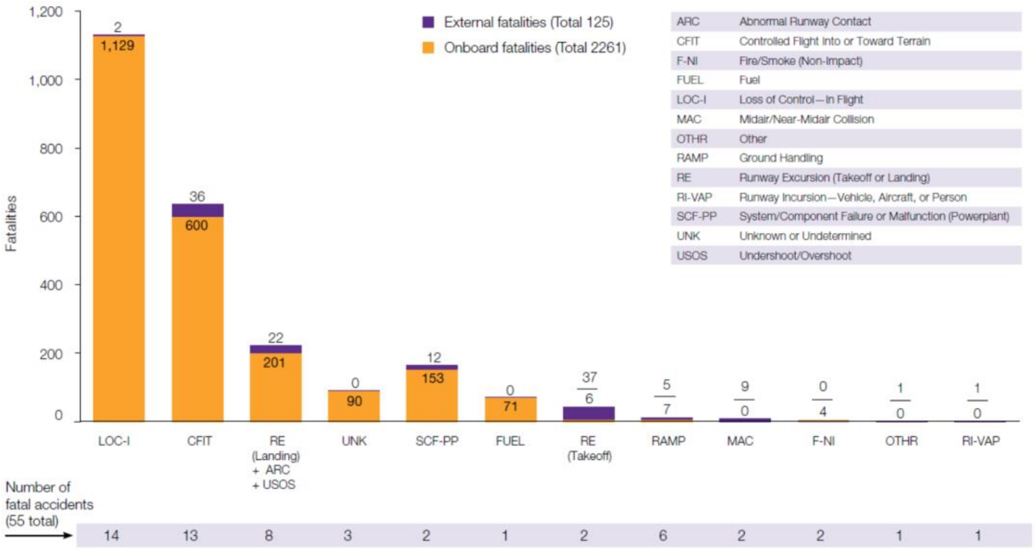


Figure 5. Aviation occurrence categories 2008 – 2017 (Ref. 7).

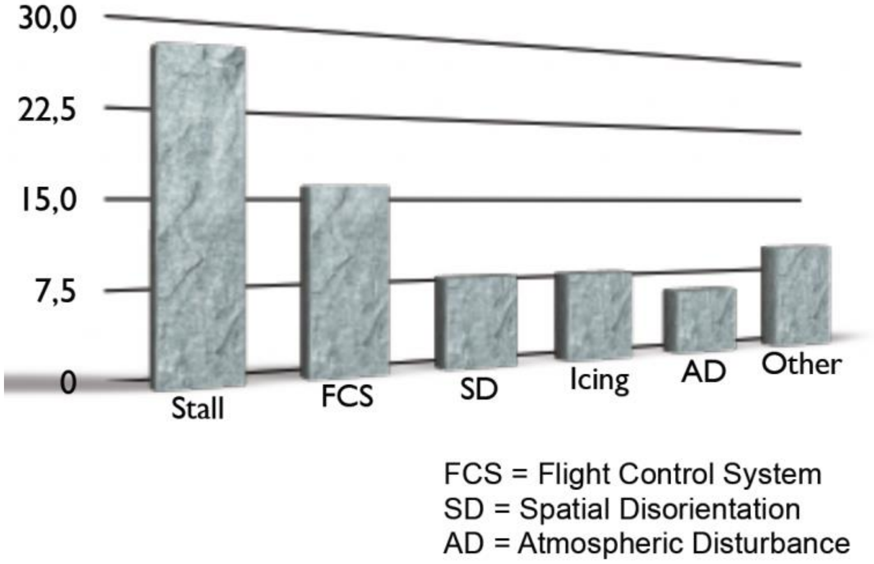


Figure 6. Numbers of LOC-I incidents and contributing factors.

The need to develop new training requirements was also identified in the National Transportation Safety Board (NTSB) report on the 2009 Colgan Air accident. The report indicated that the probable cause of the accident was the captain's inappropriate response to the activation of the stick shaker. This led to an aerodynamic stall and a loss of control on approach from which the airplane did not recover (Ref. 8). Published in 2010, the NTSB report contained several recommendations including the need to: "*Define and codify minimum simulator model fidelity requirements to support an expanded set of stall recovery training requirements, including recovery from stalls that are fully developed. These simulator fidelity requirements should address areas such as required angle-of-attack and sideslip angle ranges,* ***motion cueing*** (authors' emphasis added), *proof-of-match with post-stall flight test data, and warnings to indicate when the simulator flight envelope has been exceeded*".

The need to address LOC-I accidents for fixed-wing aircraft was a central theme for the Royal Aeronautical Society's Flight Simulation Group (FSG) 2009 Spring Conference entitled: 'Flight Simulation: Towards the Edge of the Envelope' (Ref. 9);

this initiative was also cited in the NTSB Colgan Air accident report. UPRT was proposed as a major potential contributor to enhancing aviation safety, primarily since it would introduce measures to prevent upsets. The loss of Air France 447 coincided with the start of the conference, a sobering reminder of the importance of the work to come. ICATEE was formed during the FSG Conference to deliver a long-term strategy for reducing the rate of LOC-I accidents and incidents through enhanced UPRT (Ref. 10). A key factor in the success of the work was that the committee consisted of more than 80 members drawn from manufacturers, airlines, national aviation authorities and safety boards, simulator manufacturers, training providers, research institutions, academia and pilot representatives.

ICATEE analyzed the causes of LOC-I and created two work streams. The Training and Regulations Stream addressed the development of a UPRT requirements matrix, and the Research and Technology Stream performed a thorough analysis of the technological requirements for UPRT (Ref. 11). The Technology stream reported that enhanced flight dynamics models representing post-stall behavior and icing effects were lacking. Key recommendations from the ICATEE work were as follows:

- It required an integrated approach across the fixed-wing community including manufacturers, airlines, national aviation authorities and safety boards, simulator manufacturers, training providers, research institutions and pilot representatives,
- For awareness and recognition (i.e. “prevention” training), current simulators without modification could be utilized if used in a more meaningful and proper manner,
- Type-representative models are suitable for the recovery training from stalls. Models do not need to be exact per aircraft type, but need to support the training objectives,
- Academics: the development and maintenance of applicable knowledge, complementing simulator training, to improve the pilots’ awareness of the fundamentals of aerodynamics, stall, cockpit indications, and human factors,
- Enhancements require validation by Subject Matter Expert (SME) pilots, who must be properly qualified to assess the enhancements,
- Enhancing the training benefits that can be derived from a range of training media.

Above all, international standards and civil aviation regulations would have to be adjusted to accommodate the new UPRT requirements (training, licensing and Flight Simulation Training Devices (FSTDs)).

The impact of the ICATEE work is that their recommendations resulted in a new ICAO Document 10011, “Manual on Aeroplane Upset Prevention and Recovery Training” (Ref. 12). National Aviation Authority regulations have also been impacted, with EASA UPRT requirements expected to be mandatory by December 2019 and the FAA requiring all Part 121 airline pilots to be UPRT-trained by March 2020. LOC-I prevention and UPRT feature strongly in the European Plan for Aviation Safety (EPAS) (Ref. 13), with several Rule Making Tasks identified to improve safety by engaging key stakeholders e.g. pilots, instructors, examiners, Airline Training Organizations and operators. To ensure that the fixed-wing simulator qualification process keeps in line with the new training programs, specifically related to UPRT, it has been acknowledged that updates to the simulator standards are required (Ref. 14), reflecting the need for a more dynamic and data-driven approach to standards development.

