Safety Regulation Group

PAPER 2007/03

Helicopter Flight in Degraded Visual Conditions

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Safety Regulation Group

Civil Aviation Authority

PAPER 2007/03

Helicopter Flight in Degraded Visual Conditions

September 2007

ISBN 978 0 11790 754 6

Issue 1, September 2007

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The latest version of this document is available in electronic format at www.caa.co.uk/publications, where you may also register for e-mail notification of amendments.

Published by TSO (The Stationery Office) on behalf of the UK Civil Aviation Authority.

Printed copy available from:
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Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority, and was performed by QinetiQ, Bedford. The work was originally commissioned as a proactive initiative whilst also taking advantage of the opportunity afforded by a complimentary UK Ministry of Defence (MoD) Corporate Research study into how pilots use visual cues to fly helicopters. Shortly after the start of the project, however, the hazards associated with helicopter flight in degraded visual conditions were highlighted by the fatal accident involving Twin Squirrel G-CFLT in October 1996 which added new impetus to the work.

While this work was being completed, a new international initiative, the International Helicopter Safety Team (IHST), was launched in 2006 with the goal of reducing helicopter accidents by 80% within 10 years. It is clear from the accident statistics that, if this goal is to be achieved, a large part of the safety improvement will need to be realised in small and medium helicopter operations. Early on in the IHST initiative, helicopter flight in degraded visual conditions emerged as a significant cause of accidents in the USA, Canada and a number of states within Europe. In the UK, it was shown to be the largest single cause of helicopter fatal accidents in a review published by the CAA (HELI-GASIL, December 2002). Small helicopters are particularly vulnerable to the hazards associated with helicopter flight in degraded visual conditions as they are not generally equipped with automatic stabilisation equipment. The UK is participating in IHST via the European Helicopter Safety Team (EHEST), which forms part of the European Strategic Safety Initiative (ESSI).

The work reported in this paper will be promoted within the IHST and EHEST which, it is hoped, will result in initiatives on an international basis to reduce and/or mitigate encounters with degraded visual conditions. In the UK, as an initial step, the CAA has already amended the Air Navigation Order (ANO) to introduce a minimum visibility of 1500 m for VFR flight, and a requirement for VFR flight to be conducted "with the surface in sight". The latter requirement is interpreted to mean "…with the flight crew being able to see sufficient surface features or surface illumination to enable the flight crew to maintain the aircraft in a desired attitude without reference to any flight instrument". An Aeronautical Information Circular (AIC) is being produced to underpin the change to the ANO, and to assist pilots towards a better understanding of the problems that can be associated with attempting flight by visual reference in unsuitable conditions.

This project has firmly established a direct link between flight safety, visual cueing conditions and helicopter handling characteristics. At the heart of the high accident rate is the inherent instability of many small and some medium helicopters which can rapidly lead to excessive pilot workload when attempting to fly in degraded visual conditions. An obvious step to reduce the accident rate would be to improve the handling qualities of these aircraft, but it is recognised that such a step would likely be impractical for many existing aircraft. Other means must therefore be found, and a number of recommendations are made in Section 9 of this report. One possible form of mitigation, not mentioned in the report, is the provision of a 'head-up' attitude reference; devices such as the Malcolm Horizon have previously shown some promise and might be practical to retro-fit to existing aircraft.

Safety Regulation Group
July 2007

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Abstract

QinetiQ has completed a programme of research for the Civil Aviation Authority to investigate the causes of and factors affecting civil helicopter accidents involving operations in degraded visual conditions. A review of accident data for the period from 1975 to 2004 was carried out using the CAA's MOR database, which identified a significant number of cases that involved controlled flight into terrain, and inadvertent entry into instrument meteorological conditions (IMC) followed by loss of control due to spatial disorientation.

In a follow-on simulation investigation, two test pilots evaluated aircraft with undamped rate responses and Attitude Command - Attitude Hold cyclic control responses in flight tasks and simulated visual conditions based on typical accident scenarios. Subsequent to the trial, the pilots' ratings and objective data including pilot control demands, aircraft responses and flight path were analysed to examine the impact of visual conditions on task performance and safety for the aircraft control types flown. An examination of the sufficiency of visual scenes equivalent to Useable Cue Environments of 1, 2, 3 and poorer to support pilotage was carried out using two special techniques; image analysis and tau analysis.

The results were compared with the findings of a review of the civil regulations most pertinent to civil helicopter operations in degraded visual conditions. A conceptual framework was developed based on the findings of the studies which illustrates the strong inter-dependency between helicopter handling qualities and visual cues, and the way that these impact civil operations and requirements and, ultimately, flight safety. It was concluded that the Aeronautical Design Standard-33 Useable Cue Environment and associated response type criteria could provide the basis for safer operations in the Degraded Visual Environment, including inadvertent entry into IMC, and that the Attitude Command - Attitude Hold response type is essential for these types of operations.

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Executive Summary

This report summarises the research carried out by QinetiQ for the Civil Aviation Authority (CAA) under Contract 7D/S/980/Y 'Ego-Motion and Optical Cues Applied to Helicopter Flight'. It constitutes the final programme report and its aim is to present and summarise all research activities carried out under programme Phases 1 and 2, including the methodology used, results obtained and the associated conclusions and recommendations derived. In addition, the findings of an earlier research activity carried out by QinetiQ for the CAA, which concerned the related topic of pilot field of view (FOV), are also considered.

The CAA research was undertaken in collaboration with a MoD Corporate Research Programme (CRP) study into how pilots use visual cues in the process of helicopter flight guidance and stabilisation, where the general objective was to improve the operational effectiveness and safety of military helicopter operations in degraded visual conditions. This work focused primarily on establishing experimental designs and test techniques for examination of pilot control strategy through piloted simulation experiments, where the aim was to investigate the visual information requirements for typical operational flight tasks under controlled, simulated visual conditions.

The CAA's motivation for the collaboration stemmed from the continuing incidence of serious accidents involving civil helicopter operations in degraded visual cueing conditions, where poor aircrew situational awareness, and ultimately spatial disorientation or controlled flight into terrain, have been identified as primary causal factors. The CRP study was likely to give insight into the causes of such accidents, and the CAA's objective was to identify potential developments of the civil regulations and/or associated guidance material that might help to prevent and/or mitigate accident-prone scenarios.

The approach adopted to meet this objective was, firstly, to review the relevant civil accident data to identify the principal causal factors and establish the nature and extent of the problem (Phase 1). This was followed by further investigation of these factors through piloted simulation experiments involving flight and operating conditions taken from typical accident scenarios (Phase 2/1). Data from these experiments were then analysed using special techniques developed under the CRP study, and the results compared with the findings of a review of the relevant civil regulations (Phase 2/2).

The Phase 1 review of accident data covered the period from 1975 to 2004 and was carried out using the CAA's Mandatory Occurrence Reporting System (MORS) database. The aim was to identify cases where loss of pilot situational awareness and spatial disorientation were primary causal factors. It was found that there has been a continuing incidence of such accidents, involving both private and public transport helicopter operations during the review period. A primary set of 53 Scenario 2 (controlled flight into terrain) and Scenario 3 (spatial disorientation and loss of control) cases and 1 Scenario 1 (obstacle/terrain strikes in low level flight) case was identified where degraded visual cues, poor pilot situational awareness and/or spatial disorientation were the primary causal factors. These cases involved 100 fatalities overall. Of note, Scenario 2 and 3 cases together form the single largest cause of small helicopter fatal accidents. Total occurrences per year increased over the period from 1975 to 2004 from 1 per year to approximately 2.5. From the mid-1990s onwards, the average number of Scenario 3 cases per year (1-2 cases) overtook the number of scenario 2 cases, which has remained relatively constant at 1 per year throughout the review period. This result indicates an increase in the number of accidents resulting from spatial disorientation in degraded visual conditions. A detailed case study exercise was carried out on a sub-set of seven cases selected from the primary set, which was based on source material taken from associated Air Accidents Investigation Branch (AAIB) reports and bulletins.

The Phase 2/1 simulation experiments were carried out in trial EMOCUES2 using QinetiQ's Real Time All Vehicle Simulator, where two qualified and experienced test pilots evaluated a test matrix of manoeuvres and visual conditions that was based on information extracted from the accident case studies. These experiments were designed specifically to investigate the applicability of the Aeronautical Design Standard-33 (ADS-33) Useable Cue Environment (UCE) concept and response type criteria to civil operations. To this end, test cases involved aircraft types with unstabilised rate (Basic) or Attitude Command – Attitude Hold (ACAH) responses, and visual conditions ranging from visual meteorological conditions (VMC), i.e. UCEs of 1, 2 or 3, to instrument meteorological conditions (IMC), i.e. a UCE of poorer than 3. These two types were evaluated in five different test manoeuvres, including Hover Taxi, Fly Away, Turn, Climb and Approach. The trial met its objectives and was successful in demonstrating how pilot situational awareness can be eroded in VFR operations as visual conditions degrade, a key factor being the division of attention between the guidance and stabilisation tasks.

For Phase 2/2, pilot ratings and objective data from the simulation experiments were examined further through image analysis and tau analysis, where the objective was to investigate how pilot control strategy, task performance, workload and, ultimately, flight path safety were influenced by the visual conditions, i.e. level of UCE. For image analysis, the application of a predictive model based on image metrics was demonstrated as a means of predicting pilot's HQRs, VCRs and UCE. Four image metrics that are based on fractal geometry were considered: k, β, D, α, which relate to smoothness, clutter strength (intensity), clutter uniformity and clutter density respectively. It was found that the best measures of visual cues for pilot handling were D, α and β, with D being the most important. Tau analysis was used to demonstrate the applicability of an intrinsic tau-guide model (with taudot constant) of the form [$\tau_m = k_g t + c$], (where k_g is the gradient of τ_m over T, the time to complete the manoeuvre) to the height, speed, heading and attitude control in the test manoeuvres evaluated in EMOCUES2. Results from examination of a motion tau-coupling model of the form [$\tau_v = k_m \tau_h + c$], (where k_m is the gradient of τ_v over time T) showed that, in general, there was no firm evidence of a tau coupling between speed and height in the Fly Away, Climb and Approach manoeuvres.

The aim of the review of civil regulations was to identify any deficiencies and omissions concerning degraded visual environment (DVE) operations of the type that featured in the review of accident data. Documents reviewed included JAR 27/29 and associated ACs, the relevant parts of JAR-OPS 3 and ICAO Annexes 6 and 14, and various CAA FODCOMS. The report presents the overall findings of the review and discusses potential measures that might help to reduce the likelihood of civil helicopter accidents in conditions of poor visibility, taking account of the results and findings from the earlier research activities. In addition, the findings of an earlier CAA sponsored review of pilot FOV issues are also considered. To underpin the discussion, a conceptual framework is presented which illustrates the strong inter-dependency between handling qualities and visual cues and the way that these impact civil operations and requirements, and ultimately flight safety. The mapping of the EMOCUES2 trials results onto this framework supports the case that the ADS-33 UCE and associated response type criteria provide the basis for safer operations in the DVE and, specifically, that the ACAH response type is essential for these types of operations.

Conclusions and recommendations stemming from the programme and its activities are summarised in the following.

1 Accident data

a) A primary set of 53 Scenario 2 and 3 accidents and one Scenario 1 case was identified for the period 1975 to 2004 where degraded visual cues, poor pilot situational awareness and/or spatial disorientation were the primary causal factors.

b) These Scenario 2 and 3 accidents involved a total of 100 fatalities and, together, form the single largest cause of small helicopter fatal accidents.

c) Total occurrences per year over the period from 1975 to 2004 increase from 1 per year to approximately 2.5, largely due to increasing numbers of accidents resulting from spatial disorientation in a DVE, i.e. Scenario 3 cases.

d) The majority of cases occurred during daytime and out of close contact with the surface. Although the accidents identified were the result of a number of contributory causal factors, inadvertent entry into IMC (IIMC) was probably the most significant factor.

e) Serious consideration must be given to the measures that need to be taken to reverse this trend, taking into account improvements to regulations, operating procedures and requirements or pilot training requirements.

2 Simulator investigations

a) A conceptual framework has been presented, which illustrates the strong interdependency between visual scene and handling qualities as represented by level of UCE and handling qualities according to ADS-33 Level 1, 2, 3 criteria.

b) The way in which the framework can be linked to civil requirements for handling qualities, operational constraints, training and navigation aids has also been illustrated. HQR evaluations from EMOCUES2 show good correlation, qualitatively, with the conceptual case for both the ACAH and Basic configurations.

c) The underlying argument on which the framework is based is that ACAH response types confer reduced workload through minimising the effort required for closed-loop stabilisation. In DVE conditions, this can free critical attention to enable the pilot to concentrate on the guidance aspect of flight management.

d) Regarding stability, types similar to Basic are likely to be HQR Level 2, Level 2-3 and Level 3 for UCE 1, 2 and 3 operations respectively, but ACAH would be Level 1, Level 1-2 and Level 2.

e) The Level 3 characteristics of the Basic type are likely to present a serious flight safety hazard in inadvertent DVE situations such as IIMC.

f) Associated handling problems will be exacerbated by poor/inappropriate flight controls mechanical characteristics (FCMCs). Hence, the impact of FCMCs on pilot workload should be taken into account, and better guidance is needed concerning acceptable FCMCs for all civil operations.

g) The results support the case that adoption of the ADS-33 UCE and associated response type criteria would lead to significant safety benefits for civil helicopter operations in the DVE and, specifically, that the ACAH response type should be mandatory for DVE operations.

3 Civil regulations and requirements

a) Civil regulations and requirements in the area of handling qualities are very subjective and open to interpretation by manufacturers and qualification test pilots.

b) The regulations divide operations into either VFR or IFR categories, with no consideration given to DVE operations, e.g. there are no detailed requirements or guidance given for night operations.

c) In the accident cases considered pilot workload was a key contributor, driven by circumstantial factors such as vehicle stability, poor visual cues and division of attention. The JARs do not clearly address DVE and division of attention operations, suggesting that greater clarity is required concerning the possibility of such circumstances.

d) There is a need for objective criteria with appropriate qualification boundaries that will determine and eliminate potentially accident-prone configurations such as Basic; adoption of the JAR dynamic stability requirements for both VFR and IFR types would meet this requirement.

e) Military criteria such as the ADS-33 attitude bandwidth and associated gust rejection criteria, and the related criteria for DVE (response type versus UCE) and divided attention operations could provide advisory material to improve JARs.

f) JAR-27 does not specify an attitude indicator for VFR operations; small rotorcraft should be required to be fitted with an attitude indicator to mitigate the consequences of inadvertent encounters with DVE conditions.

g) The JAR-OPS 3 requirement for the chart holder for IFR operations should be extended to all operations at night.

4 Aircraft and equipment design issues

a) The regulations do not address the need for an adequate visual reference for attitude cueing through the cockpit structure; this is essential for operations in poor visual conditions.

b) The advisory guidance concerning cockpit FOV should be made mandatory, supported by limitations regarding the permissible encroachment on FOV of additional cockpit equipment.

c) Consideration should be given to the development of improved forms of instrumentation displays to cater for the IIMC case.

5 Operational issues

a) Statistics based on the CAA's MORS database indicate that accidents tend to occur for VFR operations en-route in unrestricted airspace; this suggests that requirements (minima) need to be reviewed and strengthened as necessary.

b) When addressing requirements for visibility minima, factors such as the height that the aircraft should be permitted to fly at versus the available view over the nose of the aircraft should be taken into consideration. For a given cockpit view, the pilot's forward view diminishes with increasing aircraft height, and look down angles associated with heights of greater than 1000 ft (i.e. greater than 15-20 deg) would impose severe restrictions on the available visual cues. The likely effect of aircraft pitch attitude on pilot view should also be taken into account.

6 Pilot training issues

a) The regulations address requirements for communications to provide appropriate navigation and meteorological information, but pilots still become lost when navigating by visual references at night. Improved guidance and training for aircrew is needed.

b) FODCOMs attempt to address issues such as those noted at paragraph 5 b) and paragraph 6 a), but such measures need to be applied more widely to all civil aircraft operations. Critical training issues that might be addressed more rigorously through such measures include: recovery from visual to instrument visual flight, and divided attention operations when navigating by external references.

c) Pilots should be better trained to make informed decisions on whether to fly or not in marginal conditions, or when IMC conditions are developing enroute. This might be achieved by developing a probability index based on factors that contribute to a high risk accident scenario (e.g. meteorological conditions, visual conditions, visual range, acuity of the visual horizon, aircraft configuration, aircraft handling qualities).

d) IIMC can occur due to reduced visibility and/or an insufficiency of visual cues to support flight by visual references, e.g. over the sea or remote moorland at night. Pilot training and awareness for such cases could be supported by image analysis of digital images of typical operating conditions and UCEs, similar to those used from the simulator trial to develop the image analysis application.

7 Recommendations

a) Introduction of the IFR dynamic stability requirements as a general requirement for all operations, including VFR.

b) Introduction of appropriate requirements (or guidance) on criteria for DVE operations based on consideration, but not full adoption, of all IFR requirements for:

   i) night operations; and

   ii) operations in visual ranges of less than a ‘specified’ minima, which takes account of permitted aircraft height and associated view over the nose. Look down angles associated with heights of greater than 1000 ft (i.e. greater than 15-20 deg) would impose severe restrictions on the available visual cues.

c) Introduction of specific requirements (or guidance) on criteria for FCMCs.

d) Introduction of a requirement for an attitude indicator flight instrument for all operations, including VFR.

e) Specification and adoption of FODCOM training requirements for all civil helicopter operations that fall into the DVE category specified at b) above.

f) Raise pilot awareness of the problems associated with operations in the DVE, i.e. the interaction between vehicle handling qualities and visual cueing conditions.

g) Reduce the probability of pilots encountering DVE conditions by providing guidance on whether to fly or not in marginal conditions with the potential for DVE encounters. This could be achieved using a simple probability index based on consideration of those factors that contribute to a high accident risk scenario, including:

   i) meteorological conditions (precipitation, cloud base etc.),

   ii) visual conditions (time of day, fog/mist/haze conditions, visual range, acuity of the visual horizon etc.),

   iii) aircraft configuration (navigation aids, flight instruments, pilot FOV and layout etc.),

   iv) aircraft handling qualities (SAS, FCMCs).

h) Image analysis using the techniques presented in this report should be investigated as a means of supporting the pilot training in g), using digital images of typical operating conditions and UCEs.

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Report Helicopter Flight in Degraded Visual Conditions

1 Introduction

This report summarises the research carried out by QinetiQ for the Civil Aviation Authority (CAA) under Contract 7D/S/980/Y 'Ego-Motion and Optical Cues Applied to Helicopter Flight' [1,2,3].

The CAA project was undertaken in collaboration with a MoD Corporate Research Programme (CRP) study into how pilots use visual cues in the process of helicopter flight guidance and stabilisation [4,5,6]. A principal objective of this research was to improve the operational effectiveness and safety of military helicopter operations in degraded visual conditions through the development of fundamental design rules for pilot vision aids, and integration of vision and control augmentation.

In practical terms, the objective was to explore the way in which a pilot uses optical cues, such as optical flow and edge rate, to control ego-motion parameters such as aircraft height, speed and rate of turn. The work focused primarily on establishing experimental designs and test techniques for examination of this relationship through simulation experiments. The general aim was to investigate the visual information requirements for specified flight tasks under controlled task and visual conditions. Specifically, the aim was to establish a means of quantifying the sufficiency of a visual scene and its optical cues to support control of the ego-motion parameters and attainment of the desired performance requirements for the tasks.

The CAA's motivation for the collaboration stemmed from the continuing incidence of serious accidents involving civil helicopter operations in degraded visual cueing conditions, where poor aircrew situational awareness and ultimately spatial disorientation, or controlled flight into terrain have been identified as primary causal factors. The CRP study was likely to give insight into the causes of such accidents, and the CAA objective was to identify potential developments of the Joint Aviation Requirements (JARs) that would help to prevent and/or mitigate accident-prone scenarios. At this point, regarding the JARs it should be noted that following the formation of the European Aviation Safety Agency (EASA), some documents pertinent to the research have been renamed, for example JAR-27 and -29 are now Certification Specification (CS) 27 and 29 respectively. For consistency, the report refers to the original titles under which the documents were consulted.

The approach adopted to meet this objective was, firstly, to review the relevant civil accident data to identify the principal causal factors and establish the nature and extent of the problem. This was followed by further investigation of these factors through piloted simulation experiments, which were based on similar studies conducted under the MoD CRP study. Data from these experiments was then analysed using special techniques also developed under the CRP study. Finally, a review of the relevant civil regulations was carried out and compared with the results and findings of the simulation experiments.

The activities were carried out in two main phases, Phases 1 and 2, where Phase 2 involved two stages, Stage 1 (Phase 2/1) and Stage 2 (Phase 2/2), as summarised below.

Phase 1:

- review of civil helicopter accidents involving degraded visual cues [7].

Phase 2/1:

- piloted simulation investigation of civil accident scenarios involving degraded visual conditions [8].

Phase 2/2:

- analysis of the trials data [9];
- review of the civil regulations concerning civil operations in degraded visual condions;
- comparison with the findings from the simulation studies.

This report constitutes the final programme report and its purpose is to summarise the main research activities for Phases 1 and 2, including the results obtained and the associated conclusions and recommendations derived. In addition, the findings of an earlier research activity carried out by QinetiQ for the CAA [10], which concerned the related topic of pilot field of view (FOV), are also included.

The report structure is as follows:

- The Phase 1 review of accidents is addressed in Section 2 and Appendix A.
- The Phase 2/1 simulation investigation and associated data analysis activities are summarised in Sections 3 and 4 respectively. Appendix B shows examples of the visual images used for the simulations and data analysis. An overview of the analysis objectives, methods and findings is given in the main body of the report while more detailed accounts of the background to the methods are provided in Appendices C and D.
- An overview of the main findings of the review of civil regulations is given in Section 5, including a comparison with the Phase 2/1 results, full details of which are summarised in Appendix E.
- Section 6 discusses the findings of the pilot FOV study; the report on which these are based is presented in Appendix F.
- The overall findings from the current studies, including the way ahead, are discussed in Section 7.
- Finally, Sections 8 and 9 provide overall conclusions and recommendations. Note that the main findings for each programme activity are addressed in the relevant sections, whereas Sections 8 and 9 provide a global set of conclusions and recommendations based on the overall results and findings.

2 Phase 1 - review of accident statistics

2.1 Method

The review of accident data was carried out using the CAA's Mandatory Occurrence Reporting System (MORS) database. All private and public transport helicopter accidents and incidents during the period from 1975 to 2004 were identified, which included the following primary or secondary causal factors:

- reduced level of light and/or visibility (particularly cases where rapidly degrading visual conditions were encountered);
- pilot loss of situational/spatial/attitude awareness;
- misleading visual cues;
- pilot workload saturation; and
- controlled flight into terrain/sea.

All cases were assessed and classified according to three scenario descriptors:

Scenario 1:	cases where the primary causal factor was obstacle/terrain strikes in low level flight;
Scenario 2:	cases involving controlled flight into terrain (CFIT);
Scenario 3:	cases involving spatial disorientation and loss of control.

In order to differentiate the more significant cases, the MORS data were divided into two sub-sets, referred to as the 'primary' and 'secondary' data sets[1]. The primary set includes essentially DVE cases such as instances of inadvertent entry into IMC (IIMC), which resulted in spatial disorientation and subsequent loss of control, or CFIT, i.e. Scenario 2 and 3 cases. These cases are considered to be of most significance to the study because degraded visual cues were a key factor, either resulting from atmospheric obscuration, poor light and/or lack of surface texture and/or cues. It should also be noted that many of these cases were fatal crashes.

The secondary set is considered to be of less significance to the study because most of the cases took place in the Good Visual Environment (GVE), in low level flight close to terrain and obstacles where, in addition to visual cueing aspects, pilot judgement was also a critical factor. Typical cases include cable, obstacle, main or tail rotor strikes, crop spraying incidents and heavy landings in practice auto-rotational landings, i.e. Scenario 1 cases. Most of these were not fatal crashes, but involved some degree of damage to the aircraft.

2.2 Summary of results

The primary data set of cases from 1975 to 2004 is summarised in Table 1. Reports of 5 other accidents in 2004/5 recorded in the MOR data base appeared likely to be relevant but were excluded as the reports were incomplete, i.e. awaiting further information.

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[1] The MORS data review was carried out in two stages, the first covering the period 1975 to 2000. This was subsequently extended to cover the period 2000 to 2004 for which only cases where DVE conditions were a significant factor, i.e. only cases belonging to the primary data set were extracted and reviewed.