In terms of applying the lessons learned from the ICATEE work to future rotary wing LOC-I safety activities, there are a range of transferable items that would benefit any future initiatives. Adopting the approach suggested by Harris and ICATEE to conduct a thorough review of causal factors, related to both accidents and current training practices and needs, would be an important first step to define future work activities. LOC-I contributing factors maybe similar in both domains e.g. distraction or ineffective pilot monitoring. This could be addressed by developing skills for improved recognition and awareness of these events, especially when working as part of a crew. UPRT aids pilots in developing a mental model of how they, and the aircraft, are oriented in space; adopting this approach would also benefit rotary-wing pilots. Training exercises are learnt by rote and hence pilots have an expectation of what is to occur during the session. Exposing them to a different scenario so that they can experience the “startle” factor could aid them in managing stressful events in the future. ICATEE required a coordinated effort, not just in terms of stakeholders, but also in the media used to deliver the training.

One of the most significant ICATEE findings was that pilots often do not understand the concepts of angle of attack or energy management. A “fix” to this problem was to use flight simulators as a teaching tool rather than a testing device or a systems trainer. The ICATEE team determined that 56% of the new training program could be developed with existing Level D simulators combined with academic lessons (Ref. 11). To achieve further benefit from the use of simulators would require flight-model enhancements to better represent the missing physics e.g. post-stall behavior. A similar approach could be adopted for rotary wing applications, namely identify the main causal factors and conduct a task analysis to identify gaps in current flight models that need to be addressed.

Another addition to FSTDs that supports UPRT is the ability for the instructor to receive real-time feedback on the validity of the flight model. During some maneuvers, the pilot may tend to bring the simulator to the edge of the validated flight envelope. Clearly, this should be reflected to the instructor in order to ensure that the FSTD response accurately reflects reality.

ROTARY WING SAFETY INITIATIVES

One aim of this paper is to stimulate new collaborative research that could inform new regulatory activities to reduce the number of rotorcraft LOC-I accidents. Hence, existing safety-related research initiatives need to be acknowledged. As stated previously, setting the IHST goal to reduce the worldwide helicopter accident rate by 80% in the decade to 2016 has led to a reduction in accident rates from 4.61 to 3.49 per 100,000 hours. It has also catalyzed further analysis of the causes of rotorcraft accidents, identifying that LOC-I was a factor in 41% of the accidents analyzed.

The portrait of a typical LOC-I accident is given in Ref. 15. A Bell 206L-1 Long Ranger was being used to carry out a medivac operation at night in instrument meteorological conditions. The last minute of data depicted a turn to the left, a turn to the right, a reversal to the left, a reversal back to the right, and then a final reversal to the left (Figure 7). The NTSB report states the "*…probable cause(s) of this accident [may be] the pilot's loss of aircraft control, due to spatial disorientation, resulting in the in-flight separation of the main rotor and tail boom.*"

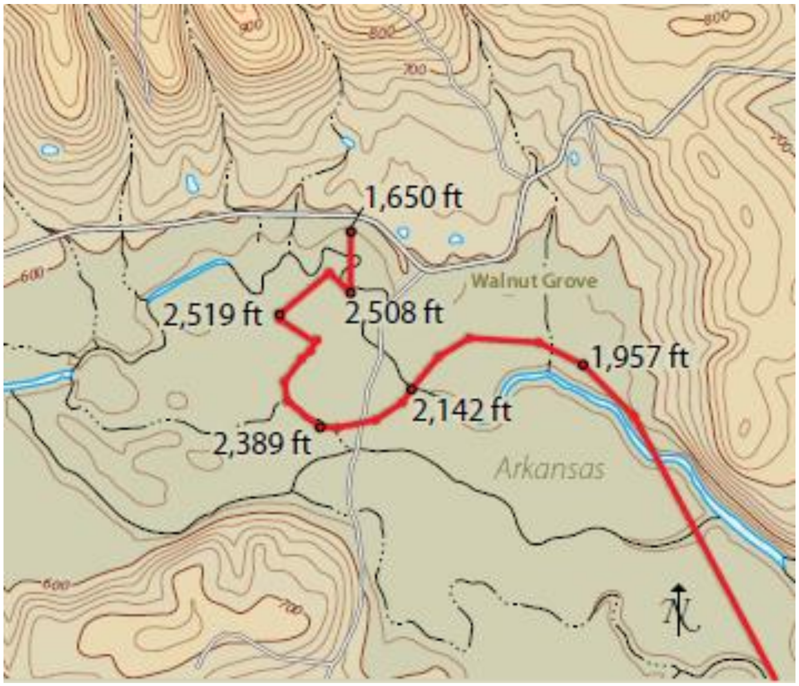


Figure 7. Final maneuvers prior to accident (Ref. 15).

The USJHAT proposed a range of intervention recommendations (IRs) (see Figure 8) to reduce accident rates (Ref. 16) including the following training (T) related IRs:

- T1060 - Simulator Training – Basic Maneuvers, Develop and implement a standard for pilot training focusing on operational-specific scenarios, human factors, and the use of simulators and flight training devices (FTDs)

- T2060 - Simulator Training – Advanced Maneuvers. Incorporate simulators into training programs that would include dynamic rollover, emergency procedures training, ground resonance, quick stop maneuvers, targeting approach procedures and practice in approaches to pinnacle, unimproved landing areas, and elevated platforms

- T6019 - Training emphasis for maintaining awareness of cues critical to safe flight. Establish training programs that train and evaluate proficiency of critical issues such as systems failures, impending weather concerns, effects of density altitude, and wind and surface conditions that can become critical to safe flight.

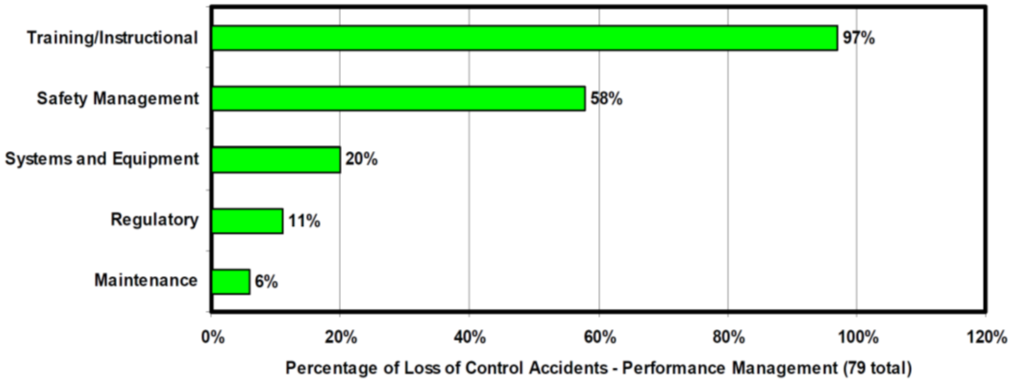


Figure 8. Top IRs from the USJHAT (Ref. 16).

(Note: Percentages are not to sum to 100% as each accident was assigned multiple intervention recommendations)

In 2016, the US Helicopter Safety Team (USHST, formed in 2013 as a regional partner with IHST) adopted a goal of achieving a 20% reduction in the US fatal helicopter accident rate by 2020. They undertook an analysis of 104 fatal helicopter accidents (2009–2013) to help identify the main common occurrence categories (Ref. 17). Using the CAST/ICAO Common Taxonomy Team (CICTT) occurrence categories, the three main categories contributing to half of the fatal accidents in that period were: LOC-I defined as loss of aircraft control or deviation from intended flightpath while in-flight, Unintended Flight in Instrument Meteorological Conditions and Low-Altitude Operations (Figure 9).