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
197602570	AIB 8/76	Hughes 369	Commercial transport?	Cruise	Turning in forward flight	3A	Ground	Cloud/fog	Poor external referencesIIMC - LOC	Fatal crash
197602991	?	Sik S61	Commercial transport	Landing	Approach to hover	2A	Offshore/ platform	Brownout	Poor height cues	Heavy landing
197800692	?	Bell 206	Inspection	Flight	Approach to hover	2A	Water/ Lake	Textureless surface	CFIT-poor height cues	Fatal crash
197802588	?	Bell 206	Commercial transport?	Cruise	Level flight	2B	Sea	Cloud	IIMC-poor height cues	Fatal crash
197902072	?	Bell 47	Commercial transport?	Cruise	Turning in forward flight	2A	Water/ lake	Textureless surface	CFIT-poor height cues	Crash
198100828	AIB 11/81	Bell 206	Commercial transport?	Cruise	Turning in forward flight	3B	Ground	Cloud	Poor external references IIMC - LOC	Fatal crash
198102180	AIB 14/81	Enstrom F28	Commercial transport?	Landing	Hover taxy	2B	Sea	Textureless surface	CFIT-poor height cues	Crash
198102469	AIB 12/ 81AAR 10/ 82	Bell 212	Commercial transport	Cruise	Turning in forward flight	3A	Sea	Cloud	Poor external references IIMC - LOC	Fatal crash
198202646	AIB 12/ 82AAR 2/ 84	Bell 212	Commercial transport	Cruise	Level flight?	2B	Sea	Cloud/Rain/ Night	IIMC-Poor height cues?	Fatal crash

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
198301880	AIB 8/83AAR 8/84	Sik S61	Commercial transport	Cruise	Decelerating in level flight	2A	Sea	Cloud/fog	CFIT-poor height cues	Fatal crash
198303269	AIB 13/83	Gazelle	Commercial transport?	Flight	Turning in forward flight	2A	Water/lake	Textureless surface	CFIT-poor height cues	Crash
198402857	AIB 2/85	Bell 206	Commercial transport?	Departure	Turning in forward flight	2B	Ground	Rising ground	CFIT-poor height cues	Fatal crash
198500007	AIB 6/85	Bell 206	Underslung load	Cruise	Level flight	2A	Snow/Ice	Textureless surface	CFIT-poor height cues	Crash?
198603942	AIB 1/87	SA332	SAR	Flight	Winching	2A	Offshore/platform	Featureless surface	Poor hover references	Passenger injury
198700043	?	Bell 222	Commercial transport	Landing	Hover	2A	Snow	Whiteout	Poor external references	Crash
198803491	AIB 1/89AAR 3/89	Sik S61	SAR	Flight	Hover	2A	Sea	Night/Fog	Poor hover references	Crash
198901728	?	SA332	Commercial transport	Cruise	Descent	2A	Ground	Cloud, Rising ground	CFIT-poor height cues	Fatal crash
198902982	?	BO105	Commercial transport?	Cruise	Level flight	3A	Ground	Cloud/Rain	Poor external referencesIIMC-LOC	Crash
198904108	?	R22	Private transport	Landing	Touch down	2B?	Ground	Fog	Poor external references IIMC	Crash
198904846	?	Hughes 369	Private transport	Cruise	Level flight	3A	Ground	Cloud	Poor external references IIMC - LOC	Fatal crash

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility (Continued)

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
198904985	AAR 5/90	Bell 206	Commercial transport?	Cruise	Level flight	3A	Ground	Cloud	Poor external references IIMC - LOC	Fatal crash
199001233	?	R22	Private transport	Cruise	Level flight	2B	Ground	Cloud, Rising ground	CFIT-poor height cues	Fatal crash
199003279	AIB 1/90AAR 2/91	Sik S61	Commercial transport	Landing	High hover	2B	Confined area	Restricted visibility	Poor hover referencesTail rotor strike	Fatal crash
199200101	3/92	R22	Private transport	Cruise	Turn & descent	3A	Ground	Cloud & Fog	Poor height cuesIIMC - LOC	Crash
199200749	AAR 2/93	SA332	Commercial transport	Departure	Turn & ascent	2A	Offshore/ Platform	Night Difficult weather	Poor manoeuvre references	Fatal crash
199202093	AIB 10/92	Hughes 369	Private transport	Flight	Low level transit	2A	Ground	Cloud Difficult weather	Poor manoeuvre references	Crash
199401912	AIB 10/94	Bell 206	Commercial transport	Cruise	Low level transit	2A	Ground	Cloud, Rising ground	IIMC - Poor height cues	Fatal crash
199405264	AIB Inc Rep 5/95	Bell 214	Commercial transport	Departure	Turn & ascent	2B	OffShore/ Platform	Night, Difficult weather	IIMC - Mis-application of IMC procedures	Near miss
199505226	AIB 3/96	Hughes 269	Private transport	Cruise	Level flight	3A	Ground	Cloud/Rain	Poor external references IMC - LOC	Heavy landing
199604736	AIB 6/97	Hughes 369	Private transport	Cruise	Level flight	3A	Ground	Night/Cloud	Poor external references IIMC - LOC	Fatal crash
199604787	AIB 4/97	SA355	Commercial transport	Cruise	Ascent in forward flight	3A	Ground	Night	Poor external references - LOC	Fatal crash

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility (Continued)

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
199605710	Irish AAIURept 1/98	Sik S76	Commercial transport	Landing	Turn in forward flight	2A	Ground	Night, Rising ground,Difficult weather	CFIT - Poor height cues	Fatal crash
199605748	AIB 9/97	Bell 206	Commercial transport	Departure	Lift-off	2A	Ground/ Confined area	Night	Poor hover referencesTail rotor strike	Fatal crash
199702041	AIB 7/97	Enstrom F28	Private transport	Cruise	Turn in forward flight	3A	Ground	Cloud/Haze	Poor external references IIMC - LOC	Crash
199705933	AIB 6/98	Bell 206	Commercial transport	Cruise	Low level transit	3B	Ground	Night, Rising ground, Difficult weather	Poor external references IIMC - LOC	Fatal crash
199705934	AIB 3/98	Bell 206	Commercial transport	Landing	Touch down	2A	Ground/ Confined area	Dusk/difficult weather/Rain/ Canopy misting	CFIT - poor height cues	Heavy landing
199800372	AIB 9/98	SA355	Practice	Departure	Initial climb	3A?	Ground	Night/Fog, Rising ground	Poor manoeuvre cues IIMC	Fatal crash
199801903	AIB 10/98	R44	Private transport	Cruise	Level flight	3B	Ground	Night/Rain	Poor external references IIMC - LOC	Fatal crash
199805910	AIB 4/99	SA355	Commercial transport	Departure	Initial climb out	3A	Ground	Night/Fog	Poor external references IIMC - LOC	Fatal crash
199806828	AIB 6/99	R44	Private transport	Cruise	Turn & descent	3A	Ground	Cloud/Rain	Poor external references IIMC - LOC	Crash
199806912	AIB 2/99	Gazelle	Private transport	Cruise	Descent	2A	Ground	Cloud, Rising ground	Poor external references IIMC	Crash

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility (Continued)

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
199901793	AIB 8/99	Bell 206	Commercial transport	Cruise	Level flight	3A	Sea	Fog	Poor external references IIMC - LOC	Crash
200000516	?	R44	Private transport	Cruise	Level flight	3B	Ground	Cloud/Fog, Difficult weather	Poor external references IIMC - LOC	Fatal crash
200006730	AAIB 2/ 2001	Bell 206	Commercial (Pipe-line inspection)	Cruise	Turn in forward flight	2A	Ground	Cloud/rain,1000-1500ft/3-6km	CFIT, distraction (caution light)	Crash (2)
200100013	AAIB 3/ 2001	Bell 206	Private transport	Approach	Turn & descent	2A	Water/lake	Poor visibility, textureless surface	Poor height/height rate cues, distraction (landing light)	Crash(1)
200100311	AAIB 12/ 2001	AS350B2	Private transport	En-route/ cruise	Tow level transit	3A	Ground	Low cloud (150-500ft), hill fog	Poor external references IIMC, LOC warning horn distraction	Fatal crash(3)/(2 serious)
200107867	AAIB 2/ 2002	R22	Private transport	Landing	Descent	2A	Ground	6KM VIS/light rain	Restricted visibility (Rain on canopy)/ height cues	Crash (2),
200200277	AAIB 8/ 2003	SA 365 Dauphin	Commercial transport	Recovery/ Approach	Level flight	2A	Sea	Poor visibility/ rain/ condensation	CFIT, distraction (clearing condensation)	Crash(0)
200200915	AAIB 8/ 2003	EC 135	Commercial (Police)	Cruise	Turn in forward flight	3B	Ground	Night, Cloud	Poor external references IIMC, inadvertent AP disconnect	Crash (3)

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility (Continued)

Occurrence Number	AIB Reference	Aircraft Type	Flight			SCE[1]	Environmental Factors		Causal Factors	Type of Crash
			Operation	Phase	Manoeuvre		Terrain	Visual		
200300253	AAIB 12/ 2003	Bell 206	Private transport	Depature/ cruise?	Initial climb out	3A	Ground	Low cloud/rain (Est 300ft/2km)	Poor external references IIMC - LOC	Fatal crash (2)
200302567	AAIB 3/ 2004	Bell 206L	Private transport	Cruise	Descent	1A	Ground	Low cloud	Tail rotor/fin hit cable. Cable at 120ft	Crash (3),
200305069	AAIB 5/ 2005	R44	Private transport	En-route/ cruise	Turn in forward flight	3A	Ground	Low cloud	Poor external references IIMC - LOC	Fatal crash (1)
200308110	AAIB 2/ 2004	Gazelle	Private transport	Approach	Descent	2A	Ground	DVE because of winter sum	Cable strike	Crash (1),
200401275	AAIB 6/ 2005	Agusta 109E	Private transport	Approach	Descent	3A	Ground	Night/cloud Fw 1200 - sct 2500ft/light rain limited vis 2.7km	Poor external references IIMC - LOC, false cues from lights on ground	Fatal crash (2)

Table 1 Cases involving loss of situational awareness or spatial disorientation in conditions of poor visibility (Continued)

[1] A = Probable, B = Possible

Referring to Table 1, columns 1-6 give factual information, starting with the MOR database occurrence number, followed by relevant AAIB report references, the aircraft type, flight operation, phase and manoeuvre. Column 7 shows the allotted accident category (Scenario 1 A/B, 2 A/B, or 3 A/B, where 'A' indicates "probable' and 'B' 'possible'), columns 8 and 9 the environmental factors including terrain and visual conditions, and columns 10 and 11 the causal factors and type of crash. The information given in columns 8 to 11 is stated explicitly in the MOR summaries, or is implicit from the description given. The same applies to the allocated categories in column 7 although here, as indicated above, the cases are also differentiated by the 'probable' (A) and 'possible' (B) descriptors.

In more detail, column 8 defines the type of terrain over which the flight operation was carried out, e.g. land, snow/ice, water, sea or to an offshore platform or ship. Column 9 gives the visual conditions expressed in relation to features that describe the nature of the degraded visual environment, e.g. cloud, fog, night, rain, textureless or featureless surface. Note that, regarding weather effects, some cases give only the general descriptor 'difficult weather'. Column 10 summarises the principal visual related causal factors that contributed to the accident, e.g. IIMC, loss of control (LOC), loss of external manoeuvre references or hover references. Finally, in column 11, 'type of crash' is intended to convey an indication of the severity of the accident, e.g. (in order of severity) 'fatal crash', 'crash', 'heavy landing', 'minor damage', 'near miss'. Hence, any accident involving fatalities is taken as the most serious case, irrespective of the level of damage to the aircraft, and the other four categories indicate a reducing scale of damage/injury to aircraft/passengers.

Some key statistics for the primary EMO data set data are summarised in Figures 1 to 6, and Table 1a. Some observations regarding the figures and their contents are discussed under the corresponding headings below; the percentages given are calculated using the total number of cases, or sub-totals from Table 1 as appropriate.

Referring to Figure 1:

- There is an average of 2 cases per year with five peaks of 3 cases (1981, 1992, 1997, 2001 and 2003), one peak of 4 cases (1996), and two peaks of 5 cases (1989 and 1998).
- Total numbers of cases for the 1970s, 1980s and 1990s increase from 5 to 16 then 21 respectively. 11 cases have been identified for just the 5 years 2000 - 2004.
- The 5 year moving averages of incidences of Scenario 2 and 3 cases show an increase in Scenario 3 cases from the mid-1990s that overtakes the number of Scenario 2 cases in 1998. The incidence of Scenario 2 cases, however, remains relatively constant over the entire review period. Thus the total number of cases per year shows an increase over 1976 to 2004 from 1 per year to approximately 2.5, indicating an increasing trend in the number of accidents resulting from spatial disorientation in a DVE.

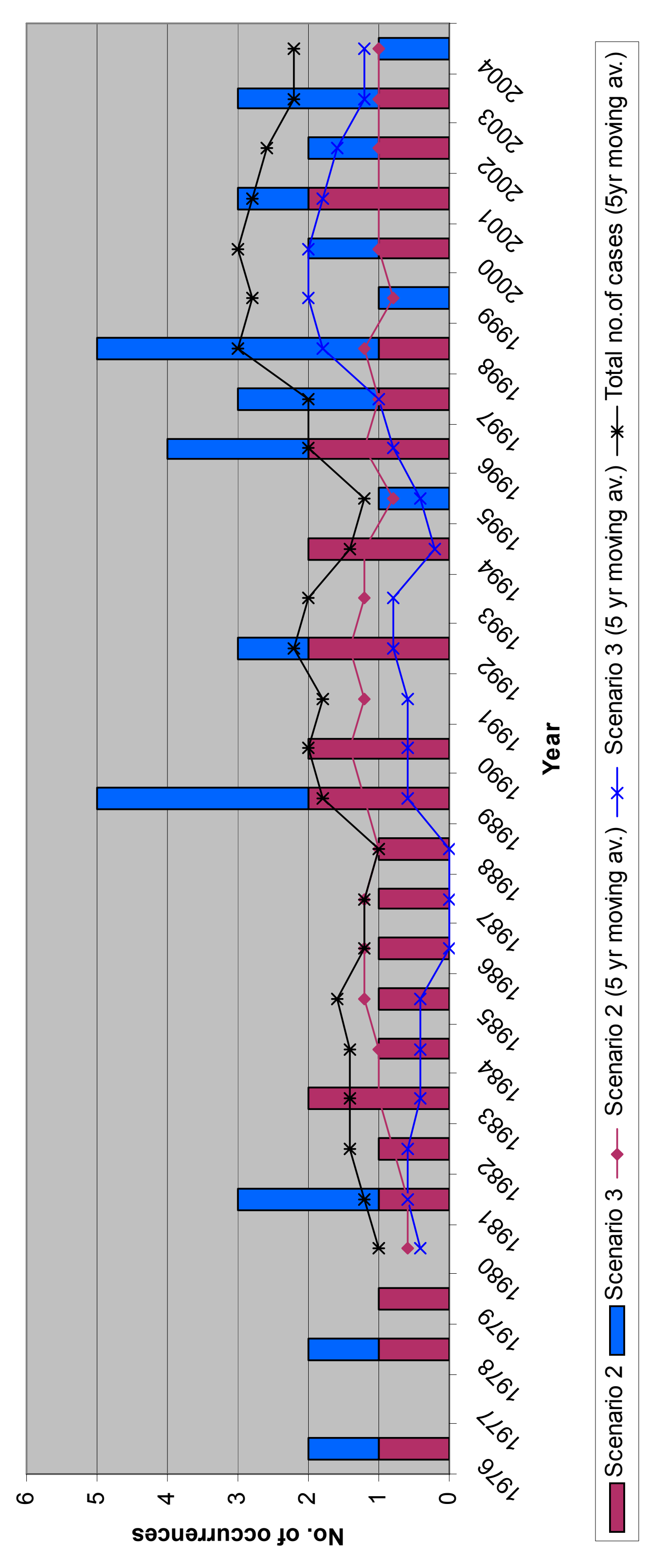

Figure 1 Number of occurrences of scenarios per year

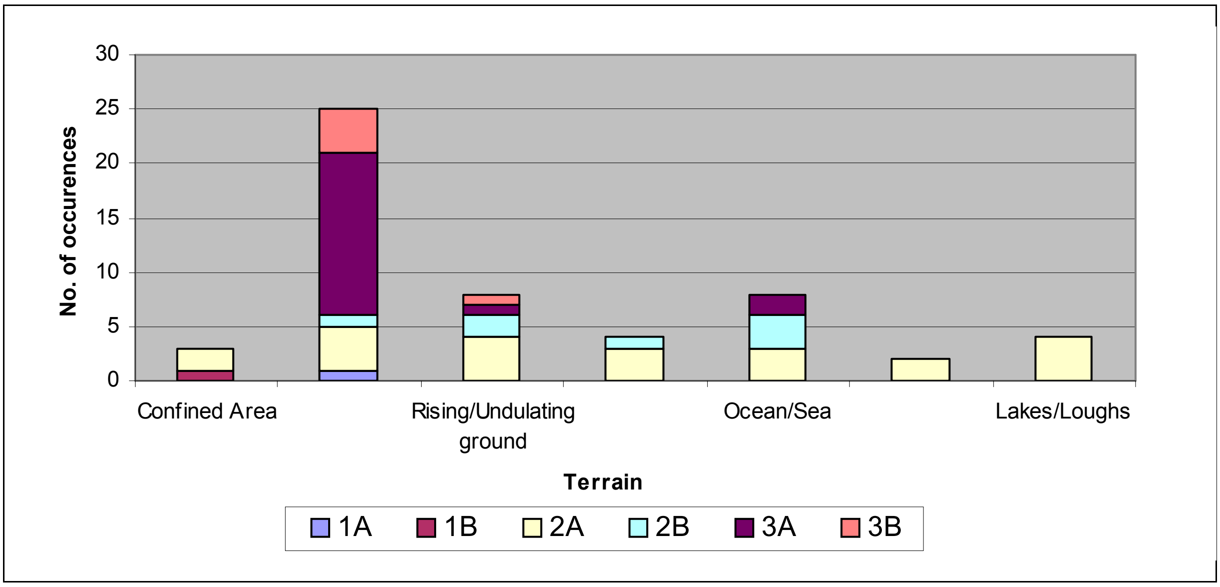

Figure 2 Number of occurrences of scenarios versus terrain

Referring to Figure 2:

The majority of cases took place over land and there was a variety of terrain textures that gave rise to problems regarding situational awareness (Scenario 2A/B cases). However, it was also possible to encounter similar problems when flying over water (including flight over inland waters or over the sea). The majority of the Scenario 3A/B cases occurred over land (the 'ground' category) and out of close contact with the surface.

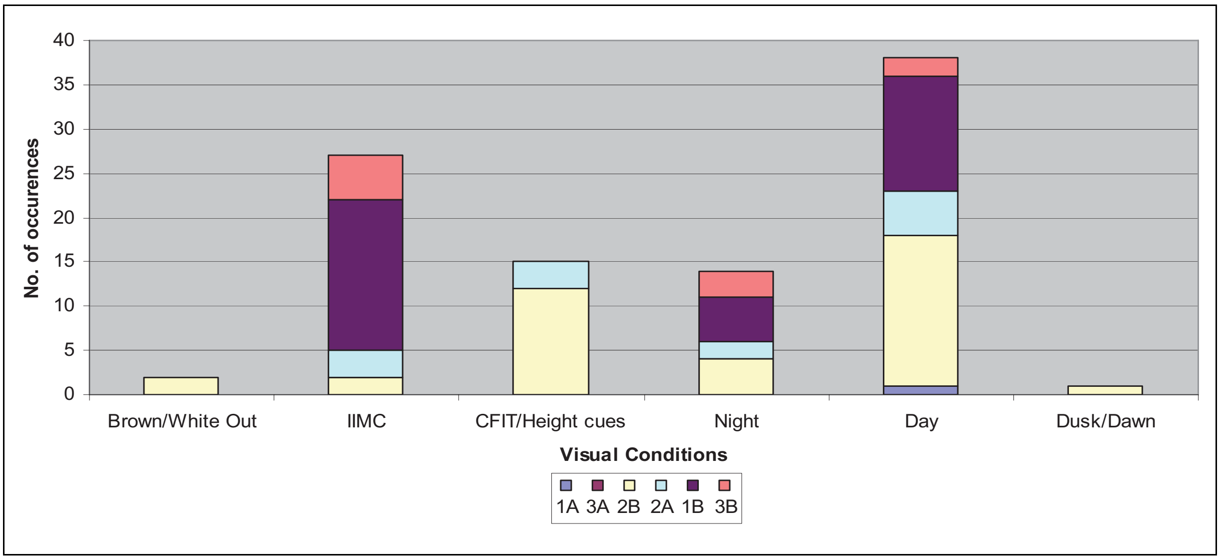

Figure 3 Number of occurrences of scenarios versus environmental visual conditions

Referring to Figure 3:

For the primary data set of 53 Scenario 2 and 3 cases and one Scenario 1 case, this figure shows the number of occurrences of Scenario versus environmental visual condition which featured in the accidents. The figure reflects that, often, more than one condition featured in an accident case (e.g. night and haze/fog), and hence the total number of scenario occurrences plotted exceeds the number of accidents (54). Most cases occurred during daytime (72%) and 74% cited weather related visual factors such as cloud, rain, snow, fog or haze. A further 11% of reports mentioned poor weather as a factor without specifying particular conditions. 13% of reports specifically mentioned poor surface texture such as flat water or snow as a causal factor. Only 3 cases (5%) featured cockpit related factors, i.e. restricted view, canopy misting, although it is interesting to note that 4 out of the 11 case reports during 2000-2004 cited a distraction in the cockpit as a possible additional causal factor (e.g. activation of visual/audio warnings). In-cockpit distraction was not cited as a causal factor for any of the earlier cases 1975-1999, although external distractions such as birds and other traffic were cited on several occasions.

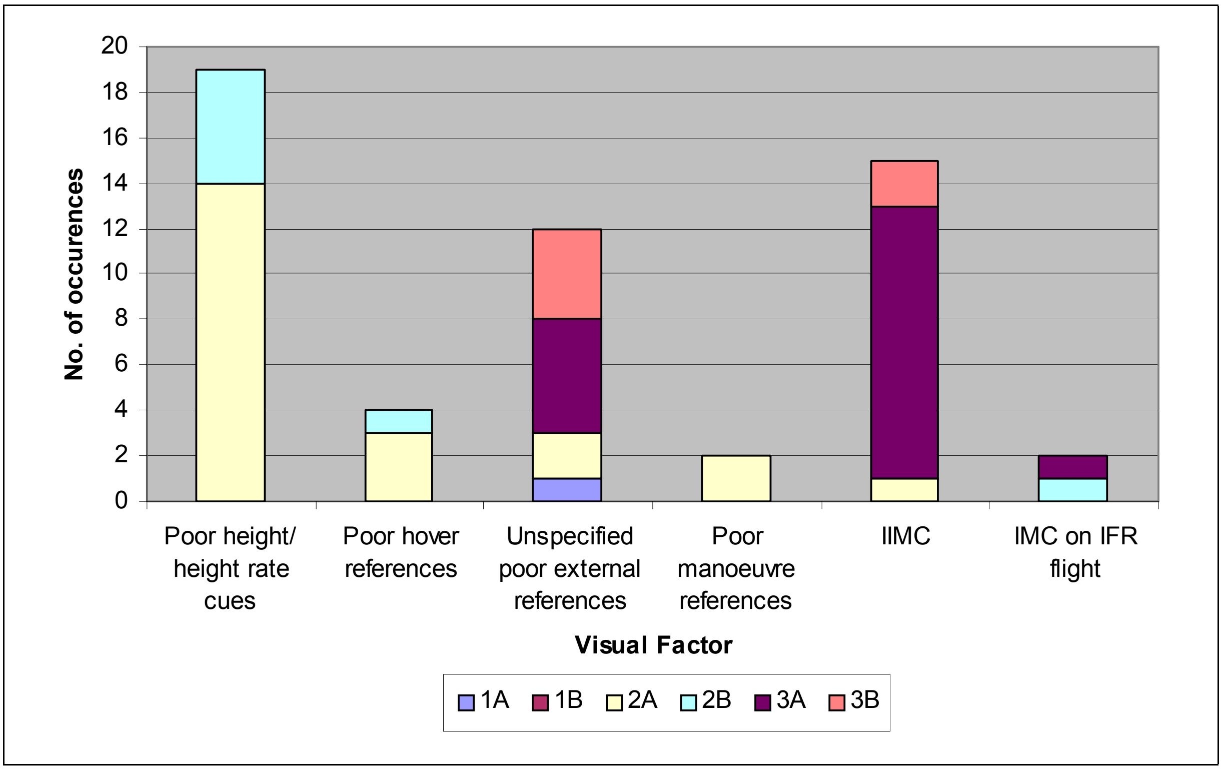

Figure 4 Number of occurrences of scenarios versus visual factor

Referring to Figure 4:

- Identification of specific visual cueing factors that featured in accidents is difficult in cases where there were no survivors and/or the CAA and AAIB reports lack definitive substantiating evidence. Therefore, 12 (22% of) cases are attributed to unspecified poor external references as illustrated in Figure 4. However, the available evidence in 10 of these 12 cases suggested IIMC as a probable factor. In addition, IIMC was cited in reports as a factor in 15 (28% of) cases. Taken together IIMC can be considered to be a probable factor in 25 (46%) of cases of which 17 (31%) probably gave rise to spatial disorientation. In addition, 2 incidents occurred where IMC was encountered on IFR flights; one where an inappropriate technique was applied during a missed approach and another where the pilot's attitude indicator proved to be unserviceable.
- There were also 19 cases (35%) of loss of situation awareness associated with poor height/height rate cues, 4 (7%) with poor hover references and 2 (4%) with poor manoeuvre references.

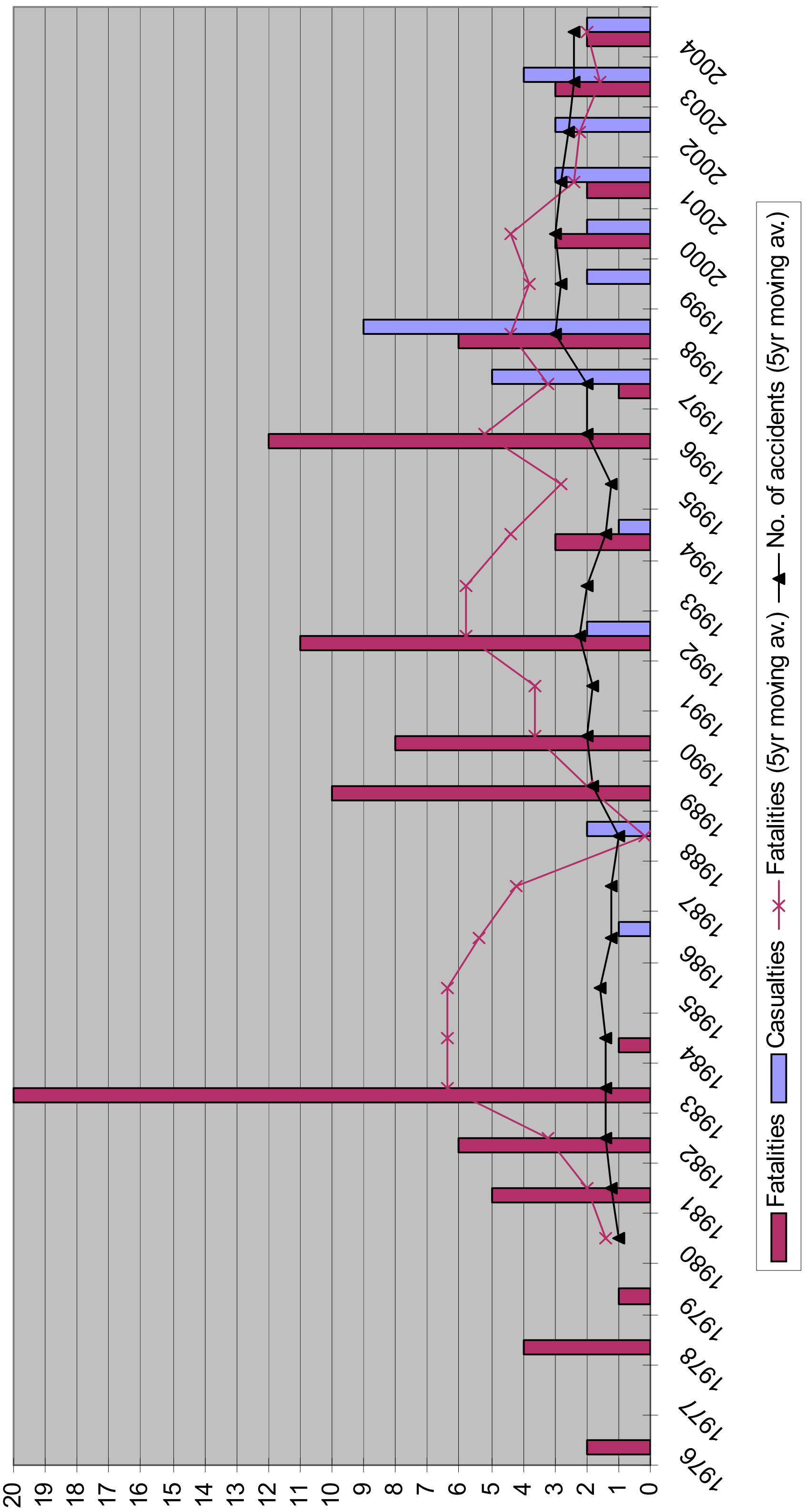

Figure 5 Total number of fatalities and casualties per year

Referring to Figure 5:

- There is an average of 3.4 fatalities per year. The single worst case in terms of fatalities, (detailed case study 5 in section 2, paragraph 3 and Appendix A, paragraph 5), accounted for 20 of these and, if they are removed from the count, the average reduces to 2.7 fatalities per year. Similarly, the overall average number of fatalities per occurrence is 2.0, which reduces to 1.5 if Case 5 is discounted.
- Regarding the longer-term trend of fatalities, the total numbers of fatalities for the periods 1976 to 1986 (10 yrs), 1986 to 1996 (10 yrs) and 1996 to 2004 (9yrs) is 39 (19 without Case 5), 32 and 29 respectively. Average numbers of fatalities per occurrence for each of the periods is 3.0 (2.2 without Case 5), 1.9 and 1.2.

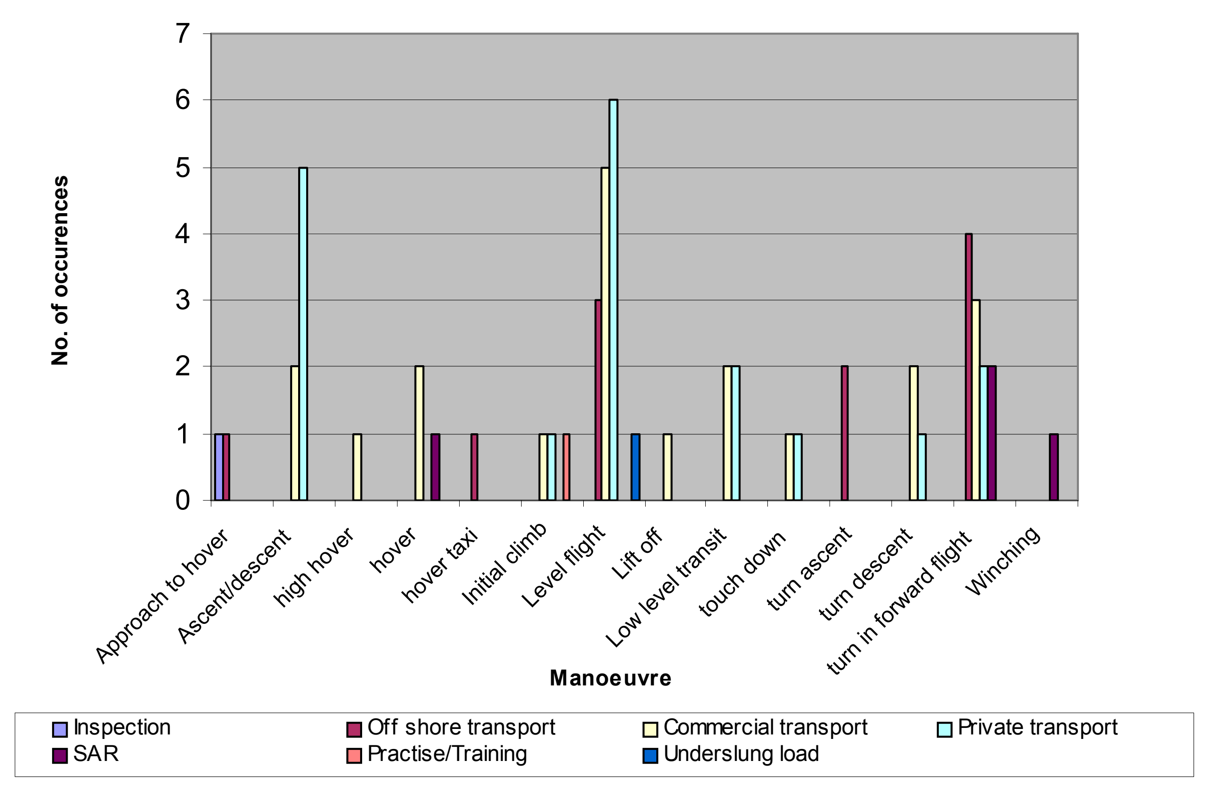

Figure 6 Number of occurrences of flight operation versus manoeuvre

Referring to Figure 6:

The data show that the accidents involved a wide range of flight operations, phases and manoeuvres, although the predominant categories are 'level flight', 15 cases (26%), 'turning in forward flight', 11 cases (19%), and ascent/descent, 7 cases (12%).

Scenario	Crashes with fatalities	Crashes with casualties	Crashes with no fatalities or casualties	Number of fatalities	Number of casualties
1	0	1	0	0	3
2	13	12	6	57	20
3	15	6	1	43	13
Total	28	19	7	100	36

Table 1a Distribution of fatalities and casualties

Referring to Table 1a:

- Approximately half (52%) of all cases resulted in fatalities, comprising 42% of all Scenario 2 cases and 68% of all Scenario 3 cases. Just over a third (35%) resulted only in casualties, comprising 39% of all Scenario 2 cases and 27% of all Scenario 3 cases.
- For both Scenario 2 and Scenario 3 cases there were approximately three times as many fatalities as casualties.
- The average number of fatalities per occurrence is 4.4 for Scenario 2 cases (2.8 without Case 5) and 2.9 for Scenario 3 cases.

2.3 **Detailed case studies**

A further subset of cases was selected from the primary data set to provide case studies for more detailed examination of the influencing factors and visual cueing issues associated with typical accident scenarios. In all, seven cases were selected as a representative sample of the different types of occurrences in the data set from 1975-2004; the key factors and basis for their selection is given below:

Case 1 Night operation under Special VFR, loss of control in a climb en-route when trying to avoid local cloud cover.

Case 2 Night operation under Special VFR, IIMC on take-off, consequent pilot disorientation and flight into obstacles.

Case 3 Night operation under VMC, IIMC during departure, consequent pilot disorientation and flight into the ground.

Case 4 Day operation under VFR, IIMC en-route, consequent loss of situational awareness when turning to avoid local cloud/fog cover.

Case 5 Day operation offshore under VFR, loss of situation awareness in poor visual conditions during the approach to land and consequent controlled flight into the sea.

Case 6 Day operation offshore under VFR, IIMC en-route and consequent loss of control in turning to avoid local cloud/fog cover.

Case 7 Night operation on approach/descent to an airfield in poor weather and possible IIMC followed by loss of control. False cues from ground cultural lighting were a possible factor.

Cases 1 to 6 only were used as a basis for the test conditions applied in the follow-on simulation trials investigations discussed in Section 3. Case 7 was identified when the accident data review was updated after the trials had been completed. Further details are given in Table 2 and a review of each case, based on the AAIB reference sources noted in column 3, is presented in Appendix A. Each case review contains a synopsis and a summary of the main conclusions and causal factors that contributed to the accident. The synopses include a summary of the main events and circumstances of the accident, and a summary of the main causal factors and conclusions as stated in the reference reports. The synopses comprise the following five sections:

Overview	a brief summary of the main details.
Background	operational aspects, details of the aircraft and its equipment, the pilot's qualifications and training, and the prevailing weather conditions.
Accident details	a more detailed description of the main events and circumstances relating to the accident.

AAIB analysis	the main findings from analysis of the available information, including survivor and eyewitness accounts, and results from wreckage/damage inspection etc.
Visual cueing aspects	an assessment of visual cueing factors and conclusions on the part that they played in the accident.

Case no.	Occurrence number	AAIB Reference source	Aircraft type	Scenario[1]	Brief Description
1	199604787	4/97 (EW/C96/10/8)	SA355	3A	Night/Special VFR, loss of control due to pilot disorientation following loss of visual references in a climb en-route
2	199805910	4/99 (EW/C98110/1)	SA355	3A	Night/Special VFR, loss of control during take-off & climb out due to pilot disorientation following inadvertent IMC
3	199800372	9/98 (EW/C98/1/5)	SA355	3A?	Night/VMC, pilot disorientation during departure and climb out caused by inadvertent IMC
4	199702041	7/97 (EW/G97/05/02)	Enstrom F28	3A	Day/VFR, pilot disorientation in a banked turn during an attempted recovery from inadvertent IMC en-route
5	198301880	8/84 (EW/C840)	Sik S61	2A	Day/VFR, Offshore, controlled flight into the sea due to poor situational awareness during final approach
6	198102469	10/82 (EW/C762)	Bell 212	3A	Day/VFR, Offshore, loss of control in a bank turn during an attempted recovery from inadvertent IMC en-route
7	200401275	6/2005 EW/C2004/03/01	Agusta 109 E	3A	Night/special VFR on approach/descent to an airfield in poor weather with possible IIMC followed by loss of control

Table 2 Study data set details

1. A = Probable, B = Possible

2.4 Discussion of Results

2.4.1 Overview

Typically, the primary data set cases were often the result of a number of contributory factors other than just those based purely on visual cueing considerations. For example, in some cases training or regulatory issues were implicated. Notwithstanding this, the review has provided strong evidence that there have been a significant number of accidents involving fatalities where degraded visual cues were the primary causal factor, resulting in loss of situational awareness and spatial disorientation. The evidence also suggests that this continues to be the case, despite the technological advances in aircraft and equipment over the 30 years covered by the accident data review, or the related mitigation measures adopted by the regulatory authorities. The March 2004 accident described in Case 7 (Appendix A, paragraph 7) is a particular case in point, as a result of which the AAIB recommended that the Rules of the Air be reviewed to consider imposing minimum day and night in-flight visibility requirements to provide an effective safety margin to prevent inadvertent flight in IMC, or loss of adequate visual references. As discussed in [11], there are systems available to mitigate the DVE problem such as automatic low height warning devices, but it is difficult to tailor these to deal with all potential circumstances that might result in an accident.

Inspection of the detailed case studies highlights a number of visual cueing issues that need to be addressed in order to reduce the probability of occurrence of potential accident situations, or loss of control when such cases have occurred. Firstly, there is a need for an improved understanding of the visual cueing attributes associated with a given DVE, and the impact that these have on a pilot's ability to control the helicopter. There is then the question of whether a developing DVE can be recognised and measured so that pilots can be forewarned of the potential danger and take appropriate action, or be provided with compensatory display information. In the event that visual cueing difficulties are encountered, there is a need to understand the information requirements and associated display formats that would best help the pilot to maintain control. Insufficient attention to displays, divided attention between displays and outside visual scene, or transfer of attention from outside visual scene to internal displays were significant contributory factors in loss of situational awareness and spatial disorientation. The evidence suggests that display formats are needed that allow a more intuitive and timely transfer or division of attention between outside scene and primary flight displays, especially for pilots who are not instrument rated.

There is also a need to address requirements for flight control augmentation for flight in the DVE. For flight under IMC, the regulations require that a helicopter is equipped with attitude stability augmentation and that the pilot has an appropriate instrument flight rating. This is not so for VFR operations and, in cases of IIMC, the pilot may be poorly placed to maintain attitude stabilisation without such equipment. Research into military rotary-wing handling qualities requirements has shown that the level of augmentation required to maintain satisfactory control in the DVE increases with the severity of visual cue degradation [12]. While visual displays can help to recover and maintain situational awareness, the desired safety enhancements are only likely to be established through a combination of both display and control augmentation.

The CRP study addressed these problems through a modelling approach and piloted simulation experiments [4,5,6]. This evaluation methodology is designed to be generic to all helicopter operations and, hence, is appropriate to both civil and military applications. The following sections discuss the findings of the review in more detail and develop the case for the simulation experiments that were undertaken to further investigate the principal issues.

2.4.2 Specific issues

It is of note that all 7 of the cases identified for more detailed examination took place under VMC and, in many, it seems that the pilot was justified in initiating the flight. Problems occurred because of the background visual conditions encountered en-route, or a sudden and unexpected deterioration in the visibility conditions. Pilots either found themselves suddenly immersed in cloud or fog where VMC flight was no longer possible (i.e. IIMC), or in a DVE condition that rendered flight using only external visual references unsafe.

For the IIMC situation, three types of pilot reaction can be identified from the data that could potentially result in a serious accident. Generally, pilots responded to the situation by endeavouring to backtrack, climb above or descend below the visual obstruction. In the first circumstance, unless they have adequate instrument training, are current and refer to instruments to effect a recovery, they can become disorientated very quickly and lose control of the situation. In the second circumstance, it is possible that the pilot will manage to maintain control of the aircraft but, because of poor situational awareness, fly the aircraft into an unsafe condition. In this case, divided attention between flight instruments and the outside visual scene can lead to a situation where the pilot fails to notice a gradual and insidious loss in height and consequently fly dangerously close to the ground. Alternatively, there may be a similar, unintended loss of speed and consequent loss of aircraft attitude stability, ultimately leading to loss of control. Division of attention is particularly relevant to low level flight where the pilot is more reliant on external cues for maintaining a safe flight path, or for maintaining position and attitude stabilisation in the hover. In the third circumstance, the pilot may attempt to establish on instruments but, because of the time needed to effect the transfer of attention, the aircraft may again be placed in a dangerous position. This is also relevant to low level flight in close proximity to the ground and obstacles.

In the DVE situation the pilot may be unaware of a loss of visual references, or be drawn into concentrating too much on external references at the expense of flight instruments. Generally speaking, the level of DVE will result from factors such as low levels of light, the presence of atmospheric haze or sun glare, lack of surface texture or features such as buildings, roads and rivers, or poorly delineated sloping or rising ground contours. These factors may combine to have a critical impact on the pilot's situational awareness through giving misleading or inadequate information regarding the aircraft's flight condition. For example, they may result in a poorly defined or missing visual horizon which will affect the pilot's ability to judge and stabilise aircraft attitude, particularly in the hover and at low speeds, or reduce the pilot's ability to detect changes in height, rate of change of height, or speed and position. Pilots have no way of knowing that they should not be relying solely on external cues, and if the cues are sufficiently degraded they may ultimately lose control of the aircraft, or fly into the ground or sea.

2.4.3 Test scenarios

The first six of the seven case studies provided a rich source of information for defining appropriate test scenarios for the simulation investigations. To illustrate this, Table 3 summarises the main visual cueing features present in the case studies, together with relevant details of the flight conditions.

As discussed in the following, this information was used to provide a basis for generic test manoeuvres based on the ADS-33 mission task element (MTE) concept and appropriate visual cueing scenarios [13,14,15].

From Table 3, regarding visual cues the feature common to all cases is the lack of definition of the visual horizon, irrespective of whether the operation was carried out at night or during the day, over land or over the sea. Other critical factors that affected flight over both land and sea included: reduced visual range and/or loss of sight of the ground due to the effects of fog or cloud; lack of detailed textural information from the background scene; in one case misleading cues from a false horizon. The flight conditions include common manoeuvre cases such as level flight, steady banked turns, level accelerations and decelerations, climbs and descents. Bringing these together, Table 4 outlines a basic civil mission profile with general manoeuvre definitions for departure, cruise and approach phases.

Case	Visual cueing features	Flight conditions
1	• Cloud layers at 1500 and 25,000 ft • Filtered/missing light from the moon and stars • No true horizons; optical perception of the visual horizon defined by the level of background light • No minor terrain features	• Level flight at 100 kn, 1500 ft agl • Climb from 1500 to 3000 ft • Changes of heading in level flight at 100 kn, 1500 ft agl
2	• Constrained visual range due to fog effects • Loss of sight of the ground due to fog effects	• Take-off, hover, and transition to 35 kn, 30 ft agl • Level banked turn in low speed flight • Heading orientation in IMC flight
3	• Transfer of attention from outside visual cues to head down flight displays • Loss of sight of the ground in a layer of mist • Indistinct visual horizon in very dark visual conditions • Compelling false horizon from illuminated line features orientated across the flight path	• Take-off, hover and transition to forward flight 40 kn, 250 ft agl • Levelling out from climb in IMC flight
4	• Hazy visual conditions with patchy cloud • Loss of sight of the ground on entry into cloud	• Level flight at 80 kn, 700 ft agl • Level banked turn through 180 deg IMC
5	• Hazy visual conditions • Poorly defined visual horizon • Lack of surface texture on the sea	• Level flight at 100 kn, 500 ft • Deceleration at 70 kn
6	• Foggy visual conditions • Reduced visual range • Poorly defined/no visual horizon • Lack of surface texture on the sea	• Level flight at 100 kn, 500 ft • Descent to 200 ft • Deceleration to 65 kn • Level banked turn through 180 deg
7	• Broken cloud base 600 - 1000 ft • Surface visibility 1.5 - 2.5 km in light rain/drizzle • Limited cultural lighting (roads, dwellings)	• Descending from 800 - 1000 ft • Descending left 540 deg turn

Table 3 Summary of visual cueing features and flight conditions

Note that Table 1 shows that the accidents identified in the study involve a wide range of flight states that span all of these phases; closer inspection (Figure 6) shows that there are peaks for the 'level flight', 'ascent/descent' and 'turning in forward flight' categories. The primary control requirements in relation to ego-motion parameters (e.g. position, speed, height, heading, attitude orientation) that the pilot must control in order to achieve the manoeuvre objectives with safety are also specified in the table.

Manoeuvre Requirement		Control Requirement
Departure	Transition from hover to forward flight, in either level or climbing flight	• Speed, height, balance and position co-ordination • Pitch attitude change • Roll, pitch yaw attitude stabilisation
Cruise	Climb from one flight level to another in forward flight	• Height and height rate management • Speed and balance co-ordination • Roll, pitch, yaw, attitude stabilisation
	Descent from one flight level to another in forward flight	
	Co-ordinated bank turns	• Roll attitude and heading change • Roll, pitch, yaw attitude stabilisation • Speed, height and balance co-ordination
Approach	Decelerating approach to hover, in either level or descending flight	• Height and height rate management • Speed, balance and position co-ordination • Pitch attitude change • Roll, pitch, yaw attitude stabilisation

Table 4 Manoeuvre and control requirements

In accordance with [3], the objective for the simulation trials was to investigate the visual information requirements needed to support pilots' control strategy in these manoeuvres through manipulation of visual scene content, initially using simple visual cueing constructs. The aim was to determine the requirements expressed in relation to the optical cues needed (e.g. optical flow, edge rate, motion parallax, object looming) for exercising control of the ego-motion parameters. Table 5 highlights the visual cueing effects and associated visual scene parameters that are relevant to the case study scenarios.

Visual Effect	Visual Scene Parameter
Day and night	• Background level of light
Landscape features	• Terrain contours - level/rising/sloping ground • Objects and obstacles
Seascape features	• Structure and bearing of surface waves
Degraded transitional rate cues	• Surface texture
Degraded height rate cues	• Features with vertical extent and texture
Degraded attitude information	• Visual horizon
Immersion in fog	• Reduced visual range • Reduced surface texture contrast
Immersion in cloud	• Loss of sight of the ground • Loss of forward vision

Table 5 Visual scene manipulation - visual effects and visual parameters

The simulation investigations were based on the manoeuvre definitions and visual scene cases presented in Tables 3 and 4, focusing on the specific cases noted in Section 2.3. The broader test objectives and issues are discussed further in Section 3.

2.5 Main findings

The initial sift of the data identified some 700 rotary-wing cases of interest involving both private and public transport helicopter operations during the period 1975 to 2004. A more detailed sift using the MOR data summaries identified a primary set of 53 Scenario 2 and 3 cases and one Scenario 1 case where degraded visual cues, poor pilot situational awareness and/or spatial disorientation were found to be primary causal factors. Between them, the Scenario 2 and 3 cases form the single largest cause of small helicopter fatal accidents. A further secondary set of 71 Scenario 1 cases was also identified where obstacle or terrain strikes in low level flight and pilot judgement of flight path clearances were critical factors[2].

A summary of the main conclusions for the primary set of nearly all Scenario 2 and 3 cases is given below. Note that relative accident rate-based statistics are not included because of the lack of information regarding operating hours for different types. Reference [7] should be consulted for a fuller account of the review and its findings.

a) The occurrences involved a wide range of aircraft types and flight operations, phases and manoeuvres, with 57% categorised as Scenario 2 cases, 41% as Scenario 3 cases and a single (2%) Scenario 1 case.

b) The total number of occurrences per year gradually increases over the period 1976 to 2004 from 1 per year to approximately 2.5. The average number of Scenario 3 cases from the late-1990s overtakes the number of Scenario 2 cases which remains relatively constant. This result indicates an increase in the number of accidents resulting from spatial disorientation in a DVE.

c) During the period 2000-2004 all four fatal accidents were private flights, representing 50% of the relevant private cases identified, resulting in eight fatalities, an average of 0.7 per occurrence. This result may reflect an increased use of private helicopters with associated lower levels of equipment fit and pilot experience compared with commercial operations. All the fatal accidents were categorised as Scenario 3 cases (i.e. spatial disorientation was a probable causal factor).

d) There were 100 fatalities overall, corresponding to an average of 1.9 per occurrence. 47% of Scenario 2 cases and 67% of Scenario 3 cases involved fatalities, and there were approximately three times as many fatalities as casualties for both Scenario 2 and Scenario 3 cases. These statistics indicate the probable severe consequences of accidents involving CFIT or spatial disorientation, especially in the case of the latter.

e) Although the accidents identified were the result of a number of contributory causal factors, IIMC was probably the most significant factor. 46% of cases probably involved (A), or possibly involved (B), IIMC of which the majority probably resulted in spatial disorientation (Scenario 3). Of the remaining cases, the majority involved CFIT (Scenario 2), which was attributable to poor height/height rate cues.

f) Most cases took place over land and a variety of terrain textures and visual conditions were encountered that resulted in poor situational awareness (Scenario 2 cases). Although fewer cases occurred over sea/water, the data show that similar situational awareness problems can be encountered when flying over water.

g) The majority of cases (68%) occurred during daytime and out of close contact with the surface. Weather related visual conditions such as cloud, rain, snow, fog or

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[2] The 71 secondary set cases are associated with the period 1975 to 2000; secondary cases during the period 2000 to 2004 were ignored.

haze were the most commonly cited causal factors and only a small minority of cases featured cockpit related factors such as restricted view, or canopy misting.

h) The findings of the review support the case that there is a need for an improved understanding of visual information and display requirements for civil flight operations in the DVE. Insufficient attention to displays, divided attention between displays and outside visual scene, or transfer of attention from outside visual scene to internal displays was a significant contributory factor in loss of situational awareness and spatial disorientation.

From [7], of the cases examined it was concluded that degraded visual cueing was probably the most significant causal factor, including instances of IIMC or controlled flight into terrain (CFIT). To further the objectives of the research, it was planned to carry out a simulation-based investigation of the circumstances and causal factors that contributed to the Scenario 2 and 3 cases. The aim was to conduct piloted evaluations in simulated visual cueing conditions representative of those under which the accidents had occurred, and then to use the results to examine the need for upgrades or amendments to the regulations to help prevent and/or mitigate such cases.