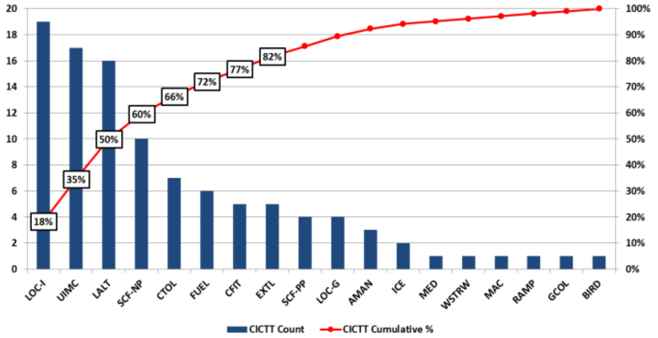


Figure 9. Pareto chart of U.S. civil helicopter fatal accident data (2009-2013) (Ref. 17).

This analysis of the accidents led to the identification of intervention strategies that could be implemented through Helicopter Safety Enhancement (H-SE) activities to tackle the underlying causal factors. Each H-SE identifies the organizations or groups who will implement the activity, a statement of the work required (informed by details of relevant accidents) and expected outputs; two simulator related activities are presented as follows.

H-SE 81, "Improve Simulator Modeling for Outside-the-Envelope Flight Conditions" was established to "*improve the accuracy of full flight simulators (FFS)/flight training devices by providing recommendations for developing better* ***mathematical physics-based models*** (authors' emphasis added) *for helicopter flight dynamics*". The goal is to "*achieve more realistic, higher-fidelity simulations of outside-the-envelope flight conditions*" and to examine the "*possible use of simulation for purposes of preventing, recognizing, and recovering from spatial disorientation*". H-SE 127A, "Training for Recognition Recovery of Spatial Disorientation" aims to "*develop training for recognition of spatial disorientation (SD) and recovery to controlled flight*." It is acknowledged in this H-SE that the helicopter community should promote the wider use of available SD simulation technology and training scenarios to create further awareness of impairment from SD and how to recover from such an event.

The need for the wider use of flight simulators to help pilots prepare for emergencies and improve safety is also acknowledged by the NTSB, in their 2015 Safety Announcement, "Safety Through Helicopter Simulators" (Ref. 18) where they note, "*it is difficult to recreate the element of surprise and the realistic, complex scenarios that pilots may experience during an emergency. Without simulators, viable lesson components may be limited*"; a theme also identified in the ICATEE work. The challenge here is to develop simulators and scenarios to help with this training. What are not included in this document are the simulation fidelity requirements to conduct such training.

In Europe, similar analyses of accident statistics have been undertaken (Ref. 19). The European Helicopter Safety Analysis Team (EHSAT), a sub-group of the European Helicopter Safety Team (EHEST) conducted reviews of two sets of accident data, 2000-2005 and 2006-2010. In this latter period some national teams were not able to analyze their results so only 30% of the 527 accidents that occurred were included in the analysis. The output of their data analysis was not presented in the same manner as the USHST's work making direct comparisons of the main accident causal factors difficult. Figure 10 shows the standard problem statements (SPS) Level 1 (IHST taxonomy of the 14 main factors contributing to an accident) that were identified in the two periods. Pilot judgment featured in almost 70% of all accidents analyzed and situation awareness in more than 33% of accidents; there were only small reductions in both in the 10-year period analyzed.

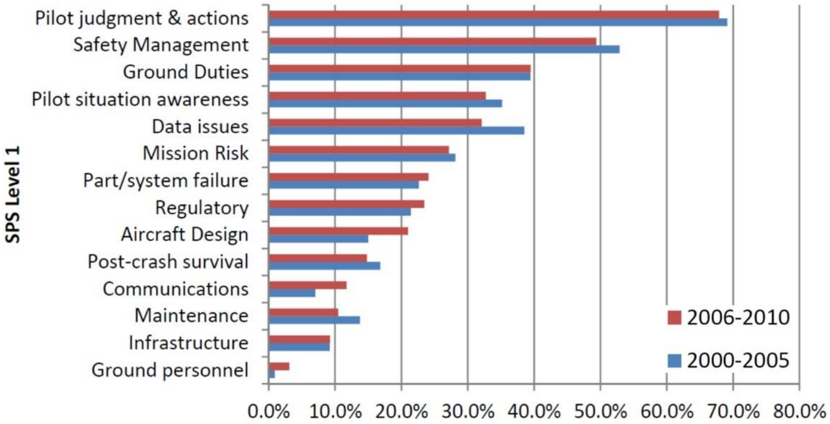


Figure 10. Percentage of analyzed accidents where SPS Level 1 was assigned at least once (Ref. 19).

The report does identify various IRs to address these problems (see Figure 11) and the results were aimed at informing the content of the rotorcraft section of the European Plan for Aviation Safety (EPAS) (Ref. 13). A training/instructional IR was identified as one of the leading IRs, although how to conduct this is not described and the need for new research was not identified as a key IR.

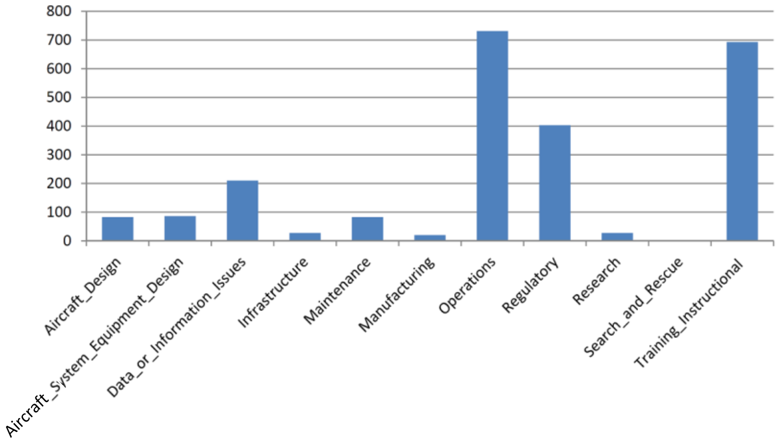


Figure 11. Number of IRs Level 1 – all accidents 2000-2010 (Ref. 19).

As part of the instructional IRs, EHEST has produced a variety of material to raise awareness of safety issues in the rotorcraft community. Reference 20, ("Training and Testing of Emergency and Abnormal Procedures in Helicopters") shows that a significant number of helicopter accidents occur during the training or testing of emergency and abnormal procedures (EAP). The leaflet aims to provide guidance to instructors and examiners to safely deliver EAP in flight. For Upset/Unusual Attitude Training, it is recommended that it should be conducted in good visual meteorological conditions with the candidate's visibility limited by screens or goggles. This type of training, according to one former instructor (Ref. 21), has hardly changed in 30 years and it is not clear how more of the same training will address the LOC-I issue highlighted earlier. In the fixed-wing UPRT development, the introduction of "failures" that enhance pilot situation awareness and teach better orientation was highlighted as an area for improvement. These may not necessarily be failures in the aircraft systems, but instead "blanking out" certain portions of the outside world and/or instrument displays to query the pilot on their situation at that time. While these are not usually included in FSTDs, the fixed wing community has found them to be helpful during UPRT and SD training.

It should be noted here that the EPAS document identifies addressing offshore helicopter LOC-I accidents as a strategic priority. However no new research initiatives have been identified to help reduce offshore accidents. Furthermore, in the EASA research agenda, section 2.4 “Rotorcraft”, (Ref. 22), there are no initiatives relating to LOC-I to aid in the reduction of accident rates. The research agenda does highlight the need to think “*out of the box*” to look at how training with new device platforms e.g. virtual reality, could be used to provide innovation for FSTD qualification, but it does not deal with specific training needs.

Rotorcraft flight simulators in Europe are qualified through CS-FSDT(H) (Ref. 23) which includes the technical minimum requirements/standards for each level of qualification (or type). Within CS-FSTD(H), the following qualification level types are identified:

- Flight and Navigational Procedures Trainer I, II, III (FNPT)
- Flight Training Device 1, 2, 3 (FTD)
- Full Flight Simulator A, B, C, D (FFS)

Table 1 indicates the training value and credits that can be derived using the different kinds of flight simulator as part of an approved training program (Ref. 24). The main market for this training is the commercial aviation sector. Reference 24 states that to comply with Private Pilot Licensing requirements, trainees should have completed at least 45 hours of flight instruction, five of which can be completed in FSTDs. It also notes, given that safety analyses point to General Aviation (GA) being a significant contributor to the high number of accidents, FSTDs should be more widely used for PPL(H) training; echoing the USHST’s recommendations.

What is absent in these rotorcraft safety initiatives is a clear, coordinated strategy of how to use modeling and simulation to support training that reduces accidents, and the supporting research required to achieve this. As the increased use of simulators has been identified as an important part of a strategy to improve safety, questions arise regarding what level of fidelity is required to achieve a positive transfer of training and how might this be assessed? Central to the utility of a simulator for delivering effective training is confidence in the fidelity standards against which it has been qualified. Uncertainties in the validity of metrics contained in the standards could undermine the benefits of training devices. A review of previous modeling and simulation research follows in the next section to identify where new contributions could be made to enhance existing standards.

Table 1. Rotorcraft Simulation Training.

Simulator Type	Training Value	Training Credits
FNPT	Ab-Initio Procedures Training Instrument Training Navigation Safety Exercises Multi-Crew Cooperation (MCC)	Up to 30% ab-initio flight hours (ATPL integrated)
FTD	Type Rating Procedures Recurrent Training	Up to 67% type rating hours
	Ab-Initio Safety Exercises MCC	Up to 33% ab-initio flight hours
FFS	Type Rating Recurrent Training Navigation	Up to 83% type rating flight hours
	Safety Exercises MCC	Up to 36% ab-initio flight hours

ROTARY WING MODELLING AND SIMULATION RESEARCH

As previously mentioned, CS-FSTD(H) defines the criteria that need to be satisfied to allow the qualification of a simulator. From a safety perspective, the criteria contained within it should be robust and unambiguous. Several studies have been conducted to examine the validity of the CS-STD(H) tolerances and criteria; an overview of this research is provided here.

GARTEUR Action Group (AG) HC-AG12 was formed to conduct a critical examination of the then existing simulator standard, JAR-STD 1H (Ref. 25), (replaced by EASA CS-FSTD(H) in 2012), including correlation of handling qualities metrics and fidelity metrics (Refs. 26-28). The work revealed a range of shortcomings and opportunities to enhance the standards with new metrics. For example, the AG showed that the relationship between fidelity and the JAR-STD 1H tolerances is sensitive to the nature of the maneuver being flown and, more significantly, that matching tolerances does not always lead to matching handling qualities. AG12 also identified the need to bridge the gap between subjective opinion and formal metrics and the importance of developing an objective means for assessing overall fidelity.

In the previous section, using flight simulators to train for emergency situations was highlighted as an important approach for improving safety. In AG12, such a case was considered - One Engine Inoperative (OEI) landings, and the suitability of the CS tolerances were examined. The Federal Aviation Administration (FAA) regulations (Ref. 29) for emergencies required that, for Category-A certification (multi-engine helicopters), helicopters should be able to continue their flight with OEI. In the case of an engine failure occurring after the helicopter has passed the landing decision point the pilot must continue the landing. The CS simulation tolerances for this case are given in Table 2.

Table 2. CS-FSTD(H) OEI Tolerances.

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

A four degree-of-freedom helicopter model (including horizontal body-velocity, rate of descent, pitch rate and the rotor rotational speed) was used to examine three test cases: reference case (where no tolerances were applied), upper limit (using the "+" tolerances in Table 2), lower limit (using the "–" tolerances in Table 2); the resulting trajectories are shown in Figure 12. A safe landing region was defined where the touchdown was within acceptable velocity limits, namely vertical velocity (*w*) less than 1.5m/sec and horizontal velocity (*u*) less than 4.5m/sec.

The allowable tolerance ranges produce a landing scatter of +200/-90m from the reference case and moves the landing velocities outside of the safe region. From a safety point of view, this variation could lead to negative transfer of training giving the trainee an incorrect understanding of the performance of the helicopter in an emergency.

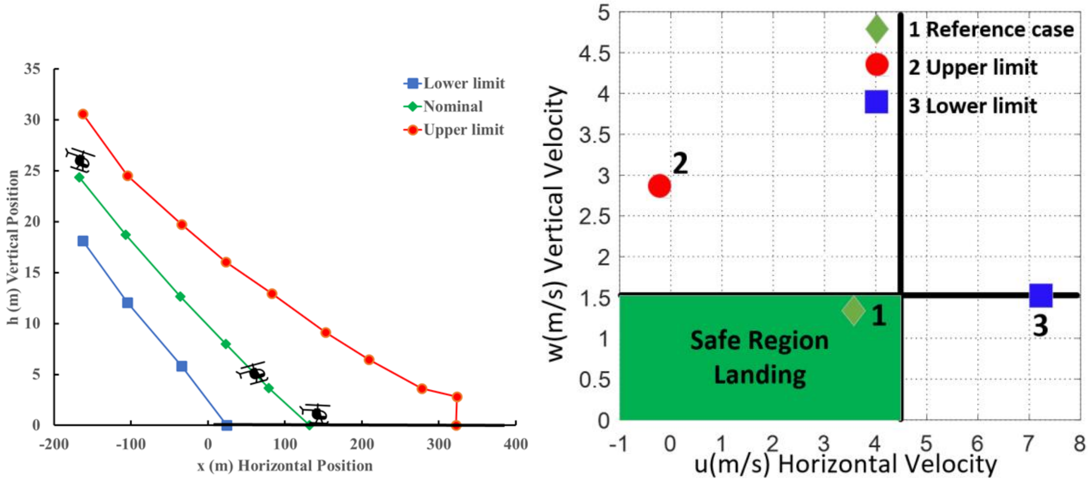


Figure 12. Helicopter landing footprint with simulation tolerances limits (Ref. 28).

Research has been conducted at the University of Liverpool (UoL) addressing the AG12 recommendations to develop a method for the subjective assessment of simulator fidelity and the formulation of new objective metrics. The simulator fidelity rating (SFR) scale (see Appendix 1) was developed in the Lifting Standards (LS1) project at UoL to provide a method for an evaluating pilot to directly rate the suitability of the overall simulation for a specified task (Ref. 30). The pilot is asked to compare the level of performance attained in flight and simulator, and to judge the level of 'adaptation' of task control strategy that was used in flight compared with simulation. New objective fidelity metrics (Ref. 31) were also developed in the LS1 project, based on ADS-33E-PRF HQ metrics (Ref. 32).

The methodologies developed in LS1 were used to investigate an objective criterion that is ill-defined in CS-FSTD(H), related to a flight-model's off-axis response (Ref. 33). CS-FSTD(H) states that, following a longitudinal input, the on-axis response of the simulation data should be within either ±10% of the achieved peak in the flight data, or ±3 deg/sec, whichever is less restrictive and the off-axis model response should be of "*correct trend and magnitude*" (CT&M) when compared to flight data. Figure 13 shows the on- and off-axis responses of a FLIGHTLAB Bell 412 (F-B412) simulation model (configured with a Rate-Command-Attitude-Hold (RCAH) system) following a 0.5-inch longitudinal input. Additional roll/pitch cross couplings were implemented in FLIGHTLAB by directing a proportion (20%, 50% and 100%) of the longitudinal control input into the roll axis. The off-axis responses exhibit the correct trend and so questions arise as to whether the magnitudes are "correct" and what effect the difference would have on a pilot's experience of the simulation?