To this end, a more detailed case study was conducted using source material taken from appropriate Air Accidents Investigation Branch (AAIB) reports and bulletins for a sub-set of seven of the 54 accidents; see Tables 2 and 3. The data from the first six cases were subsequently used as the basis for the test matrix for the simulation investigation[3]. Note that five of the six cases featured loss of control resulting from spatial disorientation where some degree of reduced visibility was encountered, including cases of IIMC, and one case featured controlled flight into the sea as a result of poor visual conditions. Four cases occurred during operations over the land and two over the sea and each occurred in one of the following phases of flight: initial departure from hover, take-off (fly away), climb en-route, turn en-route or final decelerating approach to land.

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[3] Case 7 was identified when the accident data review was updated after the trials had been completed.

3 Phase 2/1 - Simulation Investigation

3.1 General objectives

Phase 2/1 involved a piloted simulation trial, EMOCUES2, which was carried out during January 2002 using QinetiQ's Real Time All-Vehicle Simulator (RTAVS). Some problems were experienced subsequently with analysing the objective data from the trial and, in consequence, a repeat set of evaluation runs for data collection purposes was carried out during March 2003. For identification purposes, the former activity is referred to as Trial 1 and the latter as Trial 2. Trial 2 was carried out essentially as a repeat of Trial 1, but with some minor variations in the test plan in respect of the cases evaluated. Regarding the data analysis covered in Section 4, it should be noted that only the Trial 2 data were subsequently available for analysis. However, the subjective data results from Trial 1 are valid and are analysed together with the Trial 2 data in Section 3.4.

In both trials, two qualified and experienced test pilots evaluated two different civil helicopter control types in simulated flight and visual conditions representing those reported for the selected accident scenarios (Table 6). The main objectives of the trials were based on key issues that were highlighted in the review of accidents [7], including the following:

a) To investigate flight control augmentation requirements for helicopters operating in degraded visual conditions.

b) To investigate the use of flight instruments when flying in or encountering degraded visual conditions, including the impact of transferring from visual to instrument flight.

c) To investigate the interaction between the navigation, guidance and stabilisation tasks when flying in, or encountering degraded visual conditions, with or without the use of primary flight instruments, i.e. using only outside visual cues.

d) To establish the applicability of military handling qualities requirements to civil helicopter operations in degraded visual environments (DVE).

Regarding d), it was concluded from an earlier study of civil helicopter handling qualities requirements that the equivalent military requirements could provide a source of advisory guidance to improve the former [13,14,15]. Of relevance to the current study, it was considered that the Aeronautical Design Standard - 33 (ADS-33 - latest version ADS-33E-PRF [15]), and its Useable Cue Environment (UCE) concept in particular, could be applicable to civil helicopter operations affected by poor visual cues. Hence, as explained in the following sections, the ADS-33 UCE concept was used as the key basis for the trial design for the simulation-based investigation.

3.2 Application of ADS-33 UCE concept

ADS-33 is a mission-oriented standard, which specifies the control and vision augmentation requirements for military helicopters. Its requirements are specified using 'levels' that are based on the Cooper-Harper Handling Qualities Rating (HQR) scale, Figure 7, which may be summarised as follows:

Level 1 - ratings 1 to 3

- Handling qualities satisfactory without improvement, desired performance achievable with minimal pilot workload.

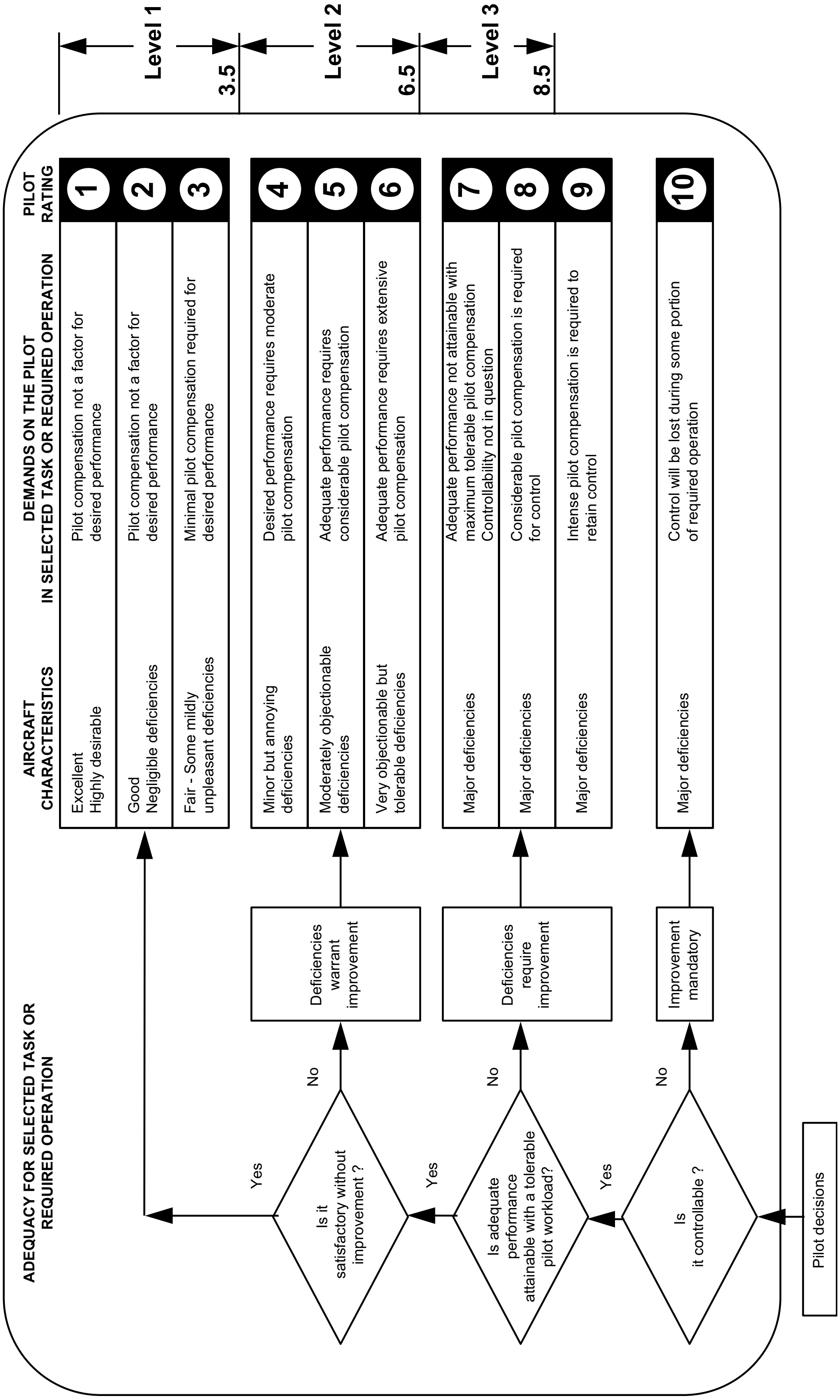


Figure 7 Cooper-Harper handling qualities rating scale and ADS-33 levels

Level 2 - ratings 4 to 6

- Handling qualities deficiencies warrant improvement, desired performance achievable with moderate (rating of 4) pilot workload, or adequate performance achievable with considerable to extensive pilot workload (ratings 5 - 6).

Level 3 - ratings 7 to 9

- Major handling qualities deficiencies, adequate performance cannot be achieved with tolerable pilot workload.

Unlike the approach in the civil standards, which address requirements for operations under either Visual Flight Rules (VFR) or Instrument Flight Rules (IFR), ADS-33 uses the UCE concept to define handling qualities criteria for flight in a range of degraded visual conditions, i.e. the degraded visual environment (DVE). To explain, UCE is quantified through pilots' visual cue ratings (VCRs), which represent a pilot's ability to use the available visual cues to perform certain defined control tasks with precision and aggression. The visual cues are divided into those which provide attitude (roll, pitch, yaw) information and those which provide translational (horizontal and vertical) rate information, and are rated on a scale of 1 (good) to 5 (poor). The UCE is derived from the attitude and translational rate VCRs using the chart shown in Figure 8.

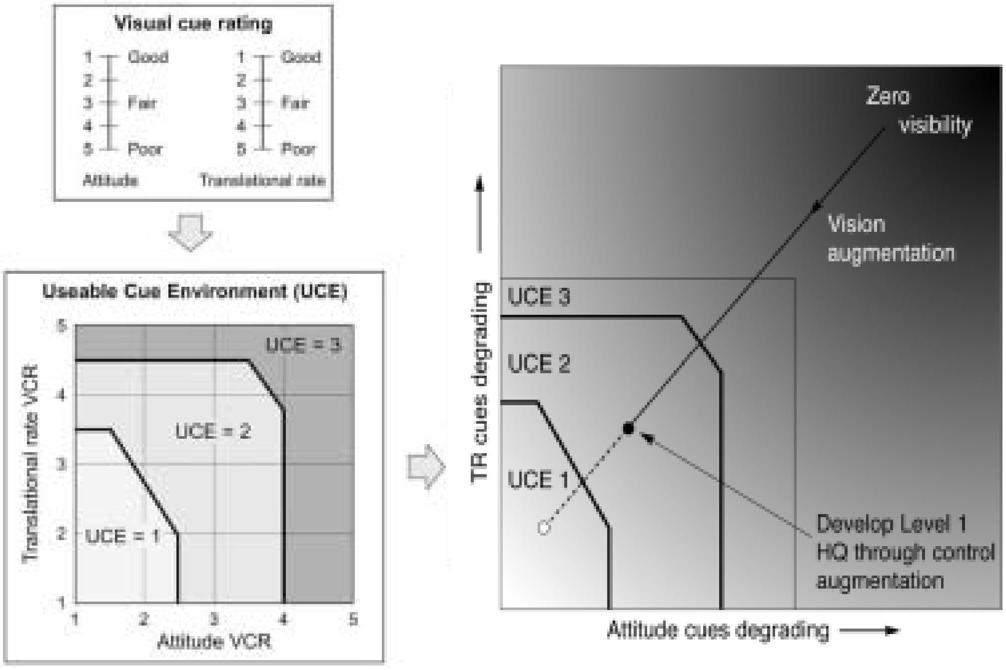


Figure 8 ADS 33 UCE concept

For UCE 1, the best visual conditions (i.e. good, daylight visual conditions), only minimal stability and control augmentation is required to achieve acceptable handling qualities. To ensure low workload and reduce the risk of loss of control through spatial disorientation, the requirements for control augmentation increase as the visual conditions degrade to UCE 2 and 3. That is, a Rate Command (RC) response type is adequate to achieve Level 1 handling qualities in UCE 1, but Attitude Command - Attitude Hold (ACAH) and Translational Rate Command (TRC) are required for UCE 2 and 3 respectively. The response characteristics for these types following a step control input are illustrated in Figure 9. Note that the level of visual degradation in UCE 2-3 is such that the pilot can still see sufficiently to fly through a cluttered terrain environment, i.e. it can be assumed that these conditions equate to civil VMC operations. As illustrated in Figure 8, the operating conditions can be well outside the UCE chart and no amount of control augmentation will make it possible for the pilot to avoid collision with the ground or obstacles. However, if the required operational conditions can be recovered to UCE 3 or better using, for example, sensors and/or visual aids, then adequate handling qualities can be built in through stability and control augmentation.

It was considered that the ADS-33 approach represented the most appropriate means of investigation for addressing the causal factors associated with the accident cases identified in the Phase 1 study, and offered a potential means of improving the safety of civil helicopter operations in degraded visual conditions in general. Accordingly, the objective of the trial was to examine the relationship of UCE and handling qualities in the context of the civil accident scenarios by experimental means. The specific aim was to investigate the impact of degraded visual cues on the pilot's ability to maintain safe control in the DVE and the application of UCE as a means of quantifying the sufficiency of visual scenes for pilotage. Beyond this, the results were used to develop the case for the application of the UCE concept in support of the JARs.

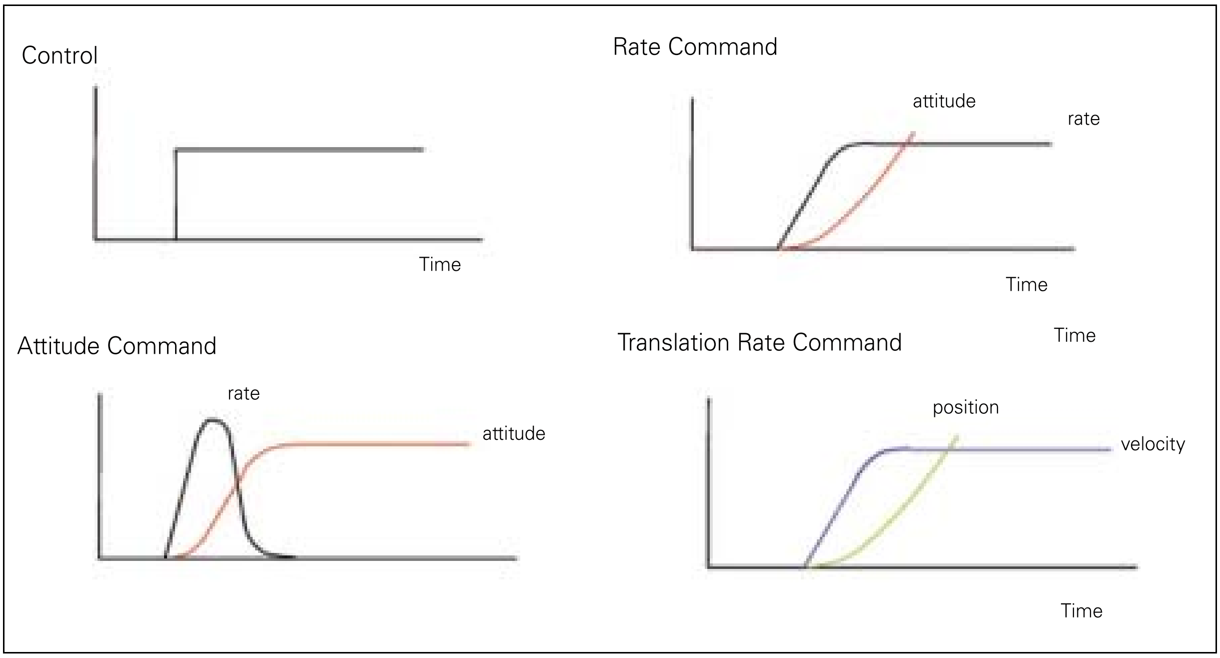


Figure 9 Characteristics of different control response types

3.3 Trial method

As noted above, the test matrix for the trial was based on the set of accident cases summarised in Table 6, and was tailored specifically to meet the objectives noted in the previous sections. The rationale for the selection of the test cases and the key experimental variables, which included the aircraft model, visual condition and test manoeuvres, are discussed below. A more detailed summary of the trial design and conduct, and its preliminary findings is given in the EMOCUES2 trial conduct report [8].

	Flight Regime	Manoeuvre states	Visual scene	Visual conditions	Aircraft configuration
1	Up and Away	1 Straight and level flight at 100 kn, 1000 ft AGL 2 Climb 1500-3000 ft	• Sparsely lit rural scene	• Night • Visibility 10 km • 83% moon • Cloud layers at 12-1500 ft and 2-3500 ft	• No autostabilisation • Cyclic - no force trimming or spring centring
2	Low level	1 Hover 2 Transition to forward flight at 25kn IGE 3 Low speed turn	• Confined space with hover pad bounded by trees	• Night • Visibility 10 km • Fog bank • IIMC	• Autostabilisation • Standard flight instruments • Inadequate attitude indicator instrument light
3	Low level	1 Hover 2 Transition and climb to forward flight at '60 kn', 250 ft AGL 3 Level out to forward flight	• Sparsely lit rural scene • Few light sources • Motorway with lights	• Night • Visibility 1.2-1.5 km • No moon • Indistinct visual horizon • Fog/mist 2-300 ft AGL • IIMC	• Autostabilisation • Standard flight instruments • AVAD height warning system
4	Up and Away	1 Straight and level flight at 78 kn, 6-700 ft AGL 2 180 deg banked turn	• Rural scene	• Day • Visibility 3.2 km • Haze + varying amounts of cloud • Cloud bank down to 50-100 ft • IIMC	No data given in the accident summary

Table 6 Summary of accident scenarios

	Flight Regime	Manoeuvre states	Visual scene	Visual conditions	Aircraft configuration
5	Up and Away	1 Straight and level flight at 110kn, 2000ft AGL 2 Transition and descent to 110kn, 500ft 3 Transition and descent to 110kn, 250 ft 4 Deceleration 110-90 kn (reducing collective + cyclic beep trim) 5 Deceleration below 90kn	• Over the sea	• Day • No discernible horizon • Haze • Visibility greater than 900 m • Calm sea, little surface texture	• AFCS (pitch, roll, yaw) • Attitude + heading hold • ASI + Flight director
6	Up and Away	• Straight and level flight at 100 kn, 500 ft AGL • Transition/descent to 200 ft AGL • Deceleration to 65 kn • Turn at 65 kn, 200 ft AGL	• Over the sea	• Day • No discernible horizon • Patchy fog • Cloud base 100-200 ft • Visibility initially greater than 10 km then down to 150 m (variable) • Calm sea, little surface texture • IIMC	• Auto stabs yaw, roll, pitch + attitude hold • Collective-yaw interlink

Table 6 Summary of accident scenarios (Continued)

3.3.1 Aircraft model

To meet the objectives of the research the simulation investigation needed to cover the range of helicopter handling qualities characteristics that featured in the accident scenarios. Given the constraints on resources, this was achieved by providing two helicopter model types: Basic, an unaugmented type with undamped rate responses, which was intended to represent a private light helicopter such as a Robinson R-22; and ACAH, a more sophisticated augmented type with attitude command-attitude hold responses, equivalent to a public transport helicopter such as a Sikorsky S-76. To complete the targeted handling qualities characterisations, the two configurations were equipped with cyclic mechanical characteristics appropriate to the two aircraft types. That is, Basic was configured with a 'friction' cyclic, while ACAH was configured with a spring trim cyclic. Although not formally evaluated it might be expected that the Basic configuration would have Level 2 - 3 handling qualities according to ADS-33 criteria and the ACAH configuration, Level 1 - 2.

3.3.2 Visual cueing conditions

To achieve results for a range of flight conditions and simulated DVEs, visual databases were designed to represent simulated visual cueing conditions with UCEs of 1, 2 and 3 or poorer. In effect, the conditions represented a controlled degradation of conditions from Visual Meteorological Conditions (VMC) to Instrument Meteorological Conditions (IMC), as determined by the level of UCE.

Each UCE condition was achieved through the application of a fog model (i.e. to attenuate the visual range and the acuity of the visual horizon), the time of day setting and manipulation of the micro (surface textures) and macro (buildings, roads, lights) cueing features within the visual scene. UCEs for the simulated visual conditions were assessed using the ADS-33 Visual Cue Rating (VCR) procedure noted above [5,15]. Four visual cueing conditions were defined as described below.

a) **Day/GVE**: Targeted UCE 1 - Good Visual Environment (GVE); a relatively cue-rich scene with dense textures and macro cues (fields, hedges, houses, roads, lights etc.); midday with unconstrained visual range and a well-defined visual horizon.

b) **Day/GVE/Fog**: Targeted UCE 2 - As for condition (a), but with a reduced visual range and reduced contrast between the ground terrain and the sky, i.e. poorly defined visual horizon.

c) **Day/DVE/Fog/Text**: Targeted UCE 3 - as for condition (b), but with sparser surface textures and macro cues.

d) **Night/DVE/Fog/Text**: Targeted UCE 3 or poorer - as for condition (c), but with adjusted time of day, i.e. midnight as opposed to midday.

It should be noted that the descriptors for the visual conditions (e.g. Day/GVE) are taken from the simulation visual database names, which reflect the way that they were constructed. 'Day' or 'Night' denotes the time of day (i.e. either mid-day or mid-night), and 'GVE' denotes a cue-rich visual scene, 'DVE' a sparse visual scene, where the latter was created by removing surface texture or macro features from the visual scene (denoted by the 'Text' element of the visual database file name). In addition, the visual cues for a given scene were further degraded by using a fog model (denoted by the 'Fog' element of the visual database file name) to attenuate the visual range and acuity of the visual horizon. Examples of the simulated visual conditions are presented in Appendix B.

To represent the IIMC situation, some test cases also involved an encounter with a sudden degradation in visibility, beyond the standard UCE scenarios. For these tests the evaluation was initialised with the Day/DVE/Fog/Text visual condition, and then an instantaneous reduction in visual range was introduced (i.e. via the fog model) at a given point in the evaluation. The pilot set out initially as if to fly the standard manoeuvre and, on introduction of the IIMC visual condition, proceeded to establish flight on instruments only and to recover to a safe flight condition.

3.3.3 Test manoeuvres

The key events and visual cueing factors associated with the six selected accident scenarios from Phase 1 were used as a basis for defining the test manoeuvres for the trial. For 3.1 (b) above, the accident reports for the selected scenarios indicate that they all involved operations under VMC [7], where the pilot was endeavouring to operate during the day or at night while maintaining visual contact with the ground. In many of the civil accident scenarios reviewed in Phase 1 pilots became unsure of navigational references as the visual cues deteriorated, which provided a significant distraction from the near term guidance and stabilisation tasks and from cockpit instruments. In these circumstances the pilot's attention is divided between the external references needed for maintaining aircraft stability, flight path guidance and navigation, and the internal cockpit references, i.e. flight instruments, for monitoring the aircraft's state. It seems that some accidents occurred when the pilot's attention was distracted by deteriorating visual cues and concern about getting lost, to the point where cockpit instruments were ignored for significant periods of time.

The intention was to investigate this aspect during the trials through so-called 'distractor tasks', which would provide a general, stylised representation of the circumstances of the selected accident scenarios. In effect they were intended to replicate the visual navigation task, requiring the pilot's attention outside of the cockpit in addition to the effort needed for scanning flight instruments. To achieve this, the pilot had to maintain a lookout for strategically positioned light sources, with the intention that location of a light would trigger a subsequent action in the manoeuvre sequence (e.g. turn, climb, level out). As a limiting case, it was also intended to evaluate the tasks without the use of primary flight instruments, which would replicate an accident scenario were the pilot has been distracted to the point where flight instruments are ignored completely. For this test case, the Day/DVE/Fog/Text or Night/DVE/Fog/Text visual condition was flown without flight instruments, i.e. the head down display (HDD) was frozen.

The task descriptions used for briefing the pilots are described below. Note that in each case, desired and adequate task performance requirements were set for control of relevant flight path parameters for each manoeuvre (e.g. height, speed). Generally speaking, values were set that were considered to be commensurate with normal levels of pilot workload under average operational conditions although, where appropriate, the requirements were intentionally specified to inject a sense of urgency into the evaluation in order to be representative of the circumstances in the accident scenarios. Note that the desired and adequate requirements are shown in brackets in the following descriptions, e.g. desired/adequate ± 5/± 10kn.

Hover Taxi: Depart from hover at 25 ft above ground level (agl) over a heli-pad, which is positioned in a confined space close to buildings and a windsock to give vertical reference cues, on a heading of 060 degrees. Hover taxi to clear the area at 25 kn (± 5/± 10 kn) and 25 ft (± 3/± 6 ft) agl, making a right turn to clear a line of buildings adjacent to the flight path with a clearance distance of 80 ft (i.e. approximately two rotor diameters). When clear and on a heading of 180 degrees, accelerate and climb away.

Fly Away: Depart from hover at 25 ft agl over the threshold of a runway. Climb and accelerate to 250 ft agl (± 25/± 50 ft) and 100 kn (± 5/± 10 kn), and continue in forward level flight. A red light will appear ahead of the aircraft at the targeted height and the task is complete when it has disappeared from view.

Turn: From forward level flight initiate a turn at 30 degrees (± 10 degrees) angle of bank and maintain height and speed at 750 ft agl (± 50/± 75 ft) and 80 kn (± 10/± 15 kn); when a red light appears ahead of the aircraft level out on a course to over-fly the light. The task is complete when the light has disappeared from view. At the initial start point, the light will be positioned out of view behind the aircraft.

Climb: From forward level flight at 1500ft agl and 100kn initiate a climb when a red light appears on the flight path ahead of the aircraft; climb as quickly as possible, while maintaining speed = 60 kn. When a second light appears ahead of the aircraft, level out at a targeted height of 2500ft agl (± 25/± 50ft) and continue in forward level flight at 60kn (± 5/± 10 kn); the task is complete when the light has disappeared from view.

Approach: From forward level flight at 750 ft agl and 100 kn, initiate a decelerating descent to a height of 250 ft agl (± 25/± 50 ft) and speed of 60 kn (± 5/± 10 kn). During the descent, a red light will appear on the ground ahead of the aircraft; the descent should be continued with the aim of levelling out and over-flying the light (lateral track error ± 50/± 75 ft) at the target height and speed. The task is complete when the light has disappeared from view.