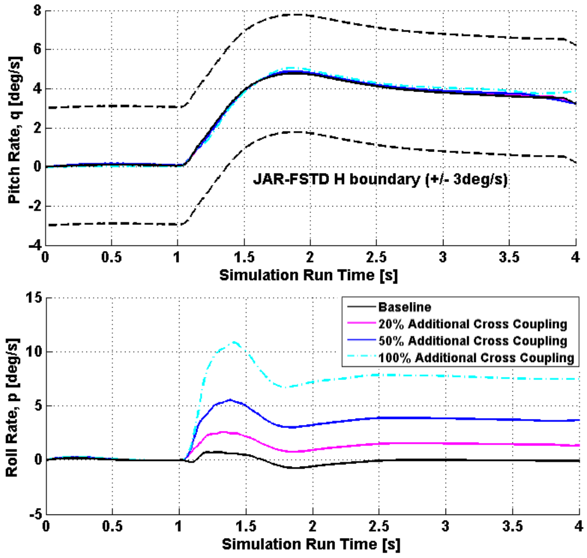


Figure 13. On and off-axis rate responses to a longitudinal cyclic input for cross coupling variations (Ref. 33).

One way to assess the effect of the additional cross-couplings is to use the inter-axis coupling criteria in ADS-33E-PRF (Ref. 32). This is defined, in this case, as the ratio of peak off-axis roll attitude response ($\Delta\phi_{pk}$) from trim, within 4 seconds, to the on-axis pitch attitude response from trim at 4 seconds, ($\Delta\theta_4$), following a longitudinal control step input. As additional cross-coupling is increased in the model the HQs degrade from Level 1 for the baseline (no addition cross-coupling) to Level 3, suggesting the fidelity of the model has been compromised (see Figure 14).

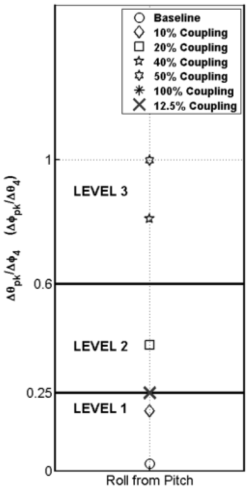


Figure 14. ADS-33E-PRF roll/pitch coupling requirements for aggressive agility (Ref. 33).

This was assessed subjectively using the SFR scale for an ADS-33E-PRF accel-decel maneuver. Pilots trained in the baseline configuration and then, following a model change, awarded an SFR based on their comparison with the baseline. The results in Figure 15 show that, as the cross-coupling increases, the SFRs awarded degrade from Level 1 to Level 3. This is indicative of a significant change in performance and considerable adaptation of task strategy (see Appendix 1). An additional cross-coupling value of 20% produced a mean SFR that was on the Level 1-2 SFR boundary indicating that, based on their subjective opinion, this would represent the boundary of an acceptable level of CT&M. Whilst these results are not comprehensive, they do show that a combination of new objective metrics and subjective assessments can be used to investigate revisions to the CS standards.

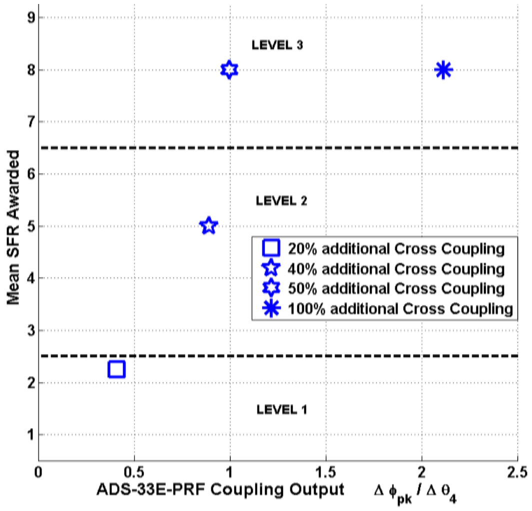


Figure 15. SFRs awarded for cross coupling tests.

To satisfy the proof-of-match tolerances for a Level D flight simulator, modifying or tuning the parameters of the flight simulation model using either a physical or non-physical process is permitted. System IDentification (SID) (Ref. 34) has been applied as an effective approach for informing this tuning process. A non-physical tuning approach has been developed by CAE (Ref. 35) which uses SID techniques to optimize simulation parameters which may not be known e.g. flap-hinge stiffness, to meet the flight simulator standards proof-of-match requirements. This approach satisfies the Level D requirements but does not necessarily capture any missing physics which may be important in LOC-I simulations.

In the LS1 project, SID was used to explore the fidelity of existing rotorcraft simulation models and to produce a rational, physics-based approach to simulation fidelity improvement through model renovation (Ref. 36). The renovation process involves augmenting the nonlinear flight-model based on differences in identified (stability and control) derivatives. Figure 16 illustrates the fidelity improvement of the renovated nonlinear FLIGHTLAB Bell412 model in the roll, pitch and yaw axes. Identification and renovation of non-physical modeling parameters in the simulation models are key to improving model fidelity, especially in dynamic maneuvers.

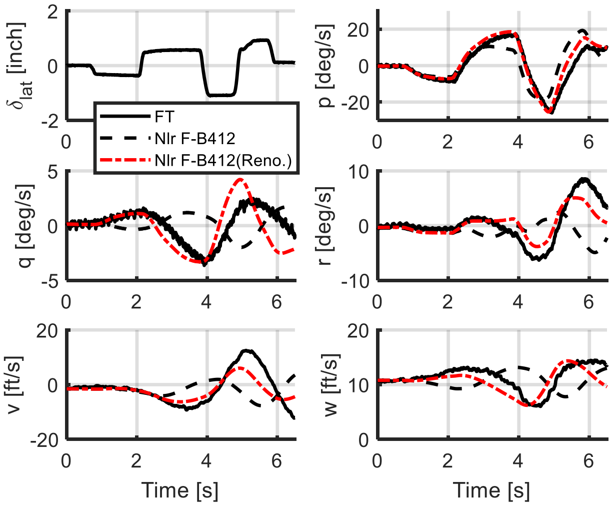


Figure 16. Comparison of responses from lateral cyclic input with the renovated nonlinear F-B412 (Ref. 36).

The above renovation method is to some extent limited due to the procedure relying on linear information extracted from the SID approach and the tuning process for repairing the deficiencies associated with the fidelity of a model. These limitations can put constraints on its application especially where nonlinearities and hereditary effects can influence the model's response, such as in edge-of-the-envelope and out-of-the-envelope flight regimes, where current flight-models are inaccurate. These deficiencies may lead to unrealistic training of maneuvers such as loss of tail rotor effectiveness (LTRE), vortex ring state/settling with power, and autorotation; topics noted for further research in the H-SE activities. The NTSB investigated 55 accidents involving LTRE during the 10-year period from 2004 to 2014. The results revealed that the pilots were unable to recover when the helicopters encountered unanticipated yaw suffered from the LTRE. Improved pilot training can help to reduce these accidents and improved simulator fidelity enables an increase in simulator/flight ratio in training.

At UoL, the Rotorcraft Simulation Fidelity (RSF) (Ref. 37) project has proposed a new identification approach in the time-domain, Additive System-IDentification (ASID), to address the nonlinearities associated with complex maneuvers. This is described in more detail in our companion paper at the VFS 75th forum (Ref. 38). In the ASID approach the model parameters are identified sequentially based on their contribution to the local dynamic response of the system, i.e. over a defined time range. One or more candidate parameters in a proposed model structure are identified using the primary response characteristic of the rotorcraft; others are then identified in a sequential manner.