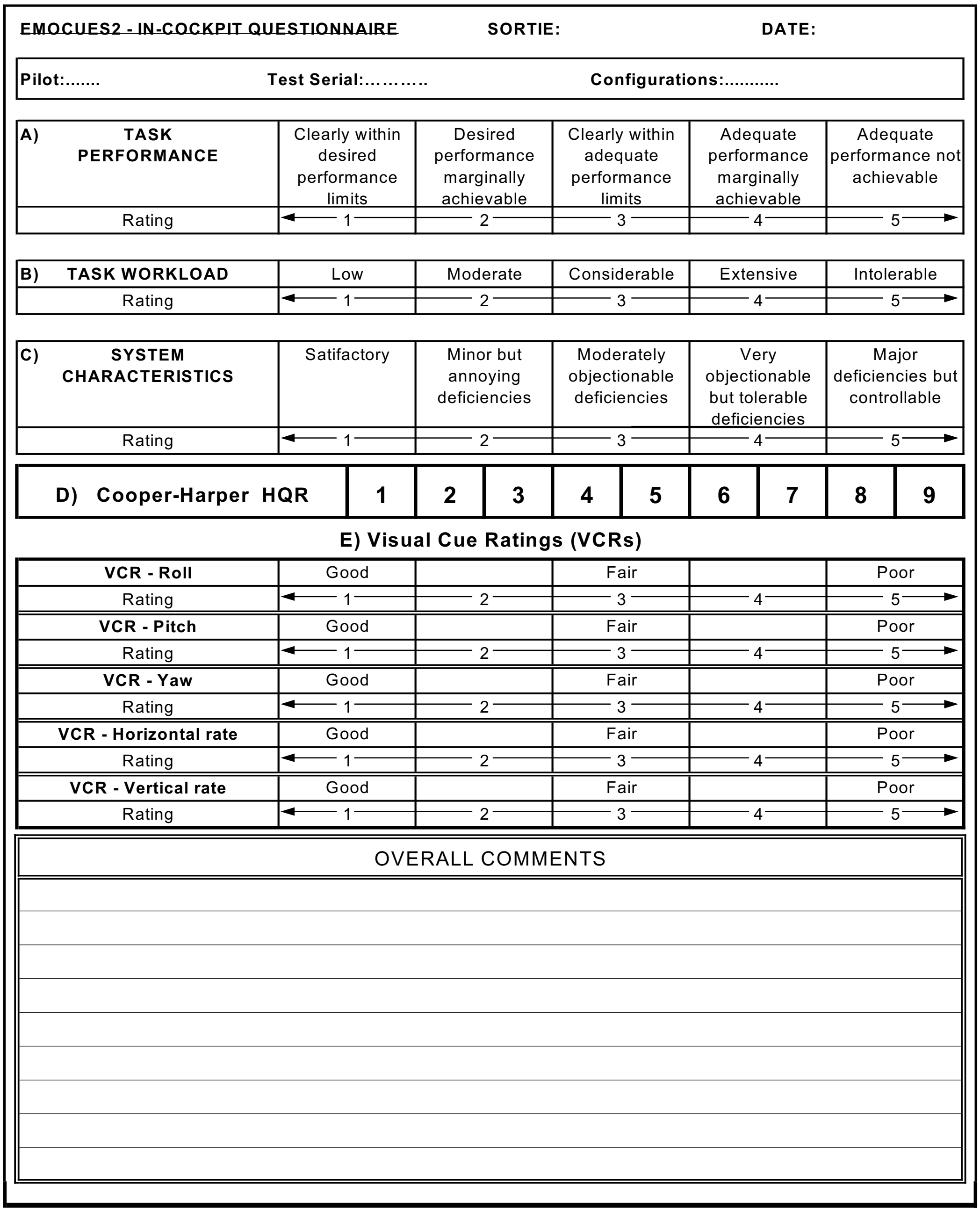
For the IIMC encounters, the point at which the IIMC visual condition was introduced depended on the manoeuvre as noted below, and some variation was introduced between runs in order to reduce the effect of anticipation.

- Hover taxi - at any point during the turn to clear the terminal buildings.
- Fly away - at any point during the climb out.
- Turns - at any point during the turn while the aircraft was established in a banked attitude.
- Climbs - at any point during the climb.
- Approach - at any point during the descent.

3.3.4 Data capture

Objective data were recorded for each evaluation including aircraft state (attitudes, rates, and accelerations), pilot's control demands and flight path condition (height, speed and position). Subjective data in the form of VCRs and HQRs were also recorded using an In-cockpit Questionnaire (ICQ), an example of which is shown in Figure 10. The ICQ has evolved over many trials applications and provides a methodical and consistent means of debriefing pilots. For each test case, the pilot flew the test manoeuvre and then awarded ratings in situ in the cockpit which were recorded at the simulator control desk, via the communications intercom, together with any additional comments.

Referring to Figure 10, the ICQ has two main sections; the first concerns Cooper-Harper handling qualities ratings (HQRs) and supporting comments; the second deals with Visual Cue Ratings (VCRs). The Cooper-Harper scale and decision tree is shown in Figure 7. The HQR is awarded based on the pilot's perception of three key issues: task performance, task workload and system characteristics. In order to assist the pilot to form an opinion, the pilot is first required to award a rating for each of these aspects using the five point rating scales in sections (A), (B) and (C) of the ICQ. The adjectival descriptors for each rating point are based on the words used in the Cooper-Harper decision tree, hence, there is an equivalence between these ratings and the overall HQR. That is, for consistency checking purposes ICQ ratings of 1 equate to a HQR in the range 1-3, 2 to a HQR 4, 3 to HQR 5, 4 to HQR 6 and, finally, a rating of 5 to a HQR of 7 or poorer. The Cooper-Harper decision tree is used to award the HQR in section (D) of the ICQ.



EMOCUES2 - IN-COCKPIT QUESTIONNAIRE **SORTIE:** **DATE:**

Pilot:....... **Test Serial:……….** **Configurations:...........**

A) **TASK PERFORMANCE**	Clearly within desired performance limits	Desired performance marginally achievable	Clearly within adequate performance limits	Adequate performance marginally achievable	Adequate performance not achievable
Rating	◄ 1	2	3	4	5 ►

B) **TASK WORKLOAD**	Low	Moderate	Considerable	Extensive	Intolerable
Rating	◄ 1	2	3	4	5 ►

C) **SYSTEM CHARACTERISTICS**	Satifactory	Minor but annoying deficiencies	Moderately objectionable deficiencies	Very objectionable but tolerable deficiencies	Major deficiencies but controllable
Rating	◄ 1	2	3	4	5 ►

D) Cooper-Harper HQR	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

E) Visual Cue Ratings (VCRs)

VCR - Roll	Good		Fair		Poor
Rating	◄ 1	2	3	4	5 ►
VCR - Pitch	Good		Fair		Poor
Rating	◄ 1	2	3	4	5 ►
VCR - Yaw	Good		Fair		Poor
Rating	◄ 1	2	3	4	5 ►
VCR - Horizontal rate	Good		Fair		Poor
Rating	◄ 1	2	3	4	5 ►
VCR - Vertical rate	Good		Fair		Poor
Rating	◄ 1	2	3	4	5 ►

OVERALL COMMENTS

Figure 10 In-cockpit Questionnaire (ICQ)

Section (E) covers VCRs. The rating scales for VCRs and the way in which they are used to determine UCEs is shown in Figure 8. VCRs are awarded according to the degree of aggression, precision and safety with which the pilot can maintain control over attitude stabilisation and flight path, given the available visual cues. A VCR is awarded for roll, pitch and yaw attitude control and for control of horizontal (lateral and longitudinal) and vertical translational rate. The aggregated ratings for a set of evaluation pilots are used to derive a UCE using the chart shown in Figure 8. That is, the ratings are first averaged and then the overall poorest ratings for translational rate (horizontal or vertical) and attitude (roll, pitch or yaw) used to derive the level of UCE.

3.3.5 Trial conduct and facility configuration for Trial 2

Trial 2 was completed using the same two evaluation pilots (P1 and P2) who participated in Trial 1, and the trial was essentially a repeat of Trial 1 but with some minor exceptions. The facility configuration, test cases, test matrix and pilot rating procedures are as described in Sections 3.3.1 to 3.3.4. Any notable exceptions are discussed in the following.

a) **Facility configuration**

In Trial 1 the RTAVS cockpit featured a window framework and coaming above the instrument panel, which partially restricted the pilot's FOV, particularly over the nose of the aircraft. For Trial 2 these features were removed and hence the pilot's FOV was less constrained. On the other hand, one pilot reported that removal of these features had the effect of taking away a useful near-field reference for judging attitude changes. As discussed in Section 3.5.3, this change had a small but noticeable impact on the VCRs awarded, especially for the manoeuvres dominated by the pitch axis, i.e. Fly Away, Climbs and Approaches.

b) **Test cases**

The visual conditions were set up in accordance with the settings used in Trial 1 for Day/GVE, Day/GVE/Fog, Day/DVE/Fog/Text and Night/DVE/Fog/Text. Qualitatively, these achieved similar visual effects as in Trial 1 for all but the night case. For Trial 2 the same settings gave what seemed to be a much darker visual appearance with fewer visual cues. P1 was the first to experience this case and, while he could fly both aircraft configurations with instruments turned on, he had greater difficulty in flying the Basic configuration with instruments turned off than was the case in Trial 1. That is, he lost control on one occasion in Trial 1, but was unable to complete any of the tasks attempted (Turns, Climbs) without losing control in Trial 2.

It is considered that this difference was likely to have been associated with the relative resolution of the fog model hue settings and the brightness, contrast and hue settings of the RTAVS visual system's projectors. The acuity of the visual horizon and mid to far field ground cues were determined by changing the hue of the fog using the fog model. It seems that the settings required to achieve the desired effect can be influenced by the projector settings, particularly at very low light levels, which is complicated by the fact that projector performance deteriorates with time. Hence, it is likely that a combination of these effects were responsible for the difference between Trial 1 and Trial 2.

Subsequent investigation with P2 showed that, qualitatively, with the current state of the projectors it was not possible to achieve the same visual appearance for the Night/DVE/Fog/Text case as for Trial 1 simply by changing the fog hue settings. However, it was found that by changing the time of day setting, which for Trial 1 was fixed at 2400hrs, a closer resemblance could be achieved. Following investigation, a time setting of 0120hrs was found to provide what was qualitatively considered to be the closest match.

3.4 Trial 1 Results

3.4.1 VCRs and UCEs

The test cases evaluated in Trial 1 are summarised in Table 7. Figure 11 summarises the VCRs awarded by the pilots for each aircraft model configuration, manoeuvre and visual condition evaluated, where the data represent the average ratings awarded by the two pilots where the test point was flown by both pilots. The figure for each test manoeuvre shows the averaged VCRs for translational rate and attitude plotted on the

UCE criteria chart, i.e. averaged translational rate VCR (y axis) versus averaged attitude VCR (x axis). The graph symbols differentiate between the visual conditions under which the manoeuvres were evaluated.

Sortie	Pilot	Model	Visual Condition	Cases evaluated
3	P1	ACAH	DAY/GVE	Hover Turn, Fly Away, Turn, Climb, Approach
4	P1	BASIC	DAY/GVE	Climb, Approach
5	P1	BASIC	DAY/GVE	Hover Turn, Fly Away, Turn
7	P2	ACAH	DAY/GVE	Hover Turn, Fly Away, Turn, Climb, Approach
	P2	BASIC	DAY/GVE	Climb, Approach
8	P2	BASIC	DAY/GVE	Hover Turn, Fly Away, Turn
	P2	ACAH	DAY/GVE/FOG	Hover Turn, Fly Away
9	P2	ACAH	DAY/GVE /FOG	Turn, Climb, Approach
	P2	ACAH	DAY/DVE/FOG/TEXT	1 Approach 2 Hover Turn, Fly Away - with IIMC
10	P2	ACAH	DAY/DVE/FOG/TEXT	Turn, Climb
	P2	BASIC	DAY/GVE/FOG	Hover Turn, Fly Away, Turn, Climb, Approach
11	P2	BASIC	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach- all with IIMC
12	P2	BASIC	DAY/DVE/FOG/TEXT	- Turn, Climb, Approach - no instruments
	P2	ACAH	DAY/DVE/FOG/TEXT	Fly Away, Turn, Climb, Approach - no instruments
13	P1	BASIC	DAY/GVE/FOG	Hover Turn, Fly Away, Turn, Climb, Approach
14	P1	BASIC	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach- all with IIMC
15	P1	ACAH	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach- all with IIMC
16	P1	BASIC	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
	P1	ACAH	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
	P1	BASIC	Night/DVE/FOG/TEXT	Turn, Climb
	P1	BASIC	Night/DVE/FOG/TEXT	Turn, Climb - no instruments
	P1	ACAH	Night/DVE/FOG/TEXT	Turn - no instruments

Table 7 Summary of test cases evaluated for Trial 1

Referring to Figure 11, generally speaking, the visual scenarios achieved the targeted UCEs. As expected, the cues degrade from UCE 1 for Day/GVE, through UCE 2 for Day/GVE/Fog to UCE 3 and poorer for Day/DVE/Fog/Text for most tasks. The Climb task was the exception, where UCE 1 was not achieved under the best visual conditions because of poor attitude and vertical rate cues when climbing with the aircraft in a nose up pitch attitude. However, from pilot comment, this is considered to be a representative result, as the reduced field-of-view (FOV) over the nose and resultant loss of view of the visual horizon tends to make this more of an instrument flight task. The constraint to the simulator's FOV over the nose during Trial 1 caused by the cockpit coaming was also a factor. For all up and away manoeuvres, as might be expected, the vertical rate cueing was the main problem and, overall, tended to be the main driver of the level of UCE. For the most degraded conditions though, attitude cues were also found to be equally poor or missing.

Where the pilots reported that cues were missing, i.e. poorer than a VCR of 5, the convention was adopted to rate these as VCR 6 (Insufficient visual cues). This allowed definition of a UCE 4 with the following distinctions:

4A Instruments required for control of translational rates, i.e. VCR 6 for translational rate and 5 or better for attitude.

4B Instruments required for control of attitudes, i.e. VCR 6 for attitude and 5 or better for translational rate.

4C Instruments required for control of translational rates and attitudes, i.e. VCR 6 for both translational rate and attitude.

All of the up and away tasks, i.e. Turns, Climbs, Fly Away, were awarded ratings in this category for the poorer visual conditions (i.e. Day/DVE/Fog/Text and Night/DVE/Fog/Text). Under these conditions the tasks were virtually flown as instrument tasks, with the outside visual cues (OVCs) only providing information on the navigation aspects of the tasks (and poor at that), and the general progress of the manoeuvre.

For the Day/DVE/Fog/Text visual conditions flown without instruments, it was found that there were sufficient visual cues to attempt to fly the manoeuvres but not with any real precision, as it was only possible to detect large deviations in height, speed and heading in particular. Generally speaking precision was the issue rather than stability and controllability for both aircraft configurations, but for the Night/DVE/Fog/Text condition the situation was different. While it was possible to detect some cues that could be used to support control of translational rates and heading, during the more dynamic phases stability and controllability of the basic configuration were in question and, in one Turns evaluation, the pilot actually became disorientated and lost control. This test was subsequently repeated without encountering the same control problem (but without accuracy) with the more inherently stable ACAH configuration.

3.4.2 Pilots HQRs

Figure 12 shows plots of pilots' attitude versus translational rate VCRs and associated HQRs for each manoeuvre and visual condition. The results for each of the two aircraft model configurations are shown on separate UCE criteria charts. Referring to the plot, in place of symbols the numbers represent the HQRs in each case and where both pilots evaluated the same test case, the data represent the averaged values, i.e. mean translational rate VCR (y axis) versus mean attitude VCR (x axis) and mean HQR (plotted number). The purpose of the plot is to illustrate the trend of HQRs versus VCRs and level of UCE, hence it does not distinguish between manoeuvres but shows a different colour code for each visual condition.

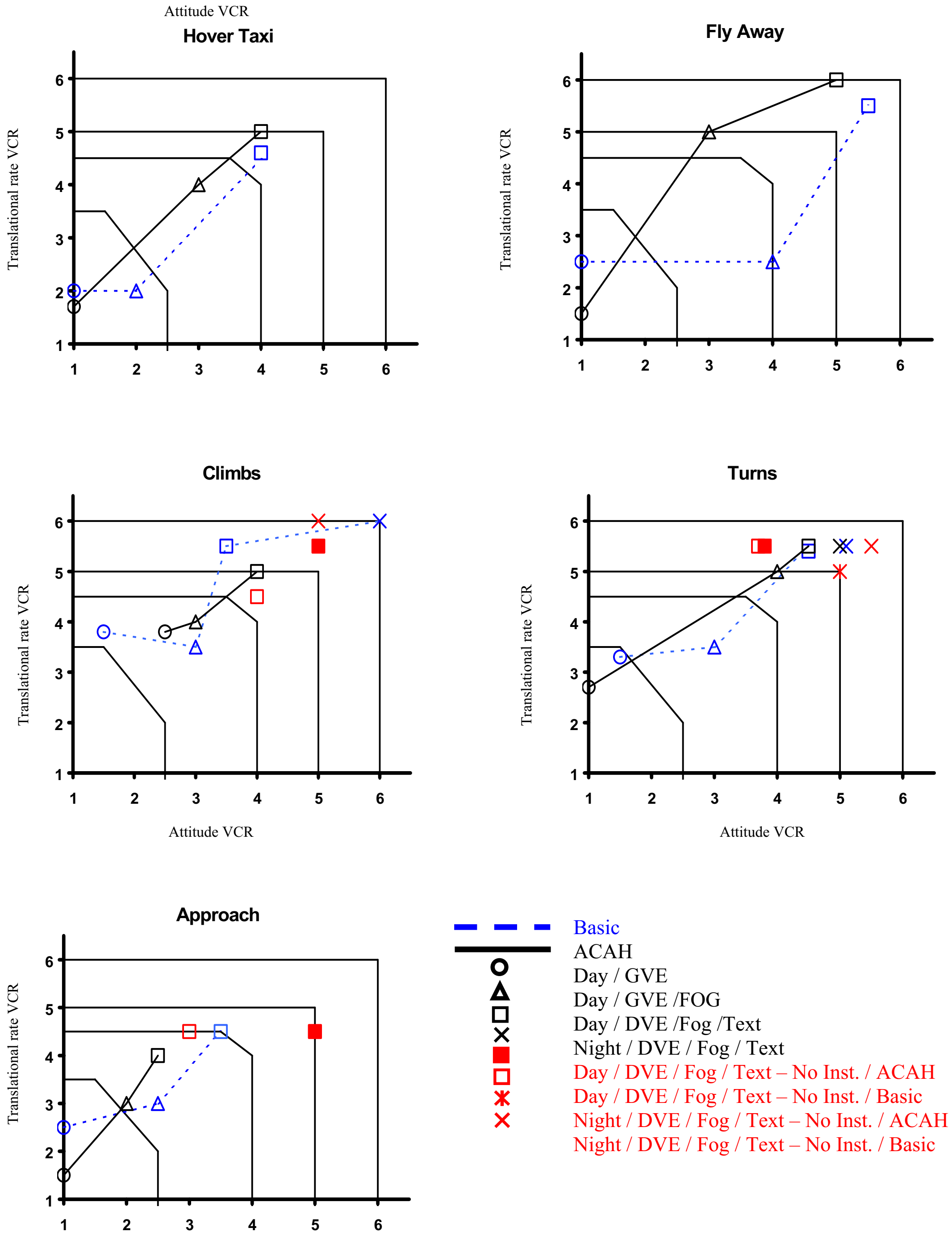


Figure 11 Trial 1 - Mean VCRs for each manoeuvre and visual condition

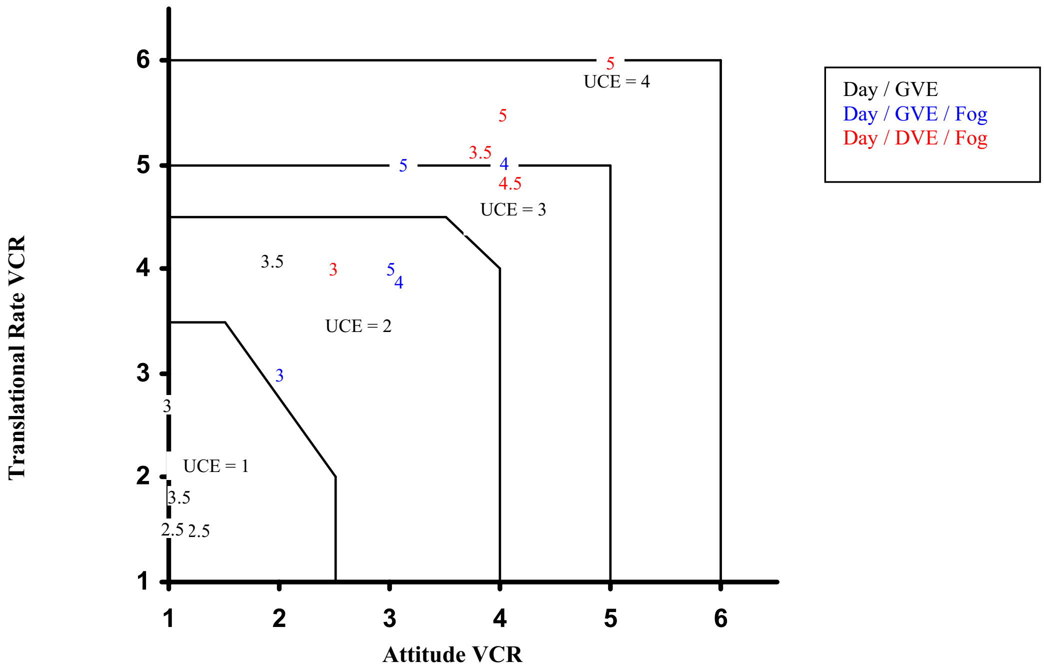


Figure 12a Trial 1 - Mean HQRs versus mean VCRs for ACAH

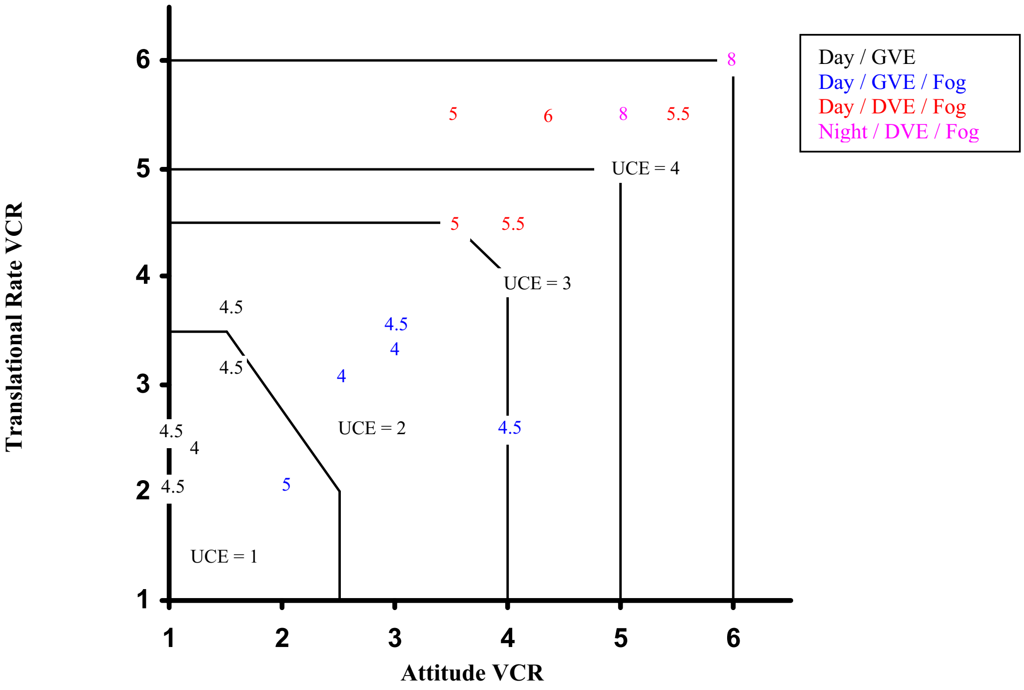


Figure 12b Trial 1 - Mean HQRs versus Mean VCRs for Basic

Referring to Figure 12a, for the ACAH configuration the general trend of HQRs was that they were mostly Level 1 ratings (HQRs 3 or better) for UCE 1 (VCRs of 1-3 for translational rate and VCR 1 for attitude), Level 1-2 (HQRs of 3 to 5) for UCE 2 (VCRs of 3 to 4 for translational rate and 2 to 3 for attitude) and Level 2 (4 or poorer) for UCEs 3-4 (translational rate VCRs of 4-6 and attitude VCRs of 4 or greater). HQRs for the Basic configuration (Figure 12b) follow a similar trend, but were all solidly Level 2 or poorer. For UCE 3-4, the HQRs range from 5 at best (adequate performance requires considerable pilot compensation) to 8 (considerable pilot compensation is required for control). The latter ratings were awarded for Turn and Climb evaluations in the poorest visual condition, Night/DVE/Fog/Text, indicating that adequate performance was unattainable and that control of the vehicle was in question. Not surprisingly, it was under these conditions that the pilot lost control when attempting the Turn manoeuvre without instruments. These test cases were not formally evaluated because of the wide performance variation, but the loss of control situation equates to HQR 10.

3.4.3 IIMC tests

With one exception, the pilots were able to continue safe flight on instruments during the IIMC tests with both aircraft configurations. This was the case even for the first attempt at evaluating the task, i.e. they had not had the opportunity to practice recovery to instruments. The Hover taxi with the basic configuration was the exception, where both pilots failed to establish on instruments and lost control of the aircraft on the first occasion that they attempted the task. They applied what they considered to be an appropriate recovery strategy but the aircraft's lack of stability in the pitch axis led to over-controlling that developed into a divergent pitch oscillation. On subsequent runs though, they were both able to anticipate and compensate for the problem, and to recover successfully.

There are a number of factors that may have contributed to this result. For example, it is likely that the tendency to over-control was partly due to a simulation effect i.e. missing motion cues. Another factor may be the difference in control strategy between flying at low level and up and away from the ground. In the former case the pilot is much more reliant on and focused on the OVCs compared to the latter and, hence, the task of establishing entirely on instruments is more difficult. When flying up and away, the instruments are referred to significantly more frequently than when flying at low level, typically between 20-30% of the time as compared with 5-10% from pilots' comments. Hence, it might be expected that the pilot's instrument scan would be more readily adapted to instrument flight when the IIMC condition was introduced when flying up and away.

3.5 Trial 2 Results

The overall coverage of test cases was similar to that achieved in Trial 1, as shown by the summary of test cases evaluated given in Table 8. The main difference is that more Night/DVE/Fog/Texture without flight instruments test cases were evaluated during Trial 2.

For the purpose of checking the consistency of the results, Figure 13 presents the Trial 2 VCR data equivalent to that for Trial 1 shown in Figure 11. Similarly, Figure 14 shows a plot of HQR versus VCR for Trial 2 comparable to that for Trial 1 presented in Figure 12.

A further comparison between the data sets for Trials 1 and 2 is made in Tables 9 and 10, which show the mean HQRs, VCRs and derived UCEs for each manoeuvre and visual condition. Differences between the two sets are discussed below.

Sortie	Pilot	Model	Visual Condition	Cases evaluated
1 and 2	P1	ACAH	DAY/GVE/FOG	Hover Turn, Fly Away, Turn, Climb, Approach
3	P1	BASIC	DAY/GVE/FOG	Hover Turn, Fly Away, Turn, Climb, Approach
4	P1	ACAH	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach - all with IIMC
5	P1	BASIC	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
	P1	ACAH	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
6	P1	BASIC	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach - all with IIMC
7	P1	ACAH	Night/DVE/FOG/TEXT	Turn, Climb
	P1	BASIC	Night/DVE/FOG/TEXT	Turn, Climb
8	P1	BASIC	Night/DVE/FOG/TEXT	Turn, Climb - no instruments
	P1	ACAH	Night/DVE/FOG/TEXT	1 Turn, Climb 2 Turn, Climb - no instruments
9	P2	BASIC	DAY/GVE	Hover Turn, Fly Away, Turn, Climb, Approach
10	P2	ACAH	DAY/GVE	Hover Turn, Fly Away, Turn, Climb, Approach
11	P2	BASIC	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach - all with IIMC
12	P2	ACAH	DAY/DVE/FOG/TEXT	Hover Turn, Fly Away, Turn, Climb, Approach - all with IIMC
13	P2	ACAH	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
	P2	BASIC	DAY/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
14	P2	BASIC	Night/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
	P2	ACAH	Night/DVE/FOG/TEXT	Turn, Climb, Approach - no instruments
15	P2	BASIC	DAY/DVE/FOG/TEXT	Climb - no Instruments
	P2	ACAH	DAY/DVE/FOG/TEXT	Climb - no Instruments
	P2	BASIC	DAY/GVE/FOG	Turn, Climb, Hover Turn

Table 8 Summary of test cases evaluated for Trial 2

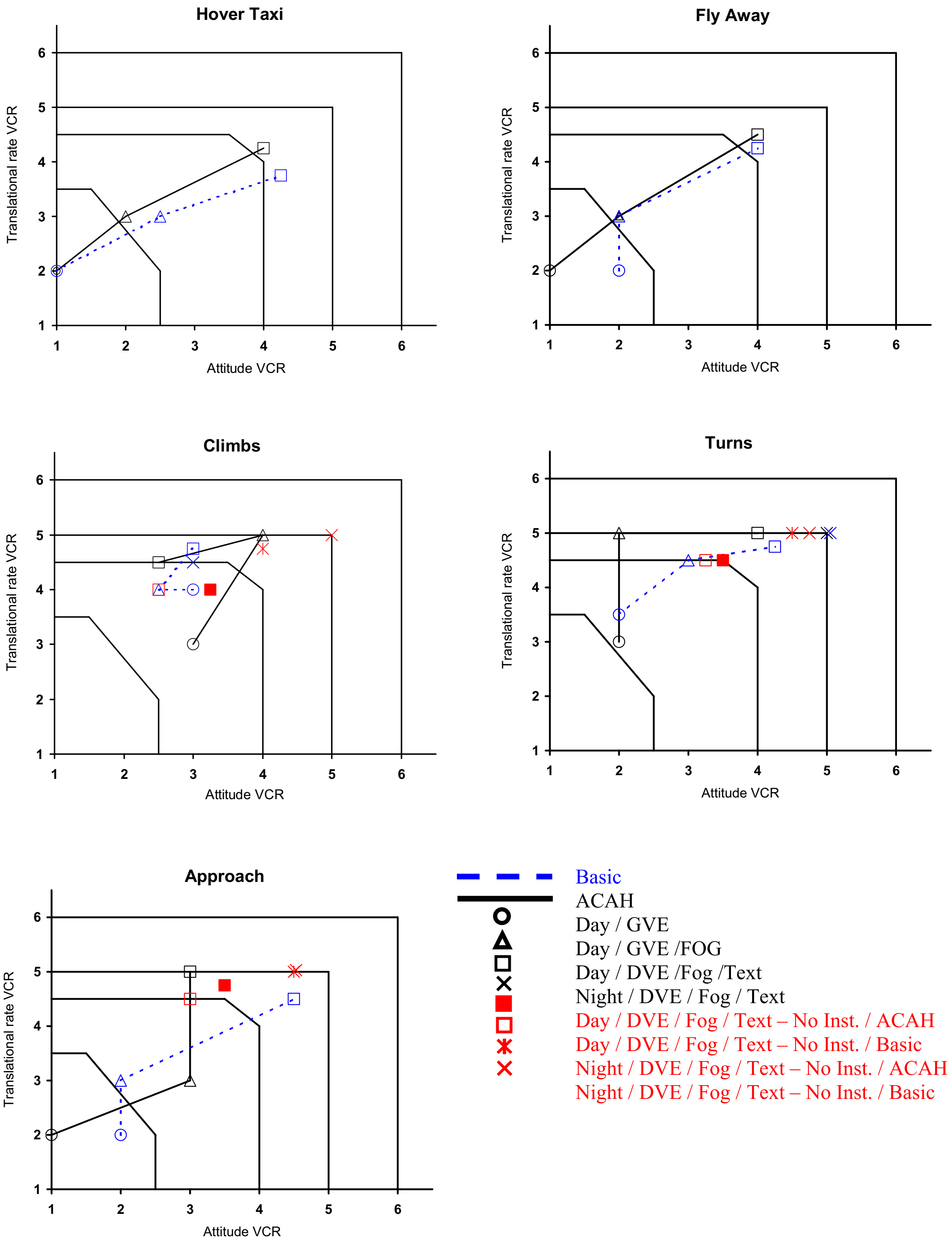


Figure 13 Trial 2 - Mean VCRs for each manoeuvre and visual condition

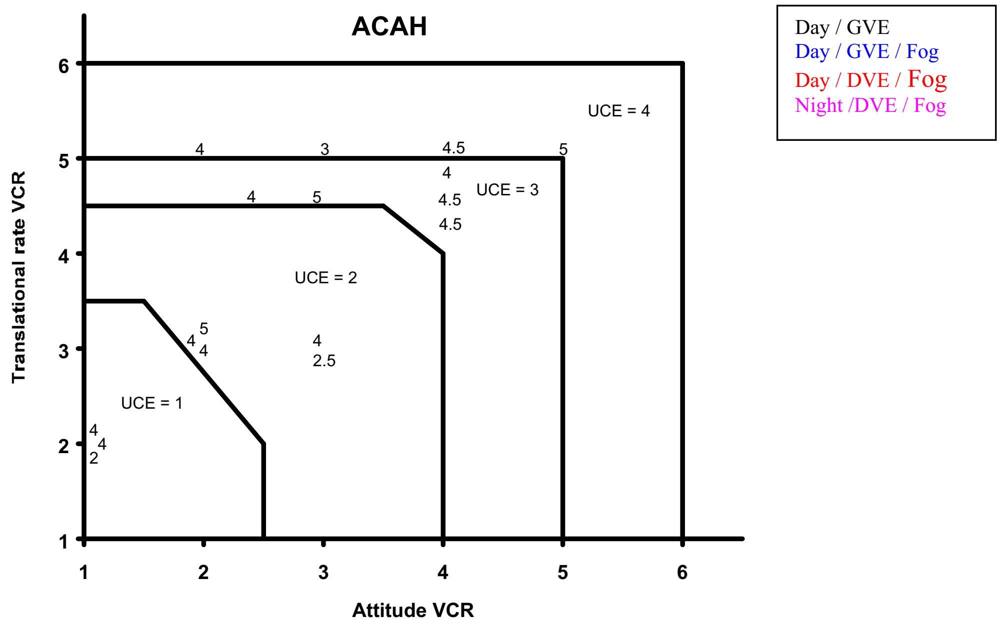


Figure 14a Trial 2 - Mean HQRs versus mean VCRs for ACAH

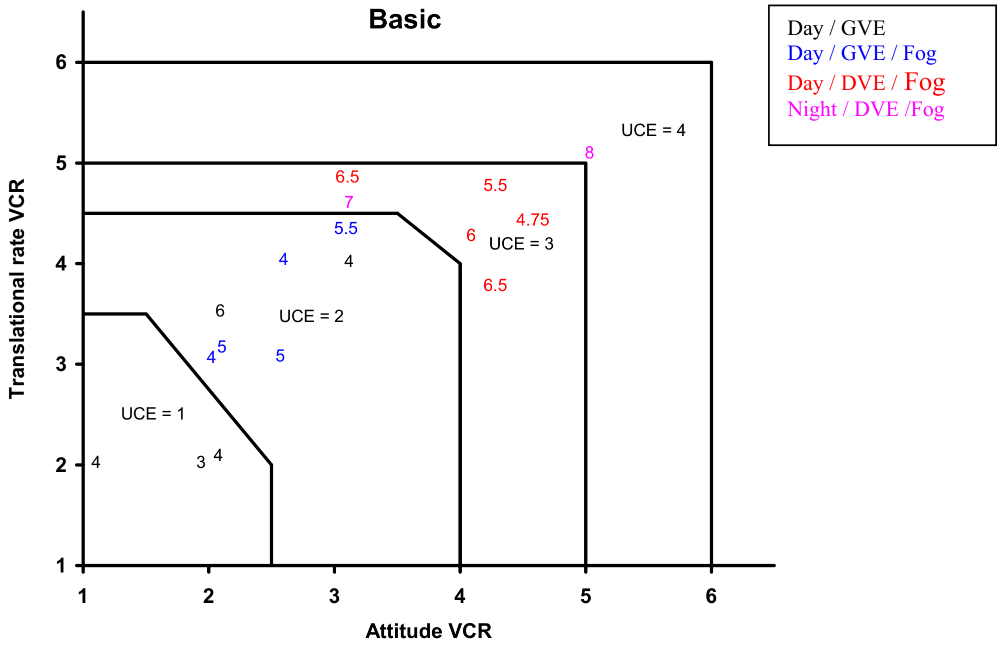


Figure 14b Trial 2 - Mean HQRs versus mean VCRs for Basic

Visual Condition	Trial	Manoeuvre (1, 2, 3)					Overall mean HQR
		Hover Turn	Fly Away	Turns	Climbs	Approach	
Day/GVE	1	3.5	2.5	3	3.5	2.5	3
	2	4	4	4	2.5	2	3.3
	1 - 2	-0.5	-1.5	-1	1	0.5	-0.3
Day/GVE/Fog	2	5	5	4	4	3	4.2
	1	5	4	5	5	4	4.6
	1 - 2	0	1	-1	-1	-1	-0.4
Day/DVE/Fog/Text	1	4.5	5	5	3.5	3	4.2
	2	4.5	5	5	3.5	3	4.2
	1 - 2	0	0.5	0.5	0.5	0	0.1
Night/DVE/Fog/Text	2	-	-	-	-	-	-
	1	-	-	5	5	-	5
	1 - 2	-	-	-	-	-	-

Table 9a Comparison of mean HQRs from Trials 1 and 2 - ACAH

Visual Condition	Trial	Manoeuvre (1, 2, 3)					Overall mean HQR
		Hover Turn	Fly Away	Turns	Climb	Approach	
Day/GVE	1	4.	4.5	**4.5**	4	4	4.3
	2	4	4	**6**	4	3	4.2
	1 - 2	0.5	0.5	**-1.5**	0	1	0.1
Day/GVE/Fog	2	5	4.5	4.5	4	4	4.4
	1	5	5	5.5	4	4	4.7
	1 - 2	0	0.5	-1	0	0	-0.3
Day/DVE/Fog/Text	1	5.5	5.5	6	**5**	5	5.2
	2	6.5	6	5.5	**6.5**	4.75	5.85
	1 - 2	-1	-0.5	0.5	**-1.5**	0	-0.65
Night/DVE/Fog/Text	2	-	-	8	8	-	8
	1	-	-	8	7	-	7.5
	1 - 2	-	-	0	1	-	0.5

Table 9b Comparison of mean HQRs from Trials 1 and 2 - Basic

🟥 1 Difference of more than 1 HQR scale point

🟪 2 Denotes where ratings cross HQR level boundaries

🟦 3 Difference of more than 1 HQR scale point and ratings across boundaries

Visual Condition	Trial	Max mean VCR*	Manoeuvres (1, 2)														
			Hover Turn			Fly Away			Turn			Climb			Approach		
			AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE
Day/GVE	1	VCR	1	1.75	1	1	1.5	1	1	2.75	🟥 1	2.5	3.75	2	1	1.5	1
	2	VCR	1	2	1	1	2	1	2	3	🟥 2	3	3	2	1	2	1
Day/GVE/FOG	1	VCR	3	4	2	3	5	🟥 3	4	5	3	3	4	🟥 2	2	3	2
	2	VCR	2	3	2	2	3	🟩 2	2	5	3	4	5	🟩 3	3	3	2
Day/GVE/Fog/Text	1	VCR	4	5	3	5	6	🟪 4	4	5.5	🟪 4	4	5	3	2.5	4	🟥 2
	2	VCR	4	4.25	3	4	4.5	🟪 3	4	5	🟪 3	2.5	4.5	3	3	5	🟥 3
Night/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	VCR	-	-	-	-	-	-	5	5	3	3	4.5	3	-	-	-
Day/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	4	5.5	🟪 4	🟨 5	5.5	🟥 4	5	4.5	3
- Without HDD	2	VCR	-	-	-	-	-	-	3.5	4.5	🟪 3	🟨 3.25	4	🟩 2	3.5	4.75	3
Night/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	5	5	3	-	-	-	-	-	-
- Without HDD	2	VCR	-	-	-	-	-	-	4.5	5	3	4	4.75	3	4.5	5	3

Table 10a Comparison of VCRs and UCEs from Trials 1 and 2 - ACAH

1. UCE 4 cases	🟪
2. UCE 4 cases	🟨
3. Attitude/Cockpit coaming cases	🟩

4. Vertical translational rate case	🟥
5. CombinedAttitude/Cockpit coaming and Vertical translational rate cases	🟩🟥

Visual Condition	Trial	Max mean VCR*	Manoeuvres														
			Hover Turn			Fly Away			Turn			Climb			Approach		
			AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE
Day/GVE	1	VCR	1	2	1	1	1	1	1	4	2	3	5	3	1	2	1
	2	VCR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Day/GVE/FOG	1	VCR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	VCR	2	3	2	2	3	2	2	5	3	4	5	3	3	3	2
Day/GVE/Fog/Text	1	VCR	4	5	3	4	6	4	4	5	3	3	4	2	2	4	2
	2	VCR	3.5	4	3	4	4	3	3	5	3	2	5	3	1	5	3
Night/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	5	5.5	4	6	6	4	-	-	-
	2	VCR	-	-	-	-	-	-	5	5	3	3	4.5	3	-	-	-
Day/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	3	5	3	3	5	3	5	4	3
- Without HDD	2	VCR	-	-	-	-	-	-	3	4	3	3	4	2	3	4.5	3
Night/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	5.5	5.5	4	5	6	4	-	-	-
- Without HDD	2	VCR	-	-	-	-	-	-	4	5	3	3	4.5	3	-	-	-

Table 11 Comparison of P1's VCRs for Trial 1 versus Trial 2 - ACAH

🟩 Cases where improved handling qualities led to improved VCRs (see Section 3.5.3)

3.5.1 Pilots ratings

Comparing Figures 11 and 12 with 13 and 14, the general trends of the ratings for the two trials are similar but there are some differences between ratings for specific manoeuvres and visual conditions. These differences are highlighted in Tables 9 and 10, and are discussed further in the following sections.

3.5.2 HQRs

On the whole, there is good agreement between the two data sets and all but three cases are within one HQR scale point. Importantly, in most cases both sets of ratings fall into similar handling qualities levels (i.e. Level 1, 2 or 3 - see Figure 7). There are four ACAH and one Basic case where ratings cross over a level boundary. The variations in the two rating sets are most likely the result of a combination of factors including the small sample size, relative level of practice for each manoeuvre and variations in the level of aggression applied in the execution of the tasks. The latter has a significant impact on pilot workload and consequently the rating awarded. The cases where the mean rating difference is greater than one scale point are discussed below.

a) **Day/GVE, ACAH, Fly Away**

Mean rating of 2.5 for Trial 1 versus 4 for Trial 2. The scale of the difference is probably attributable to the small sample size, where two ratings were averaged for Trial 1 but only one rating (for P2) for Trial 2. P2 actually rated the same case as HQR 3 in Trial 1 versus HQR 4 in Trial 2 which, in effect, means an assessment of 'satisfactory without improvement' versus 'minor but annoying deficiencies'. It is likely that this variation is a due to the relative levels of practice in the test manoeuvre.

b) **Day/GVE, Basic, Turns**

Mean rating of 4.5 for Trial 1 versus 6 for Trial 2. The difference is probably attributable to the small sample size again. P2 actually rated the same case as HQR 5 in Trial 1 versus HQR 6 in Trial 2, which is an acceptable difference.

c) **Day/DVE/Fog/Texture, Basic, Climbs**

Mean rating of 5 for Trial 1 versus 6.5 for Trial 2. The difference in this case is likely to be attributable to the level of aggression with which the task was flown. For Trial 2, pilot P2 noticeably flew this manoeuvre very gently initially and awarded a HQR of 4. He then repeated it with greater aggression, i.e. using a larger pitch attitude to increase the rate of climb, which resulted in a HQR of 7 because of the higher workload. In Trial 1 both pilots flew a similar control strategy and awarded HQRs of 5.

3.5.3 VCRs

As noted above, the general trends of the ratings are similar for both trials, in that the UCE degrades with visual condition (see Figs 11 and 13). As with the HQRs, in most cases the UCEs derived from the VCRs for both Trial 1 and Trial 2 fall into similar levels (i.e. UCE 1, 2 and 3 - see Figure 8). Again, it is considered that variations in the two rating sets are generally due to factors such as the small sample size, relative level of practice for each manoeuvre and variations in the level of aggression applied in the execution of the tasks. Regarding the latter, this can impact the VCRs because they are awarded on the basis of the levels of aggression and precision with which a manoeuvre can be accomplished (see Figure 8).

Visual Condition	Trial	Max mean VCR*	Manoeuvres (1, 2)														
			Hover Turn			Fly Away			Turn			Climb			Approach		
			AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE	AT	TR	UCE
Day/GVE	1	VCR	1	2	1	1	2.5	1	1.5	3.25	1	1.5	3.75	2	1	2.5	1
	2	VCR	1	2	1	2	2	1	2	3.5	2	3	4	2	2	2	1
Day/GVE/FOG	1	VCR	2	2	1	4	2.5	3	3	3.5	2	3	3.5	2	2.5	3	2
	2	VCR	2.5	3	2	2	3	2	3	4.5	3	2.5	4	2	2	3	2
Day/GVE/Fog/Text	1	VCR	4	4.5	3	5.5	5.5	4	4.5	5.5	4	3.5	5.5	4	3.5	4.5	3
	2	VCR	4.25	3.75	3	4	4.25	3	4.25	4.75	3	3	4.75	3	4.5	4.5	3
Night/DVE/Fog/Text	1	VCR	-	-	-	-	-	-	5	5.5	4	6	6	4	-	-	-
	2	VCR	-	-	-	-	-	-	5	5	3	3	4.5	3	-	-	-
Day/DVE/Fog/Text - Without HDD	1	VCR	-	-	-	-	-	-	4	5.5	4	4	4.5	3	3	4.5	3
	2	VCR	-	-	-	-	-	-	3.25	4.5	3	2.5	4	2	3	4.5	3
Night/DVE/Fog/Text - Without HDD	1	VCR	-	-	-	-	-	-	5.5	5.5	4	5	6	4	-	-	-
	2	VCR	-	-	-	-	-	-	4.75	5	3	5	5	3	4.5	5	3

Table 10b Comparison of VCRs and UCEs from Trials 1 and 2

[1] AT = Attitude VCR, TR = Translational Rate VCR

[2] Highlighted cases denote where derived UCEs cross level boundaries, including the following cases:

1. UCE 4 cases	🟪
2. UCE 4 cases	🟨
3. Attitude/Cockpit coaming cases	🟩

4. Vertical translational rate case	🟥
5. CombinedAttitude/Cockpit coaming and Vertical translational rate cases	🟩🟥

P1 also noted a handling qualities influence on VCRs for the ACAH configuration, in that in Trial 2 (but not in Trial 1) he noted that attitude cues in the poorer visual conditions were less critical for this configuration (because of its enhanced stability) and in consequence tended to award improved VCRs. A comparison of P1's VCRs for Trials 1 and 2 is shown in Table 11, and this effect can be seen in the cases highlighted. It should also be noted that in most of these cases however, the overall effect is negligible as the actual UCE is more dominated by the (vertical) translational rate VCR. That is, Figs 12 and 14 indicate that the average translational rate VCR is about one point higher (poorer) than the attitude VCR, for ACAH and Basic in both Trials 1 and 2.

Referring to Table 10, there are 21 cases (shown highlighted in colour) where different UCE levels were achieved for Trial 2 and Trial 1, 8 for ACAH and 13 for the Basic configuration. These can be attributed to three specific factors as discussed below:

a) **UCE 3 versus UCE 4**

From Table 10, 11 of the cases (highlighted in purple) are attributable to a specific difference in approach adopted by the pilots for awarding VCRs in the two trials. In Trial 1, as discussed in Section 3.4.1, the pilots noted that for the more degraded visual conditions it was not possible to detect any outside visual cues for a given VCR parameter. To cater for this situation, the convention was adopted to award a VCR of 6, with an associated UCE of Level 4. However, in Trial 2 this issue did not arise and pilots adhered to the standard VCR range and UCE levels, even for the reportedly more degraded simulated night time cueing conditions (see Section 3.4.1). Hence the most degraded cases achieved a UCE of 4 for Trial 1 but UCE 3 for Trial 2.

b) **Vertical rate cues**

In all visual conditions and manoeuvres, pilots seemed to have the greatest difficulty in achieving consistent VCRs for the vertical translational rate parameter. From Table 10, without any particular bias to either trial, there are 8 cases (highlighted in red or red/green) where differences in the vertical rate VCRs gave rise to different levels of UCE for Trials 1 and 2.

c) **Cockpit coaming**

As noted in Section 3.3.5, removal of the cockpit coaming in Trial 2 had a small influence on VCRs awarded for the Climbs and Approach manoeuvres. There are four cases (highlighted in yellow in Table 10) where improved attitude VCRs contributed to an improved level of UCE in Trial 2 which, from pilot comments, are likely to be attributable to this factor.

3.5.4 Discussion

The primary aim of Trial 2 was to acquire a replacement objective data set, but it resulted in the generation of two sets of subjective data. As discussed above, the main differences between them relate to the VCR data, as the HQR data sets are essentially similar in the main trends. As summarised in the following points, there are differences between the two sets of VCRs due to the way that the pilots applied the rating scale, or because of changes in the trial configuration.Pilots' VCRs were sensitive to the effects of changes in the trial configuration. That is, removal of the cockpit coaming improved the downward field of view but removed a significant visual reference frame for attitude judgement. This reflects that factors such as the cockpit field-of-view and internal visual references are an essential factor in the assessment of VCRs and the associated UCE.

a) The treatment of what are perceived to be missing cues; it is considered that the approach applied in Trial 1 provides a consistent framework for this circumstance. However, there is also an issue concerning the pilots' ability to consistently recognise when cues are missing, i.e. they may experience difficulty in controlling the aircraft but not be able to differentiate the causes.

b) Leading on from b), assessment of VCRs should in principle be based on handling qualities considerations, i.e. how aggressively and precisely the aircraft can be flown in a given visual environment. However, the results suggest that the pilots tended to use the VCRs for direct assessment of the visual cues, with the exception of P1's approach in Trial 2. The requirement in Trial 1 to adopt the convention for UCE 4 (i.e. missing visual cues) supports this point.

c) Notwithstanding the foregoing, the VCR assessments did provide a means of establishing the relative cueing benefits of the visual scenarios in relation to the pilots' ability to fly the test manoeuvres. However, the experience also suggests that consistency of application of the VCR scale could be improved by specific training and familiarisation, perhaps using a set of example training cases.

The VCR data from Trial 1 was subsequently used for the follow-on image analysis exercise (Section 4) as it was considered that they represented the most consistent data set for that exercise.

As a final point, the comparison made here of the two sets of results supports the case that those for Trial 2 do not change substantially the findings from Trial 1 as discussed in Section 3.4. The similarity of the results also demonstrates the robustness of the trial methodology and approach.

3.6 Overall findings

The results highlighted a number of key issues within the context of the general objectives of the research, which are discussed in the following sections.