The results in Figure 17 illustrate the effectiveness of the ASID approach, comparing with the linear perturbation (Pert.) method and the conventional StepWise Regression (SWR) approach in the time domain (Ref. 39). ASID and SWR were applied on the 6 degree of freedom roll dynamics, using an equation-error process. The roll acceleration $\dot{p}$ curves of ASID and SWR in Figure 17 were constructed using the identified derivative values (e.g. rolling moment due to roll rate, L_p) derived from the corresponding flight test data (e.g. roll rate p), respectively.

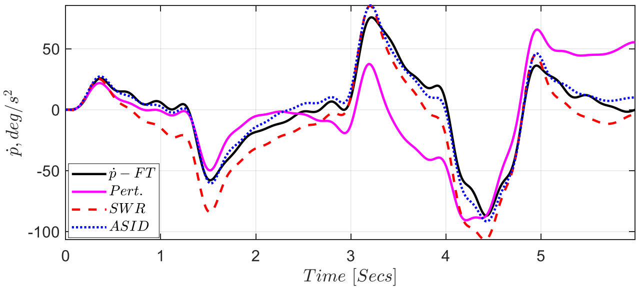


Figure 17. Comparison of fit across three approaches: Perturbation, SWR and ASID.

Figure 17 shows the best fit with flight test data is achieved by the ASID method. SWR shows a poorer fit between 0.5 and 3sec, mainly due to the poorly identified derivatives (e.g. rolling moment due to pitch rate, L_q). The fit with linear perturbation derivatives from the F-B412 diverges after 1.5sec, mainly due to L_q being significantly different from flight test. These results demonstrate the effectiveness of ASID to derive derivative values that result an improved fit. The RSF research is applying ASID to more complex maneuvers. Combining the results from different maneuvers in a new renovation process offers the potential for capturing a fuller range of physical effects that may be important, but only weakly present in simpler maneuvers.

MOTION CUEING RESEARCH

In 1910, Flight magazine (Ref. 40) reported, "*Even the most apt pupil is certain to find himself in difficulties at some time or another during his probation… The Invention therefore of a device which will enable the novice to obtain a clear conception of the workings of an aeroplane and conditions existent in the air without any risk personally or otherwise is to be welcomed without doubt. Several have already been constructed to this end, and the Sanders Teacher is the latest to enter the field.*" The Sanders "Teacher" (Figure 18) featured aircraft parts (a 'first' in simulators) and a turn-table and rocker system that allowed the trainee to experience the effect of wind in the simulator; a first step in motion cueing and the topic of "motion cueing" (and by this we are considering vestibular motion cueing), and its benefit in simulator-based training is still being debated.

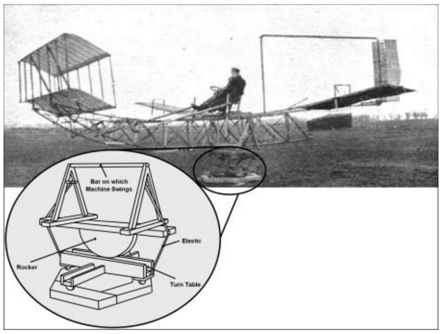


Figure 18. Sanders Teacher.

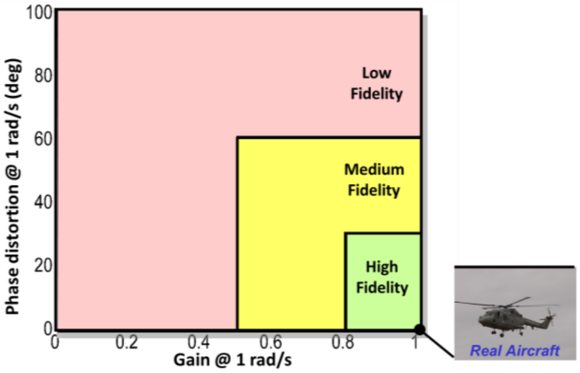
One of challenges in this debate is the lack of supporting evidence in the simulator standards regarding the benefit of motion cueing. Burki-Cohen et al. (Ref. 41) noted, "*The existing standards for flight simulation qualification, all of which entail a requirement for platform motion cueing, have a twenty-year record of meeting the requisite requirement for transfer of performance. In the absence of competing evidence to the contrary, it is therefore prudent to maintain these standards in the interest of public safety*". In a subsequent paper, Longridge et al. (Ref. 42) reported that in fixed-wing simulators motion improved the acceptability of the simulator, pilot performance and control behavior in the simulator, but found no evidence of the benefits of motion in transferring to the aircraft. McCauley (Ref. 43), investigated the need for motion bases in army helicopter simulators and found that, whilst flight simulators were identified as "*unquestionably valuable for training safely*", no evidence to support effectiveness of motion platforms for training was found.

When examining the current standards, there is no clear guidance on when motion is required for a given training task. As shown in Table 3 and there are no fidelity tolerances provided for the roll, pitch or sway motion envelopes provided. There are different motion requirements for the FSTD levels shown (e.g. A/B and C/D) but no rationale is provided for the validity of these criteria. For the 'lower' level FTD devices, there is no requirement for motion.

Table 3. CS-FSTD(H) Motion Requirements (Ref. 23).

TESTS	TOLERANCE	FSTD Level						
		FFS				FTD		
		A	B	C	D	1	2	3
4. MOTION SYSTEM								
a. Motion Envelope								
(1) Pitch								
(i) Displacement								
± 20°		✓	✓					
± 25°				✓	✓			
(ii) Velocity								
± 15°/s		✓	✓					
± 20°/s				✓	✓			
(iii) Acceleration								
± 75°/s^2		✓	✓					
± 100°/s^2				✓	✓			
(2) Roll								
(i) Displacement								
± 20°		✓	✓					
± 25°				✓	✓			
(ii) Velocity								
± 15°/s		✓	✓					
± 20°/s				✓	✓			
(iii) Acceleration								
± 75°/s^2		✓	✓					
± 100°/s^2				✓	✓			
(3) Yaw								
(i) Displacement								
± 25°			✓	✓	✓			
(ii) Velocity								
± 15°/s		✓	✓					
± 20°/s				✓	✓			
(iii) Acceleration								
± 75°/s^2		✓	✓					
± 100°/s^2				✓	✓			

Motion fidelity criteria have been proposed by Sinacori (Ref. 44) based on measures of the gain and phase shift between the flight-model output and the motion system commands at a frequency of 1rad/s. The criteria were developed from investigations of an ‘S’-turn maneuver along a runway at 60kts with a six-degree-of-freedom model of a high-performance helicopter. Figure 19 shows Sinacori’s translational fidelity criteria and the three-point fidelity rating scale used to elicit pilot opinion on the fidelity of the motion cues. It should be noted that Sinacori stated these criteria “*have little or no support other than intuition*”.



High	Motion sensations are close to those of visual flight
Medium	Motion sensation differences are noticable but not objectionable
Low	Differences are noticable and objectionable, loss of performance, disorientation

Figure 19. Sinacori’s translational fidelity criteria (Ref. 44).

Despite this statement, Sinacori’s criteria have been as the basis for motion fidelity testing. Hodge et al. (Ref. 45) reviewed research undertaken for roll-sway motion tuning. Figure 20 shows the results from this review. The different gains and break frequencies used in the studies are shown in parenthesis, suggesting that high fidelity motion can be achieved, based on Sinacori’s criteria, through selective tuning of the motion filter parameters.

Hodge et al. (Ref. 46) used a short-stroke hexapod simulator (Ref. 47) to investigate optimizing the cues with third-order filters in the roll and sway axes (A1 to A6 in Figure 20 indicate the configurations tested in Ref. 46). A 10-point motion fidelity rating scale was devised to elicit pilot opinion, since the participating test pilots considered the previous three-point scale to be too coarse to distinguish the subtle differences in motion cues (Ref. 48). Pilots judged that good motion cues could be obtained in a small motion platform by careful selection of the roll and sway-axis motion gains (K_ϕ, K_y) and that roll-axis break frequency ($\omega_{hp\phi}$) had a dominant effect on motion fidelity (see Figure 21).

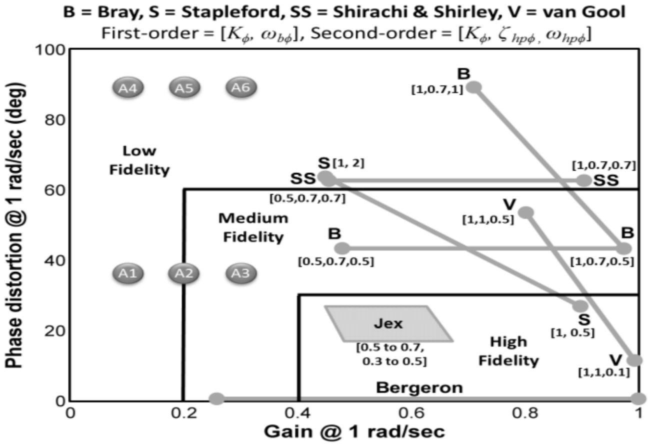


Figure 20. Sinacori's rotational fidelity criteria.

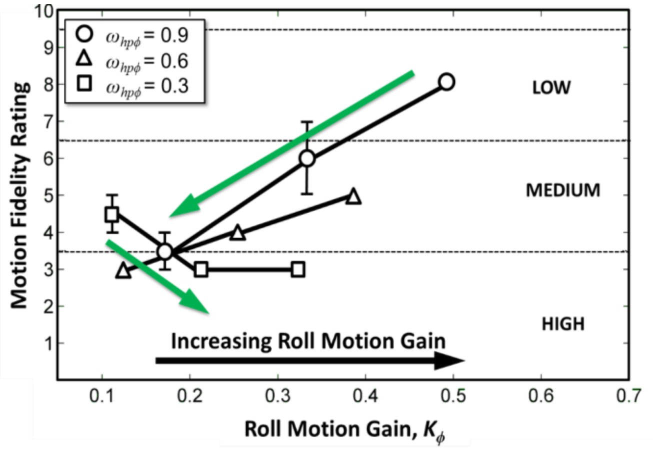


Figure 21. Effect of roll motion gain and break frequency on motion fidelity.

Whilst there have been several studies examining the effect of motion on single or limited axis tasks, there is still the need to examine the motion requirements for multi-axis tasks, considering aircraft with different levels of handling qualities undergoing a range of different dynamic maneuvers. Manso et al. (Ref. 49) conducted simulator experiments that examined the effect of motion cueing on task performance and workload for a range of test maneuvers. Three test pilots flew three rotorcraft response types - Attitude Command Attitude Hold (ACAH), Rate Command Attitude Hold (RCAH) and bare airframe; covering a range of handling qualities. The ADS-33E-PRF test maneuvers (bob-up, pirouette, precision hover, lateral reposition and accel/decel) were flown with different levels of task aggressiveness. A comparison was made for each maneuver between testing with no motion and a motion case, with a subjectively tuned set of motion drive laws. For the precision hover task, the results indicate that, as the HQs degrade, there is a larger difference in the HQ ratings (HQRs) awarded for the no-motion versus motion cases (Figure 22, Ref. 49).

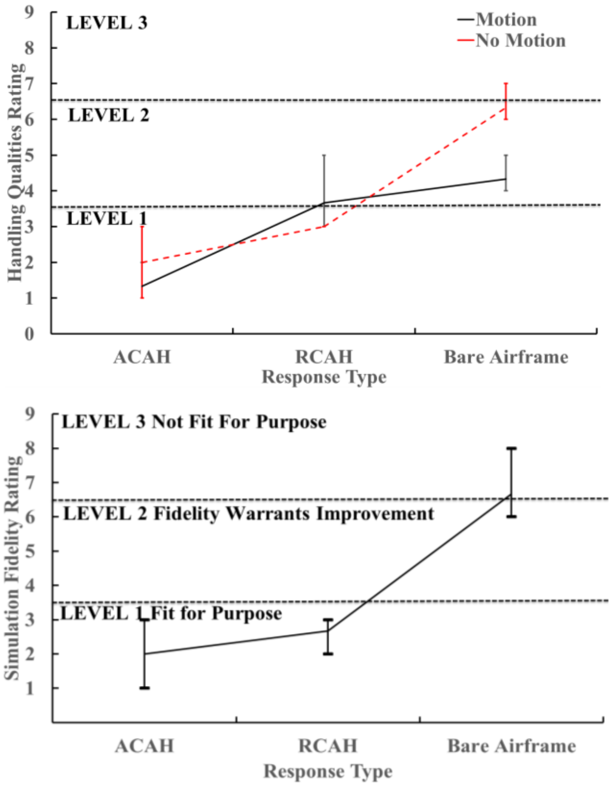


Figure 22. HQR (upper) and SFR (lower) results for the Precision Hover task.

The SFR scale was used to compare motion to no-motion cases with the pilots "training" in the motion case and then assessing the effect of no-motion on the test maneuver. The pilots awarded poorer average SFRs as the HQs degraded and comments from the pilots indicated that they were lacking feedback from the motion platform which led to a degradation in task performance and considerable task strategy adaptation. The results suggest that simulator motion fidelity requirements are not only task-based but are also dependent on the handling qualities of the aircraft being flown.

An attempt to change the focus of simulator standards to be more training-led has been made in the development of ICAO 9625 (Ref. 50). ICAO 9625 establishes the simulation fidelity levels required to support the range of training tasks carried out for different pilot licenses and ratings. It recognizes the need for training specific features and fidelity requirements. Each simulation feature e.g. cockpit layout, flight model has a required level of fidelity e.g. generic, representative and specific or none, if the feature is not required, for a given training task. Whilst it does not provide any new fidelity tolerances, Reference 50 does include details of an objective motion cueing test (OMCT), which measures the performance of the complete motion system, including the motion drive algorithm (Ref. 51). In Ref. 51 it was noted that OMCT was developed from the assessment of fixed-wing simulators and further work is required to examine requirements for rotorcraft. This need was confirmed by Jones et al. (Ref. 52) who examined the suitability of OMCT criteria for a rotorcraft pirouette, lateral reposition and a pursuit tracking task. The subjective motion fidelity ratings awarded by the pilot for the tasks investigated were not in agreement with the fixed-wing boundaries. The work identified the need for further research to define rotorcraft specific OMCT boundaries. A similar recommendation was made by Dalmeijer et al. (Ref. 53) who noted that whilst the OMCT requirements for heave motion were satisfactory for rotorcraft, further research was required to define rotorcraft specific boundaries.

A challenge in trying to discern the utility of motion cueing in flight simulators from the published literature is that results are presented for different simulators, with different capabilities, simulating different tasks whilst using different flight models. As noted by Grant (Ref. 54), experiments are rarely repeated before trying to extend the work using new methods. Hence if the new study contradicts any previous work it may not be clear if this is due to a different simulator or test protocol being used. It is anticipated that understanding the possible contributions of vestibular motion cueing to the simulation of LOC-I will require a more coordinated approach to help inform future simulator and regulatory requirements.