3.6.1 Handling qualities and UCE

Figure 15 shows a summary of HQRs awarded for the ACAH and Basic configurations. The figures given in the colour shaded strips represent the overall mean HQRs for both Trial 1 and Trial 2 data, for each visual condition evaluated. For comparison, the UCEs derived from the VCRs awarded by the pilots for each test manoeuvre and visual condition are also shown. The colour shading (green - amber - red) has been added to emphasise the perceived degradation in handling qualities (and hence safety) as the visual conditions degrade and the relative differences in HQRs awarded for the two configurations.

In summary, the key overall results are as follows:

a) The ACAH configuration achieved mostly Level 1 ratings (HQRs 3 or better) for UCE 1, Level 1-2 ratings (HQRs of 3 to 5) for UCE 2 and level 2 ratings (4 or poorer) for UCE 3. HQRs awarded to the Basic configuration followed a similar trend but, because of higher workload, were generally 1 to 2 HQR rating points higher.

b) For the UCE 3 and poorer visual conditions, HQRs for the Basic configuration ranged from 5 at best (adequate performance requires considerable pilot compensation) to 8 (considerable pilot compensation is required for control). In the poorest visual condition (Night/DVE/Fog/Text) the pilot lost control when attempting Turn and Climb manoeuvres without instruments, which equates to HQR 10.

c) The visual scenarios generally achieved the targeted UCEs of 1, 2 and 3, and the trial met the objective of investigating the potential for application of the UCE concept to civil operations. From discussions with the CAA pilot involved, it was apparent that the concept could potentially be applied in support of civil regulations to address operations in conditions that could not be clearly categorised as VMC or IMC.

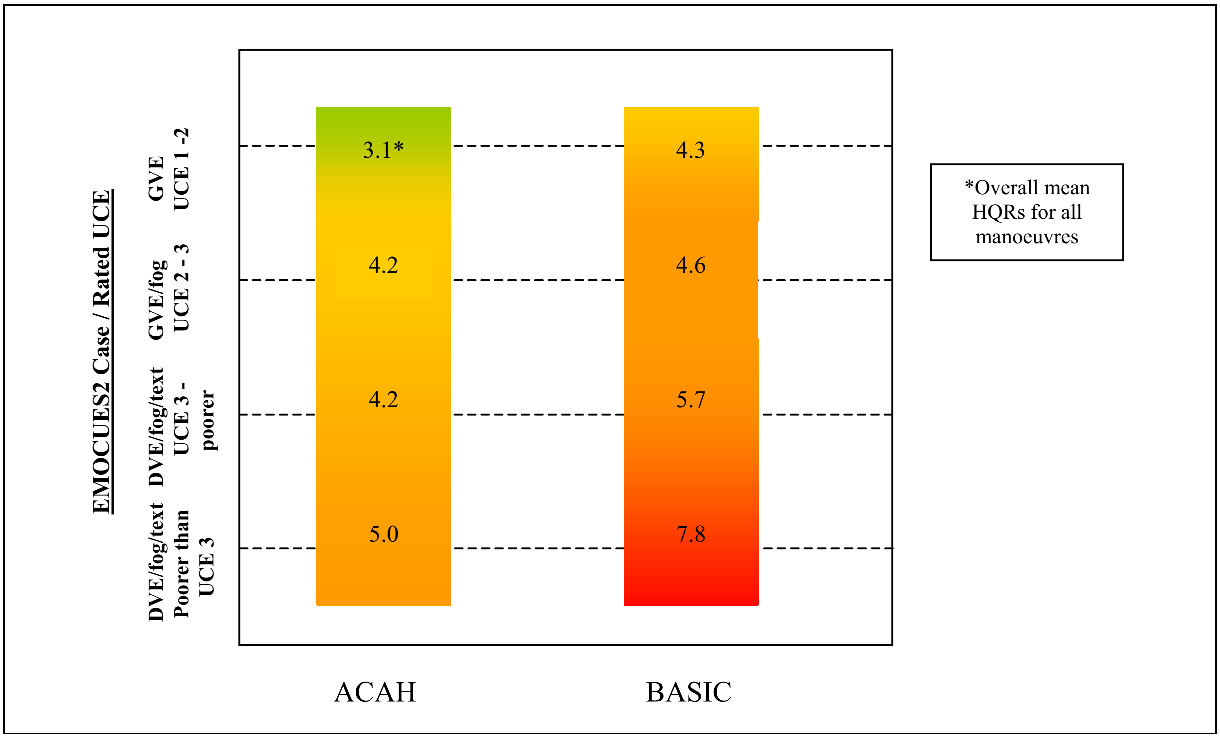


Figure 15 EMOCUES2 data - HQRs versus UCE

With regard to the results for the Basic configuration, it is probably fair to say that if the pilot was under similar workload pressures as in the real world, then it is likely that the handling qualities would have been found to be significantly more intrusive than was the case in the simulator. A key factor in this would be the level of distraction presented by the need to navigate by visual references in quite degraded visual conditions.

A further point to note is that pilot experience was inevitably a factor in the results achieved. Both pilots have logged many hours and have considerable experience in flying a range of different helicopters, including civil and military types, in both VFR and IFR conditions. At the time of the trials, they were both IFR qualified. This factor was mitigated to some extent in that they both endeavoured to relate their ratings and comments to civil qualification requirements and abilities of the 'average' pilot. At the same time, some of the difficulties that they experienced in evaluating the more extreme test cases (e.g. Basic configuration in Day/DVE/Fog/Text and Night/DVE/Fog/Text conditions) can be attributed to simulation effects (e.g. no motion cues, relatively low resolution visuals compared with the real world). All things considered, it is likely that the results may be conservative in respect of the average pilot, particularly those for the Basic configuration. That is, it is likely that the average pilot would have experienced greater difficulty in maintaining a safe margin of control in the simulated test cases and conditions, and that this is equally likely to be true for real world operations.

3.6.2 Application of the UCE concept

One of the issues relates to the trial method and application of the UCE concept which was originally devised for low level, nap-of-earth operations in close proximity to the ground and obstacles where, of necessity, the aircraft is flown essentially 'eyes-out' of the cockpit. Hence, UCE is used out of context in the current application when applied to the up-and-away manoeuvres. In principle, the UCE should be established using an aircraft configuration with Level 1 rate command response characteristics [15], so that the ratings will reflect control problems caused by the visual cues and not be unduly influenced by the vehicle's handling characteristics.

In the current application, it could be said that the VCRs provide a measure of visual cues in relation to the handling characteristics of the specific configurations, as opposed to an assessment of the scene's generic cueing properties. To support this, the averaged VCRs for the Basic configuration (see Figs 11 and 13) show some bias towards poorer attitude cues when compared with the ACAH ratings, reflecting the greater stability-related control problems with that configuration. However, as noted in section 3.5.3, the (vertical) translational rate VCR was a more dominant factor in determining the actual UCE.

On the whole, it is considered that the UCE concept worked well as a means of subjective assessment of the visual scenarios and, from observation, the trend of the VCRs is well correlated with pilots' HQRs. The results reflect that, for manually piloted manoeuvres under visual flight operations, translational rate control and attitude stabilisation are the main control issues even in up-and-away tasks.

3.6.3 Division of attention

The tests flown without instruments demonstrated how flight control can break down when the pilot cannot sustain the necessary division of attention between flight instruments and the outside visual scene. Even when instruments were available, the tasks were essentially flown visually for all visual conditions evaluated, and reportedly between 75 and 95% of the pilot's attention was focused on the outside visual cues (OVCs). The remainder of the time was spent on checking flight instruments for datum height, speed, heading and attitude references and aircraft state information (rotor speed, torque etc.). This level of attention to the OVCs was probably needed in order to establish and maintain tau-guidance strategies for the attitude stabilisation and flight path guidance control tasks and for navigation [4,5,6].

In degraded visual cueing conditions, more of the pilot's attention is required to maintain these strategies in order not to lose place in the visual control loops and the navigation task, potentially leaving less time for reference to flight instruments. At the same time, the visual cues can degrade to the point where they become inadequate to support visual control, leading to greater uncertainty concerning the perceived versus actual aircraft state, and placing greater emphasis on the need to refer to flight instruments. Ultimately of course, if the cues are sufficiently degraded, the task can only be safely continued through flight on instruments.

It appears that accidents can and do occur in situations were pilots are unaware of this situation developing and are seduced into fixating on the OVCs at the expense of flight instruments. In the simulator experiments both pilots were very experienced in instrument flight operations and were able to cope with the degraded visual conditions evaluated, even with the less stable aircraft configuration, by transferring to instruments when necessary. Test cases flown without instruments were intended to emulate the situation where instruments are referred to infrequently, or ignored altogether, and resulted in loss of control in the case of the Turn manoeuvre.

3.6.4 Attitude references

Pilots' VCRs were sensitive to the effects of changes in the trial configuration. That is, removal of the cockpit coaming improved the downward field of view but removed a significant visual reference frame for attitude judgement. This demonstrates that factors such as the cockpit field-of-view and internal visual references are an important factor in the assessment of VCRs and the associated UCE.

3.6.5 Way ahead

Following the trial, the immediate thought was that the results emphasised the need to address the case of operations that cross over from visual to the instrument flight regime, including cases of inadvertent encounters with IMC conditions en-route, perhaps due to deteriorating weather and ambient light. At the same time, the work under the MoD CRP programme indicated that in good visual conditions a pilot uses tau-guidance strategies [4,5,6] to control the aircraft and that these can break down as visual conditions degrade. As discussed in Section 3.2, control augmentation was also recognised as a key factor in maintaining safe control in DVE operations. Hence, it seemed that the best approach for addressing the problems highlighted by the trial would be through stability augmentation to address the need for attitude stabilisation, combined with a display or sensor to augment the visual scene. It was also considered that it would be of benefit to provide support for the navigation task, through provision of some form of basic flight management system for example. However, some caution may be required in introducing such navigation aids (e.g. GPS), as it has been suggested that they can tempt pilots to fly when they would otherwise have not. As a result, this could lead to increased exposure to marginal flying conditions and the likelihood of Scenario 3 type accidents.

3.7 Conclusions

The general conclusion from both trials was that they had addressed the objectives and issues raised in the project proposal [1], and provided sufficient data for application of the analysis techniques developed under the MoD CRP Programme. The points given below summarise some detailed initial conclusions that were drawn from the trials.

a) The visual scenarios generally achieved the targeted UCEs of 1, 2 and 3; the Climb task was the exception, where UCE 1 was not achieved under the best visual conditions (Day/GVE) because of poor, but representative, attitude and vertical rate cues when climbing with the aircraft in a nose up pitch attitude.

b) For all up and away manoeuvres, vertical rate cueing was generally the main issue and was a key factor in VCRs awarded and overall level of UCE. For the most degraded scenes though (Day/DVE/Fog/Text and Night/DVE/Fog/Text), attitude cues were also found to be equally poor or missing.

c) The Turn and Climb tasks achieved mean VCRs of between 4 and 5.5 (UCE of 3 - 4) for the poorest visual conditions (Day/DVE/Fog/Text and Night/DVE/Fog/Text), reportedly because the pilots had to resort to instruments as the OVCs only provided information on the navigation aspects of the tasks. The same is also true for the Fly Away task in the Day/DVE/Fog/Text condition (note, this manoeuvre was not evaluated in the Night/DVE/Fog/Text condition).

d) For the tests flown without instruments, it was found that there were sufficient visual cues to attempt to fly the manoeuvres in all but one case (Turns evaluation with the Basic configuration in the Night/DVE/Fog/Text condition), but not with any real precision.

e) The ACAH configuration achieved mostly Level 1 ratings (HQRs of 3 or better) for UCE 1, Level 1-2 ratings (HQRs of 3 to 5) for UCE 2 and Level 2 ratings (HQRs of 4 or poorer) for UCEs 3-4. There was no threat of loss of control with ACAH in any of the test manoeuvres or conditions.

f) HQRs awarded to the Basic configuration followed a similar trend to ACAH, but were generally 1 to 2 rating points poorer. For the poorest UCE 4 visual condition

(Night/DVE/Fog/Text) however, the pilot lost control when attempting a Turn manoeuvre without instruments, which equates to a HQR of 10.

g) The VCRs awarded reflected the handling characteristics of the specific configurations, where those for the Basic configuration show a bias towards poorer attitude cues when compared with the ACAH ratings, reflecting the greater stability-related control problems with that configuration. However, the (vertical) translational rate VCR was a more dominant factor in determining the actual UCE.

h) Pilots' VCRs were sensitive to the effects of changes in the trial configuration. That is, removal of the cockpit coaming improved the downward field of view but removed a significant visual reference frame for attitude judgement. This reflects that factors such as the cockpit field-of-view and internal visual references are an important factor in the assessment of VCRs and the associated UCE.

i) The UCE concept worked well as a means of subjective assessment of the visual scenarios and, qualitatively, the trend of the VCRs is well correlated with pilots' HQRs. The results indicate that translational rate control and attitude stabilisation were significant factors in control during the up-and-away tasks flown.

j) The tests flown without instruments simulated adequately the scenario of pilots fixating on OVCs for navigation information at the expense of aircraft control, i.e. division of attention between flight instruments and the outside visual scene. When instruments were available, the visual distraction tasks included in the scenarios resulted in the tasks being flown essentially visually, even when the conditions were severely degraded, and reportedly between 75 and 95% of the pilots attention was focussed on the OVC, with the remainder spent on checking flight instruments.

k) Both pilots were experienced in instrument flight operations and were able to cope with the degraded visual conditions evaluated, even with the less stable aircraft configuration, by transferring to instruments when necessary. However, without instruments, stability and controllability for the Basic configuration were more marginal, particularly in the dynamic phases of the manoeuvres.

l) The pilots were generally able to continue safe flight on instruments for the IIMC tests, for both aircraft configurations, but the Hover taxi with the Basic configuration was an exception. Both pilots failed to establish on instruments and lost control of the aircraft on the first occasion that they attempted the task, although on subsequent runs they were both able to recover successfully. It is thought that simulation effects due to missing motion cues are likely to have played a part in this. Another factor may have been that relatively greater attention is given to OVCs when flying close to the ground and obstacles and, hence, it might be more difficult to establish instrument flight when compared with up and away flight.

m) The results support the case that, for the flying tasks considered, for operations in the DVE, or in IIMC situations, stability augmentation is critical to flight safety for the enhanced attitude stabilisation it provides.

n) Division of attention between the attitude stabilisation, flight path guidance and navigation tasks is a significant flight safety issue for operations in the DVE. To help mitigate the problem, improved displays of critical pilotage information (attitude, speed and height rate information) are required to augment the visual scene.

o) Similarly, it would also be of benefit to provide support for the navigation task, through provision of a basic flight management system for example. Caution may be required, though, as this could potentially tempt pilots to fly in marginal flying conditions, hence increasing the likelihood of Scenario 3 type accidents.

p) Pilot experience was likely a factor in the results achieved. Both pilots have considerable experience in both VFR and IFR conditions and were both IFR qualified at the time of the trials. Some of the difficulties experienced in evaluating the more extreme test cases (e.g. Basic configuration in Day/DVE/Fog/Text and Night/DVE/Fog/Text conditions) can be attributed to simulation effects (e.g. no motion cues, relatively low resolution visuals compared with the real world). However, it is likely that the results are conservative in respect of the average pilot, particularly those for the Basic configuration, meaning that the workload of an average pilot would likely be higher.

q) The results from Trial 2 are broadly consistent with those from Trial 1 and do not substantially change the conclusions of Trial 1. The Trial 1 VCR results should be used for the image analysis exercise as they represent the more consistent data set.

4 Phase 2/2 - analysis of trials data

4.1 Introduction

The EMOCUES2 trial was followed by a deeper examination of the results through analysis of the objective data from Trial 2 and comparison with pilots' ratings [9] using techniques that had been developed under the MoD's CRP programme [4,5,6]. These included two special analytical procedures, image analysis and tau analysis, which were applied to investigate how factors such as pilot control strategy, task performance, workload, and flight path safety were influenced by the available visual cues (i.e. UCE), for the two aircraft response types evaluated.

The following sections provide an overview of the methods, results and findings from this exercise. Further background information is provided in Appendices B and C and a more detailed summary of the results and findings is given in the data analysis report [9].

4.2 Image Analysis

This section addresses the application of fractal image metrics to the prediction of pilot ratings using the approach developed under the MoD's CRP Ego-Motion project and reported in [9].

4.2.1 Background

For the MoD's CRP Ego-Motion project, the aim was to derive a model based on image metrics for use as a means for predicting VCRs and derived Useable Cue Environments (UCEs), or HQRs, based purely on analytical extraction of visual scene features. Four image metrics that are based on fractal geometry [16,17] were considered: k, β, D, α, which relate to smoothness, clutter strength or intensity, clutter uniformity and clutter density respectively. It was found during the MoD CRP programme that the best indicators of visual cues for pilot handling were k and D, with D being the most important.

The image data were correlated with pilots' VCRs and a simple relationship between image metrics and pilot ratings was identified, whereby the image metrics D and k were sufficient as a basis for prediction of pilot performance [5]. The analysis process involved computing the image metrics from visual images of each of the visual conditions evaluated by the pilots, and comparing these with the associated pilot ratings. The prediction model was established by finding a functional relationship between the image metrics and a 'training' set of ratings, using least-squares regression. A brief overview of the background to the analysis and the associated modelling approach is given in Appendix C.

For the EMOCUES2 data analysis, the aim was to use a similar approach to investigate a means of predicting the difficulty of accomplishing a given handling task using images representing the outside visual scene viewed by the pilot. Hence, in this analysis, the same metrics (k, β, D and α) were computed for the 17 images from the EMOCUES2 trial, and their relationship with the associated pilot ratings was assessed.

For the purposes of the analysis the images were numbered as defined in Table 12, which also summarises the pilot ratings that were awarded. Examples of the images analysed are given in Appendix B. Note that the examples shown for the degraded visual conditions, i.e. Day/DVE/Fog/Text and Night/DVE/Fog/Text, are to some extent unrepresentative because some of the surface textures apparent in the simulator visuals have been lost in the reproduction process. This problem does not affect the actual images used for the analysis exercise as these were translated into digital format in the image capture process. It should also be noted that only the pilot ratings for the Basic configuration from Table 12 were used for the initial development of the case for the prediction of pilot ratings using image metrics, as presented in Figures 16 to 27. For each analysis performed, the mean and standard deviation (sd) for the difference between the pilot rating and the rating predicted using the model developed from the MoD CRP programme were calculated. Interestingly, in all cases the mean values fall within the range +/- 0.06, i.e. they are all virtually zero. This is a characteristic of the statistical model fitting process described in Appendix C. Hence, for the analysis cases presented below, the sd is used as a relative measure of the dispersion of the predicted data versus the pilot ratings.

It should also be noted that, as for the MoD CRP programme analysis [5], a random jitter was added to the rating value in all the plots of pilot HQRs to aid visualisation. Without this jitter, many of the ratings are identical and, therefore, the points in the plots are more difficult to resolve. The jitter applied is within the range (-¼,¼) hence, as the original ratings are integers, no information has been lost.

Manoeuvre	**Visual case and identifiers used for image analysis**	**Model config**	**Mean HQR**	**VCRs**		**UCE**
				Attitude	**Trans rate**	
Hover Taxi	1 Day/GVE	ACAH	3.5	1	1.75	1
		BASIC	4.5	1	2	1
		Average	4	1	1.88	1
	2 Day/GVE/Fog	ACAH	5	3	4	2
		BASIC	5	2	2	1
		Average	5	2.5	3	2
	3 Day/DVE/Fog/Text	ACAH	4.5	4	5	3
		BASIC	5.5	4	4.5	3
		Average	5	4	4.75	3
Fly Away	4 Day/GVE	ACAH	2.5	1	1.5	1
		BASIC	4.5	1	2.5	1
		Average	3.5	1	2	1
	5 Day/GVE/Fog	ACAH	5	3	5	3
		BASIC	4.5	4	2.5	2
		Average	4.75	3.5	3.75	2
	6 Day/DVE/Fog/Text	ACAH	4	5	6	4
		BASIC	5.5	5.5	5.5	4
		Average	4.75	5.25	5.75	4

Table 11 Pilot ratings used for image analysis

Manoeuvre	Visual case and identifiers used for image analysis	Model config	Mean HQR	VCRs		UCE
				Attitude	Trans rate	
Turns	7 Day/GVE	ACAH	3	1	2.75	1
		BASIC	4.5	1.5	3.25	1
		Average	3.75	1.25	3	1
	8 Day/GVE/Fog	ACAH	4	4	5	3
		BASIC	4.5	3	3.5	2
		Average	4.25	3.5	4.25	2
	9 Day/DVE/Fog/Text	ACAH	5	4.5	5.5	4
		BASIC	6	4.5	5.5	4
		Average	5.5	4.5	5.5	4
	10 Night/DVE/Fog/Text	ACAH	-	5	5	3
		BASIC	8	5	5.5	4
		Average	8	5	5.25	4
Climbs	11 Day/GVE	ACAH	3.5	2.5	3.75	2
		BASIC	4.5	1.5	3.75	2
		Average	4	2	3.75	2
	12 Day/GVE/Fog	ACAH	4	3	4	2
		BASIC	4	3	3.5	2
		Average	4	3	3.75	2
	13 Day/DVE/Fog/Text	ACAH	3.5	4	5	3
		BASIC	5	3.5	5.5	4
		Average	4.25	3.75	5.25	4
	14 Night/DVE/Fog/Text	ACAH	-	-	-	-
		BASIC	8	6	6	4
		Average	8	6	6	4
Approach	15 Day/GVE	ACAH	2.5	1	1.5	1
		BASIC	4	1	2.5	1
		Average	3.25	1	2	1
	16 Day/GVE/Fog	ACAH	3	2	3	2
		BASIC	4	2.5	3	2
		Average	3.5	2.25	3	2
	17 Day/DVE/Fog/Text	ACAH	3	2.5	4	2
		BASIC	5	3.5	4.5	2
		Average	4	3	4.25	3

Table 11 Pilot ratings used for image analysis (Continued)

4.2.2 Predictions of UCE with Standard Metrics

Figure 16 shows the prediction of UCE based on *k* and *D*, each point being annotated with the image identifier from Table 12. The overall correlation obtained is similar to that obtained for the MoD CRP study [5]. The standard deviation is 1.111, and there are 5 cases where the predicted UCE is greater than 1 scale point away from the actual value. Prediction of UCE is poor for images 9 and 13 in particular (for examples of the associated visual images, see Appendix B, Figs 9 and 13 respectively). These images comprise nearly blank scenes with few visual cues, except a string of lights. According to the strict criteria specified in [5], these images should provide fairly good visual cues because:

- the visual cues are sharp, focussed (low *k*) and therefore define position accurately;
- the visual cues are sparse, and not distributed uniformly over the image (low *D*). They are sufficient in number and widely spaced to give a good indication of position without being too numerous to extract a clear pattern.

The images are lacking in overall brightness and contrast (β), however, and have a relatively small number of cues (α); both of these deficiencies might detract from pilot performance. In the MoD CRP study β and α did not contribute significantly to the accuracy of prediction of UCE, but the range of visual conditions was not so extreme for those data [5]. When the visibility is very poor, it is possible that β and α play a more important role in determining pilot handling qualities and UCE.

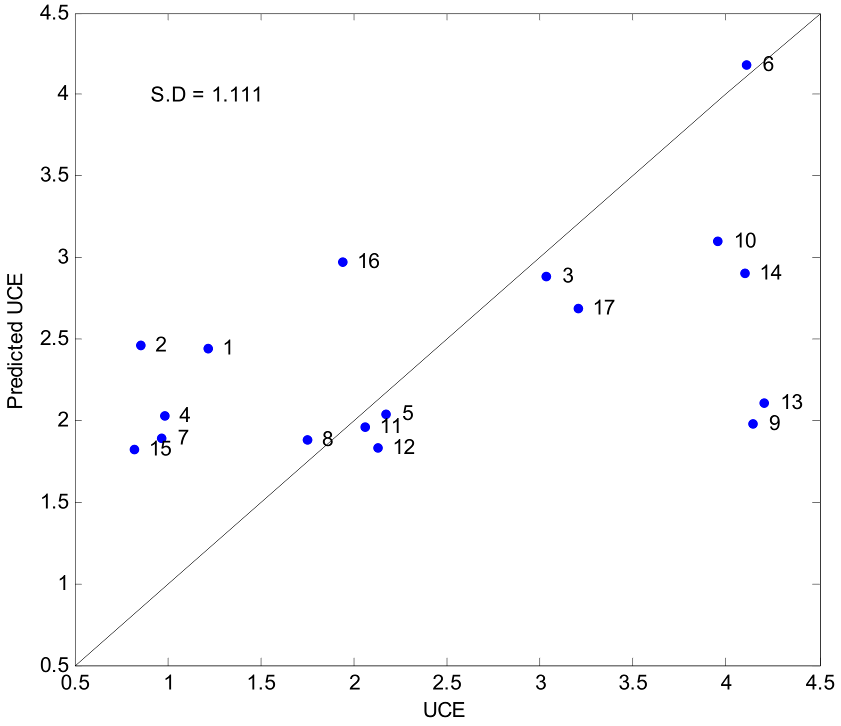


Figure 16 Prediction of UCE based on k and D

Figure 17 shows the prediction of UCE based on *k*, *D*, β and α. The standard deviation of 0.799 indicates an improvement over using only *k* and *D*, but there are still 4 cases where the predicted UCE is greater than 1 scale point away from the actual value. The prediction for image 9 has improved significantly, but not for image 13. The error for image 16 has also increased significantly (i.e. from approximately +1 to +1.75).