DISCUSSION AND NEXT STEPS

An examination of rotorcraft accident statistics has shown that, despite the excellent work undertaken internationally to reduce the accident rate, it is likely to be some time before the safety targets are met. Furthermore, whilst the overall accident rate trend is downwards, LOC-I accidents, one of the main contributing factors to the rates, are increasing. When faced with an unacceptable LOC-I accident rate in the fixed-wing community, a coordinated effort between all stakeholders was required to develop the UPRT program to tackle this problem. Some elements of UPRT can be transferred to rotorcraft training such as including startle in scenarios, education to develop skills for better awareness and recognition and, most importantly, more effective use of flight simulators to support the overall training needs.

To improve flight-models for use in LOC-I training, an assessment of current CS standards should be undertaken to identify where new fidelity criteria/tolerances are required. Several initiatives related to this have been launched but this should be extended to the wider international community as was the case with ICATEE. Improvements in rotorcraft modeling should be physics-based and research is needed here to inform the development of new standards.

Understanding the simulation fidelity requirements for different levels of training devices will be an important aspect of future LOC-I training. It is anticipated that training could be conducted using a range to simulators to ensure that LOC-I training provision is available throughout the rotorcraft community. This could include the use of desktop simulators and developing technologies such as virtual reality. The challenge of using such technologies, and how regulations might need to be more flexible to allow the uptake of new technologies, is one of the themes of the Royal Aeronautical Society's 2019 Spring Flight Simulation conference (Ref. 55) and should also be considered in any new LOC-I initiative.

The role of motion cueing in LOC-I training needs should be carefully examined. Whilst valuable research has been undertaken to examine how motion tuning can change the task performance achieved by pilots in different scenarios and devices, a consolidated approach using common fidelity metrics and methods should be developed. Without this approach, it would be difficult to provide the supporting evidence needed in any new standards as to how vestibular cueing should be provided in simulators.

In the Liverpool RSF project, the authors are developing a rational, physics-based approach for improving simulation models. Improvements in fidelity assessments and metrics e.g. for use in motion cueing, are also an important part of the RSF project. The outputs from this research can be used as part of any new LOC-I modeling and simulation initiative.

CONCLUDING REMARKS

LOC-I events are a significant element of rotorcraft accident statistics. Several initiatives have been launched to try address this problem. When faced with a similar problem in the fixed-wing community, a coordinated international activity was required to develop new training requirements to improve flight safety. The authors of this paper would welcome input and contact from the rotorcraft community to plan a dedicated workshop on this topic at a future VFS/ERF/FAA/EASA/RAeS meeting to develop new rotorcraft safety focused research. Driven by the need to improve rotorcraft safety, the workshop could focus on the training needs, modeling and simulation challenges and regulatory issues that need to be tackled to advance the state of the art in this area.

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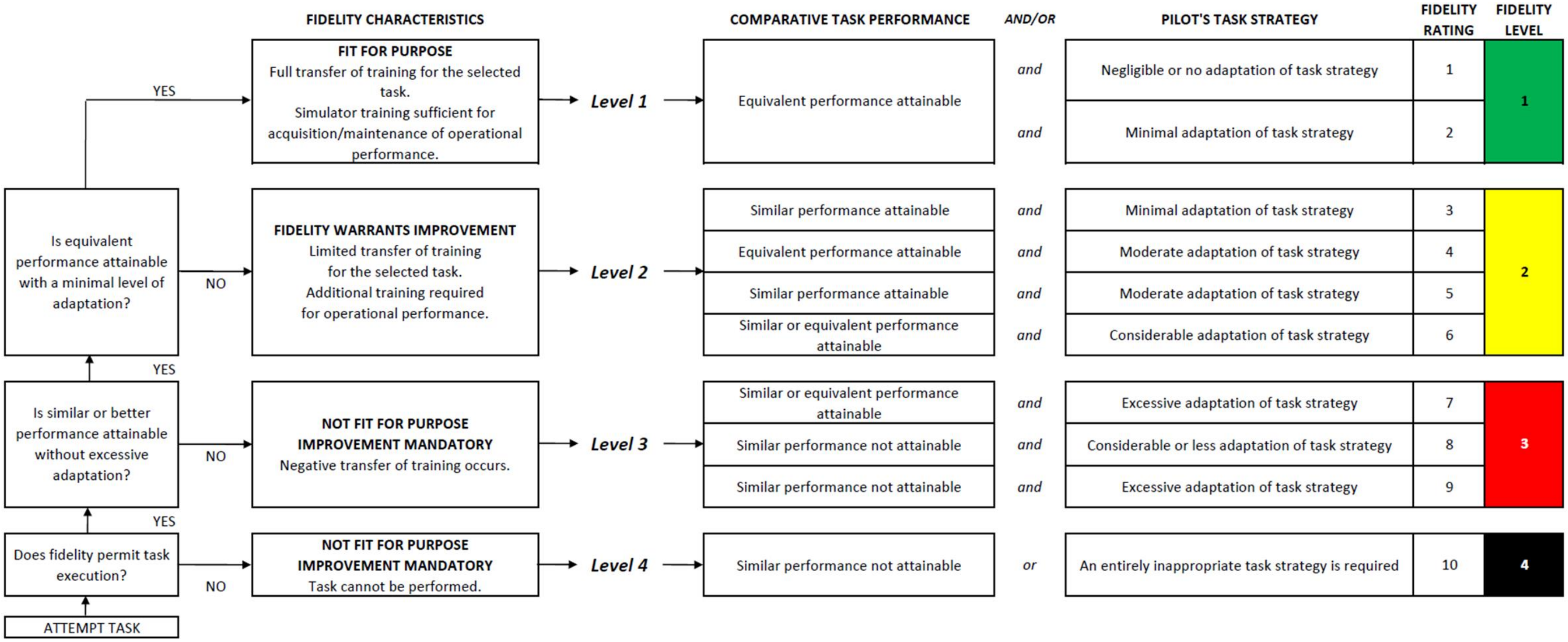
APPENDIX 1 – SIMULATOR FIDELITY RATING SCALE (REF. 30)



FIDELITY CHARACTERISTICS		COMPARATIVE TASK PERFORMANCE	*AND/OR*	PILOT'S TASK STRATEGY	FIDELITY RATING	FIDELITY LEVEL
FIT FOR PURPOSE Full transfer of training for the selected task. Simulator training sufficient for acquisition/maintenance of operational performance.	*Level 1*	Equivalent performance attainable	*and*	Negligible or no adaptation of task strategy	1	**1**
			and	Minimal adaptation of task strategy	2	
FIDELITY WARRANTS IMPROVEMENT Limited transfer of training for the selected task. Additional training required for operational performance.	*Level 2*	Similar performance attainable	*and*	Minimal adaptation of task strategy	3	**2**
		Equivalent performance attainable	*and*	Moderate adaptation of task strategy	4	
		Similar performance attainable	*and*	Moderate adaptation of task strategy	5	
		Similar or equivalent performance attainable	*and*	Considerable adaptation of task strategy	6	
NOT FIT FOR PURPOSE **IMPROVEMENT MANDATORY** Negative transfer of training occurs.	*Level 3*	Similar or equivalent performance attainable	*and*	Excessive adaptation of task strategy	7	**3**
		Similar performance not attainable	*and*	Considerable or less adaptation of task strategy	8	
		Similar performance not attainable	*and*	Excessive adaptation of task strategy	9	
NOT FIT FOR PURPOSE **IMPROVEMENT MANDATORY** Task cannot be performed.	*Level 4*	Similar performance not attainable	*or*	An entirely inappropriate task strategy is required	10	**4**