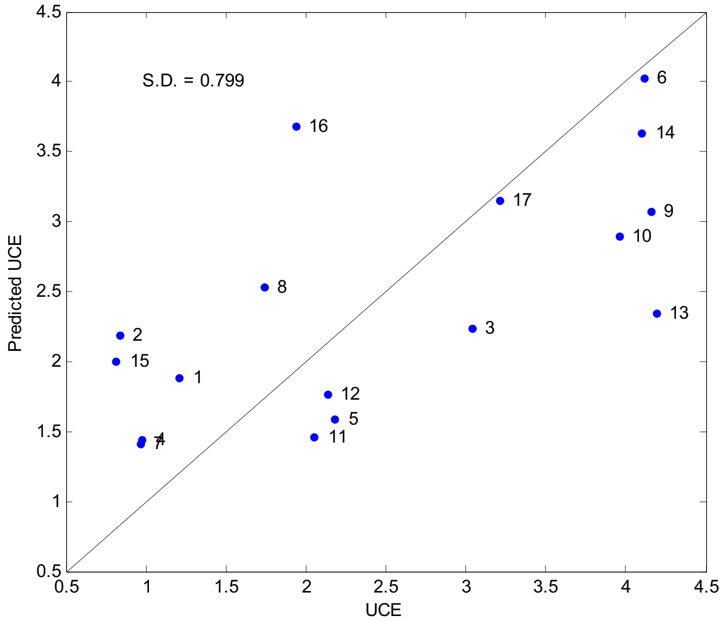


Figure 17 Prediction of UCE based on k, D, α and β (original version)

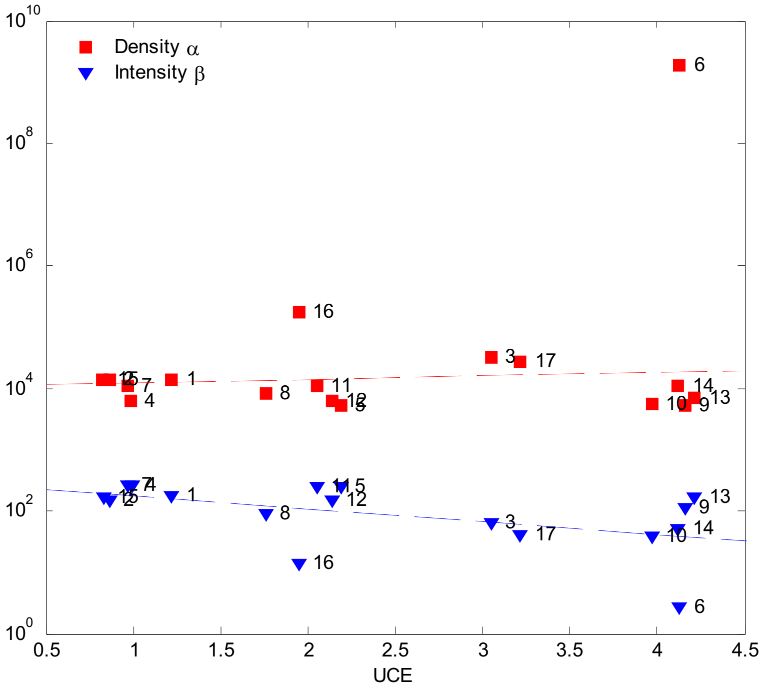


Figure 18 α and β based on original fractal model

Figure 18 plots the variation of β and α with UCE, where it might be expected that the average density (α) and intensity (β) decrease as the helicopter handling becomes more difficult (i.e. as the level of UCE increases). However, surprisingly these trends are only weakly observed in Figure 18 and there are some major anomalies.

Image 6 (Appendix B, Figure 6) is the most extreme anomaly, which may be because there are no visual cues of any significance; the scene is dominated by extremely faint texture that is a regular chequered pattern. This creates a very large number of very faint visual cues (too faint to be noticeable), which is why α is so large and β is so small. β is consistent with a visual perception of image intensity, but α is not consistent with a visual perception of cue density because the cues are too faint to see. To correct this anomaly, however, would require a detailed knowledge of visual perception, in particular the intensity and edge strength thresholds that trigger a focus of attention. This defeats the original purpose of the fractal image metrics which was to provide a relatively simple, generic characterisation of image content. Detailed visual perception models would also be invalid if machine vision were to be used to assist pilot tasks in the future. The next most obvious apparent anomaly is image 16 (Appendix B, Figure 16), which is similar to image 6 albeit with more pronounced surface texture features. As with image 6 though, the cues are still faint, which would explain why α is large and b small compared with the general trend for UCE.

Images 3 (Appendix B, Figure 3) and 17 (Appendix B, Figure 17) have rather high values of a in relation to UCE, possibly because in both cases there is a local region that is rich in visual cues: the landing pad in image 3 and a runway in image 17. These cases imply that pilots have a preference for visual cues that are widely dispersed (though not uniformly distributed) rather than concentrated in only one part of the image.

The remaining apparent anomalies concern the very poor visibility cases where UCE=4, in which the background is typically very dark or foggy and there is a relatively small number of perceptible visual cues, mostly strings of lights. These scenes, in direct contrast to image 16 (Appendix B, Figure 16), have fairly intense cues (the lights are bright) but are few in number. Hence it is not surprising that the value of β is comparable to a scene with a low UCE (better visibility), but it is surprising that the value of α is not much lower than the other scenes. The anomaly in α is caused by the way the fractal statistical model is calibrated from the image data, as explained next.

4.2.3 Modified Metrics α and β

All four metrics are based on fitting a statistical model to the image data and, like all such models, stability is related to the quantity of the data in the image. For example, the accuracy of the sample mean in estimating the true mean of a distribution is proportional to the square root of the number of samples. Likewise, when there are a small number of visual cues it is more difficult to estimate the fractal parameters accurately.

α and β are relatively unstable image parameters compared to k and D, especially when there are a small number of visual cues. The parameters k and D are more stable, and hence less reliant on a good fit to the image data than α and β. This is because a and β depend very strongly on k and D, but not vice-versa. k and D represent how strongly the intensity and overall number of visual cues depend on their size. Both are exponents, so the average cue intensity (edge strength) is proportional to average cue size raised to the power of k, and D is a similar exponent for the number of cues. α and β are measures of average cue density and intensity, but factored by size raised to the indices D and k respectively. It follows that β is very sensitive to errors in k and α is very sensitive to errors in D. Moreover, when images have significantly different k or D, comparisons of α and β are not equivalent to comparisons of average cue intensity and density, because the scale normalisation factors are governed by k and D.

This problem can be circumvented by using fixed values of k and D for the calibration of α and β whilst still recording the true values of k and D for subsequent prediction of pilot handling. The metrics α and β are no longer totally dimension-independent, but they provide a more stable indication of two aspects of image content: the density and intensity of the visual cues. Average values of $k = -0.5$ and $D = 1$ were used for the calibration of α and β.

Figure 19 plots the modified values of α and β against UCE, and indicates that there has been little improvement in the anomalies in β, including images 6 and 16. Not surprisingly, therefore, Figs 20-24 show that the revised predictions of UCE based on various subsets of k, D and modified β, α show little or no improvement over the results shown in Figure 17. Because of the large dynamic range of β and α, logarithms of these values have been used in the linear least squares regression used to predict UCE. D, β and α combined (Figure 21; sd = 0.799) give nearly the same prediction as all four metrics (Figure 20; sd = 0.790), which implies that k does not add much information. However, any pair chosen from D, β and α gives a significantly poorer prediction (Figs 22, 23, 24; sd's in the range from 0.926 to 1.127) than all three combined, implying that all three parameters provide salient independent information. It follows that pilots' assessment of the quality of visual information in these cases depends primarily on uniformity, number and intensity of visual cues in the scene.

Overall, the best prediction of UCE is that based on k, D and modified β, α (Figure 20) and is within 1 UCE of the actual value in all but two cases, images 3 and 13 (Appendix B, Figs B3 and B13). Image 3 has quite a large number of strong visual cues, but they are concentrated in one region, the helipad. It may be that this image is not typical of what was viewed by the pilot during the manoeuvre; the helipad is very close to the helicopter, and therefore fills quite a large proportion of the image. The intensity and density of visual cues would be much smaller if the helicopter was much further away from the helipad, and it is noted that the distance from the helipad is significantly greater in images 1 and 2. It is therefore suggested that the UCE assigned by the pilots might have been based on more than just the image data provided in image 3.

Of all the cases where a UCE of 4 was assigned, image 13 (Appendix B, Figure B13) has the brightest visual cues; the road lights are clearly visible and form a long straight line that should be of significant use in establishing the orientation and direction of flight of the helicopter. There is, however, very little else in the scene that would aid stabilisation or flight path guidance. One factor that might inhibit guidance is that the lights are collinear, so there is insufficient information for complete triangulation. It is possible to augment the fractal image metrics with information about such geometric alignment, but this issue would add significantly to the complexity of the prediction of pilot handling, and possibly reduce the robustness of the approach.

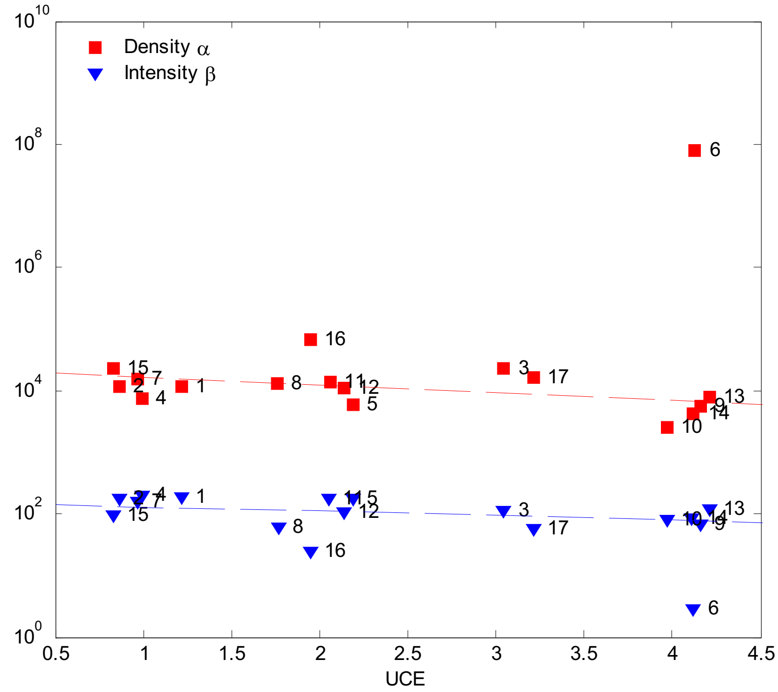


Figure 19

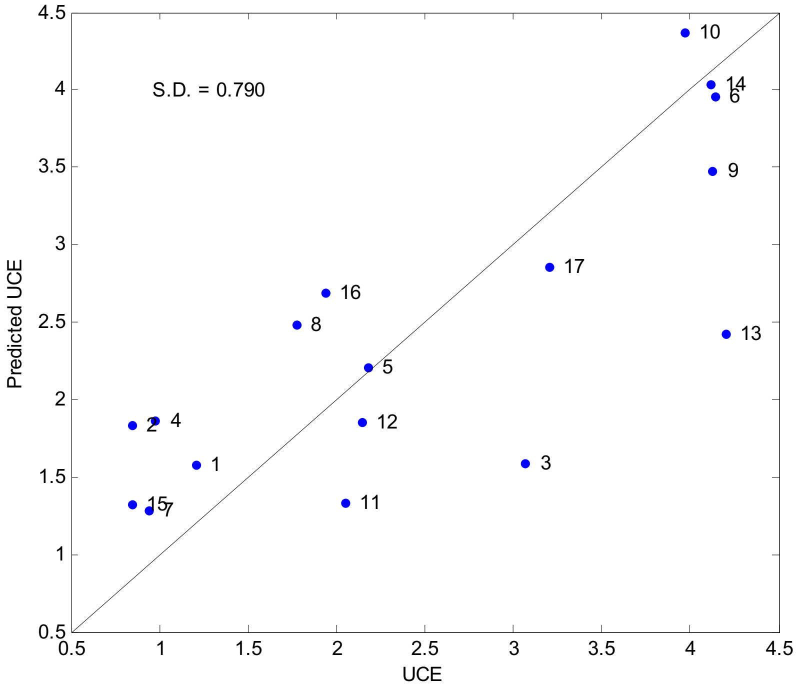


Figure 20 Prediction of UCE based on k, D and modified α, β

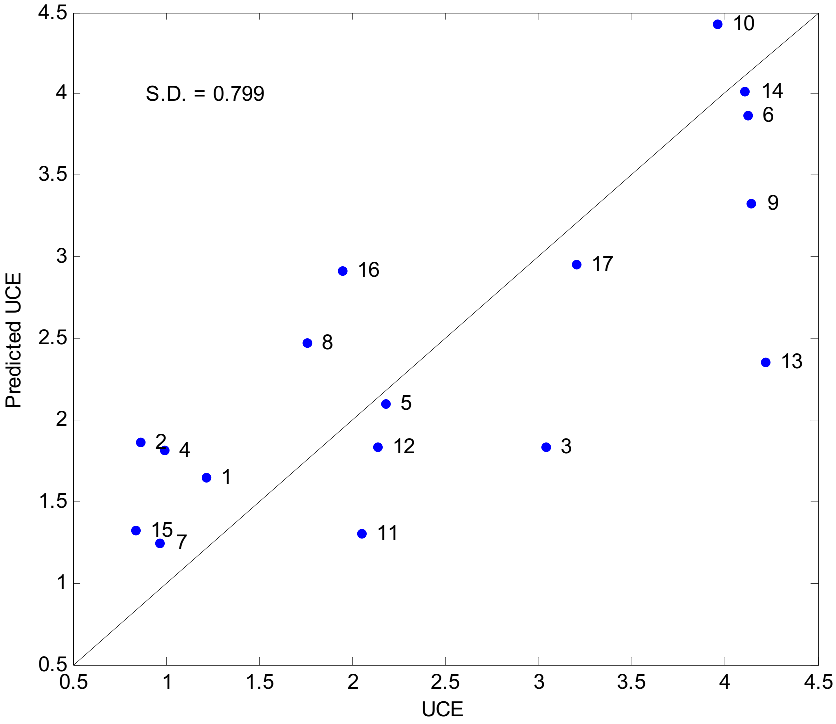


Figure 21 Prediction of UCE based on D and modified α, β

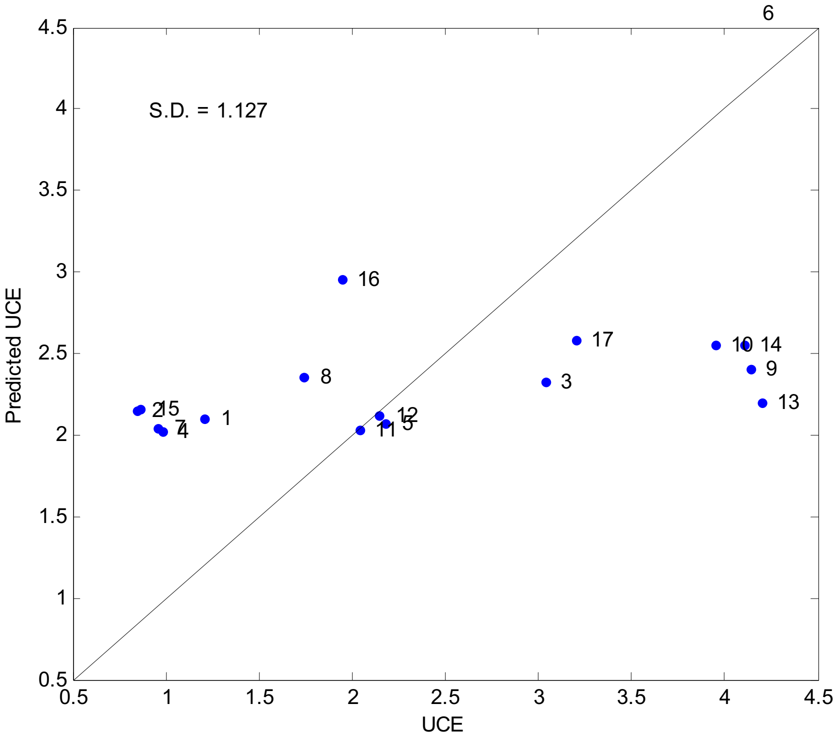


Figure 22 Prediction of UCE based on D and modified β

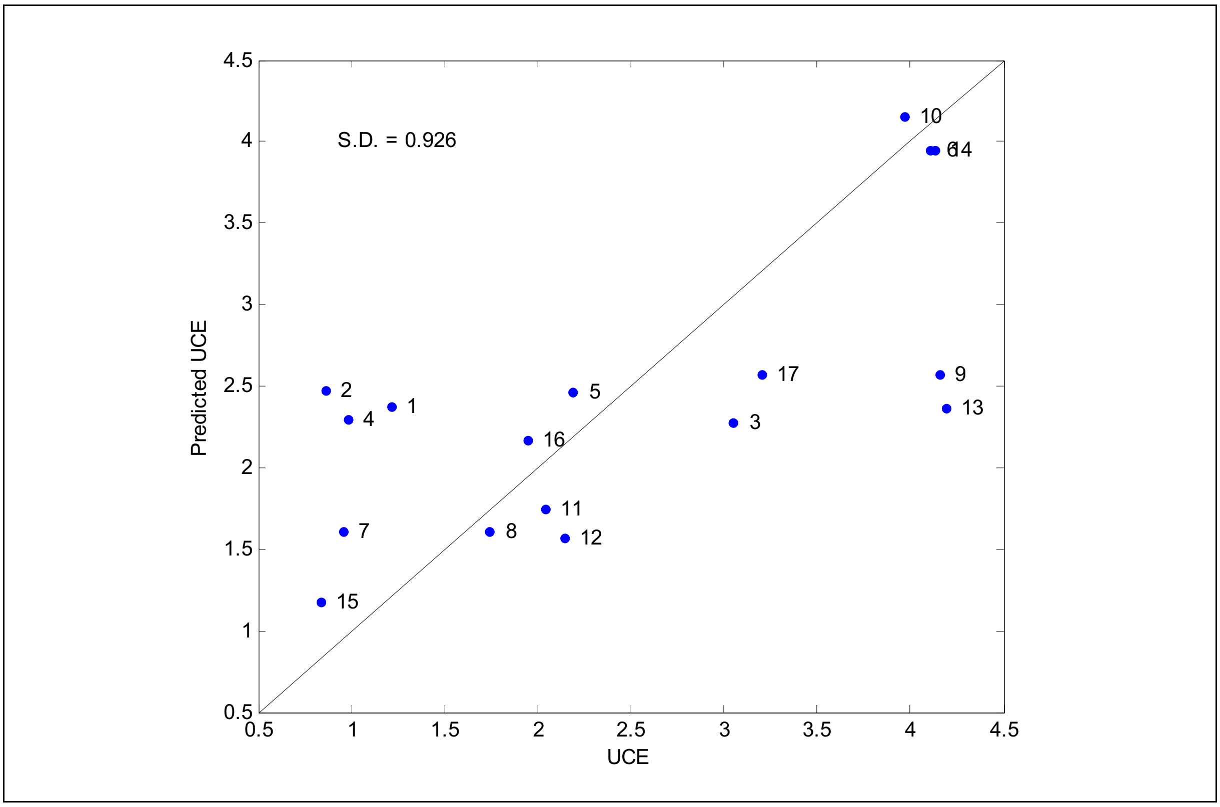


Figure 23 Prediction of UCE based on D and modified α

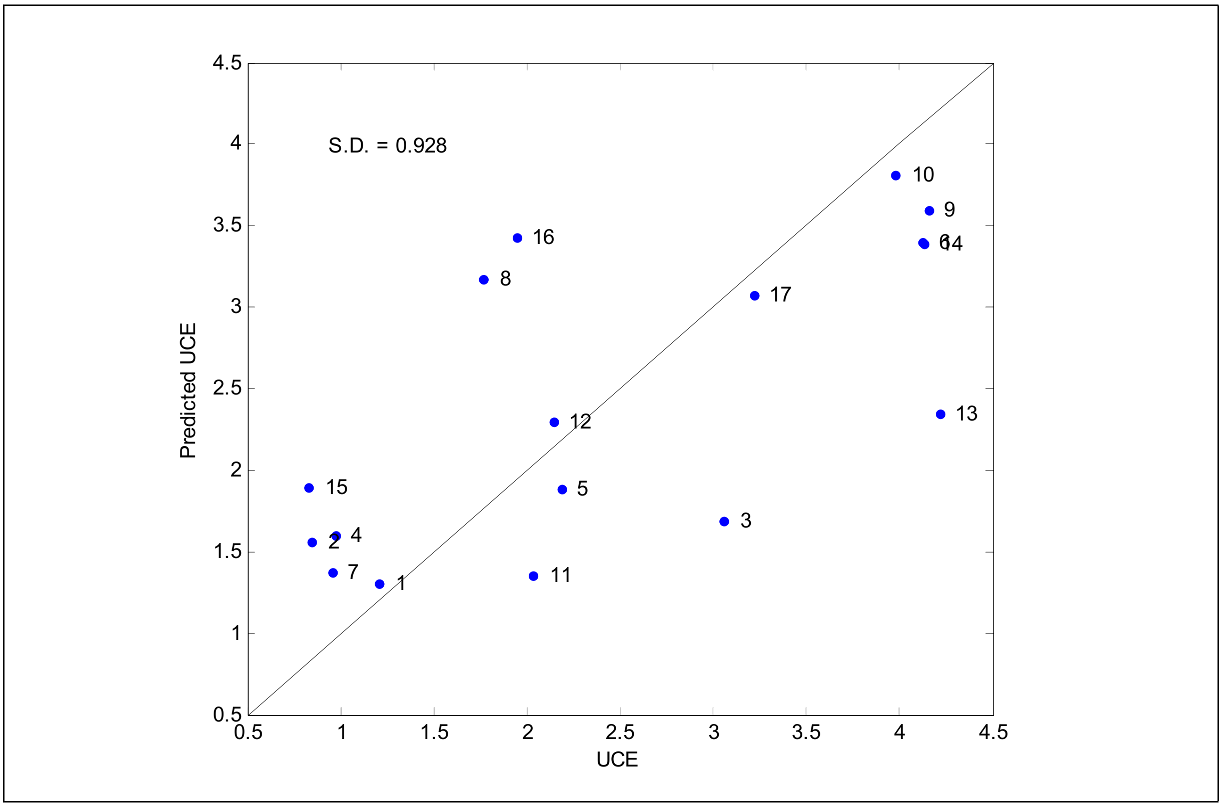


Figure 24 Prediction of UCE based on modified α, β

4.2.4 Helicopter stability and prediction of VCRs and HQR

This section considers the prediction of the Visual Cue Ratings (VCRs) and the Handling Quality Rating (HQR). To a greater or lesser degree these ratings, and UCE since it is a function of the VCRs, depend not only on the visible scene from which the fractal metrics are derived, but also on the configuration of the helicopter (e.g. whether stabilised). In this section the helicopter configuration is incorporated into the prediction of the pilot handling metrics. It should be noted that, throughout this section, α and β are derived using the modification to the fractal model described in Section 4.2.3.

Figures 25-27 show the predictions of attitude VCR (VCR (a)), translational rate VCR (VCR (t)) and HQR respectively, based on D, α, β. The predictions of HQR (Figure 27; sd = 0.550) are generally better than VCR (a) (Figure 25; sd = 0.852) and UCE (Figure 20; sd = 0.790). For HQR all cases (allowing for jitter) are within one rating of the actual values, while for VCR (a), predicted ratings fall within one rating in all but 4 cases (images 3, 4, 5 and 16), while UCE values fall within one rating in all but 3 cases (images 2, 3, and 13). The prediction of VCR (t) is similar to that for VCR (a) (Figure 26; sd = 0.916), with all but 4 cases (images 2, 3, 13 and 16) within one rating of the actual values.

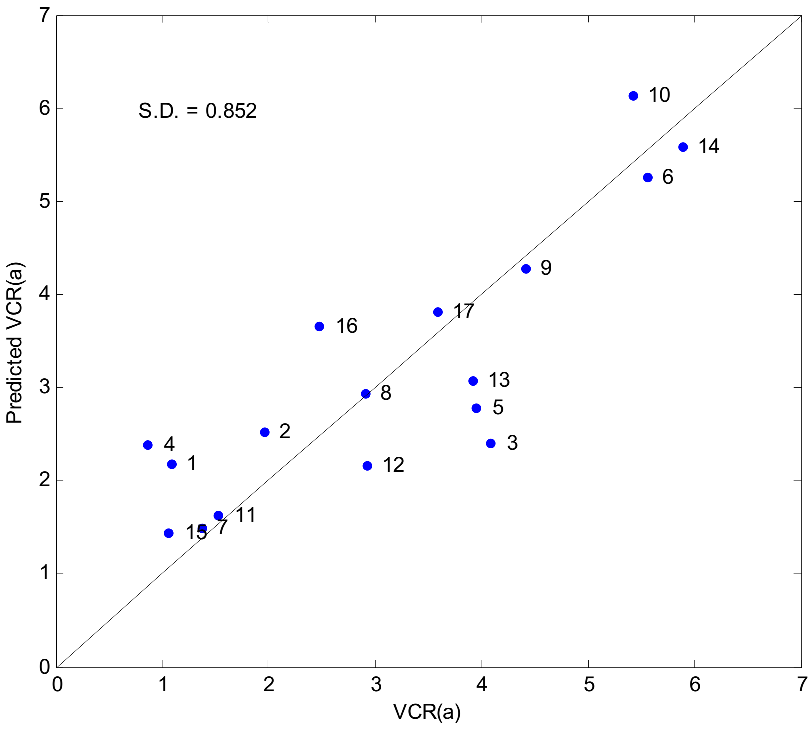


Figure 25 Prediction of VCR(a) based on D, α, β

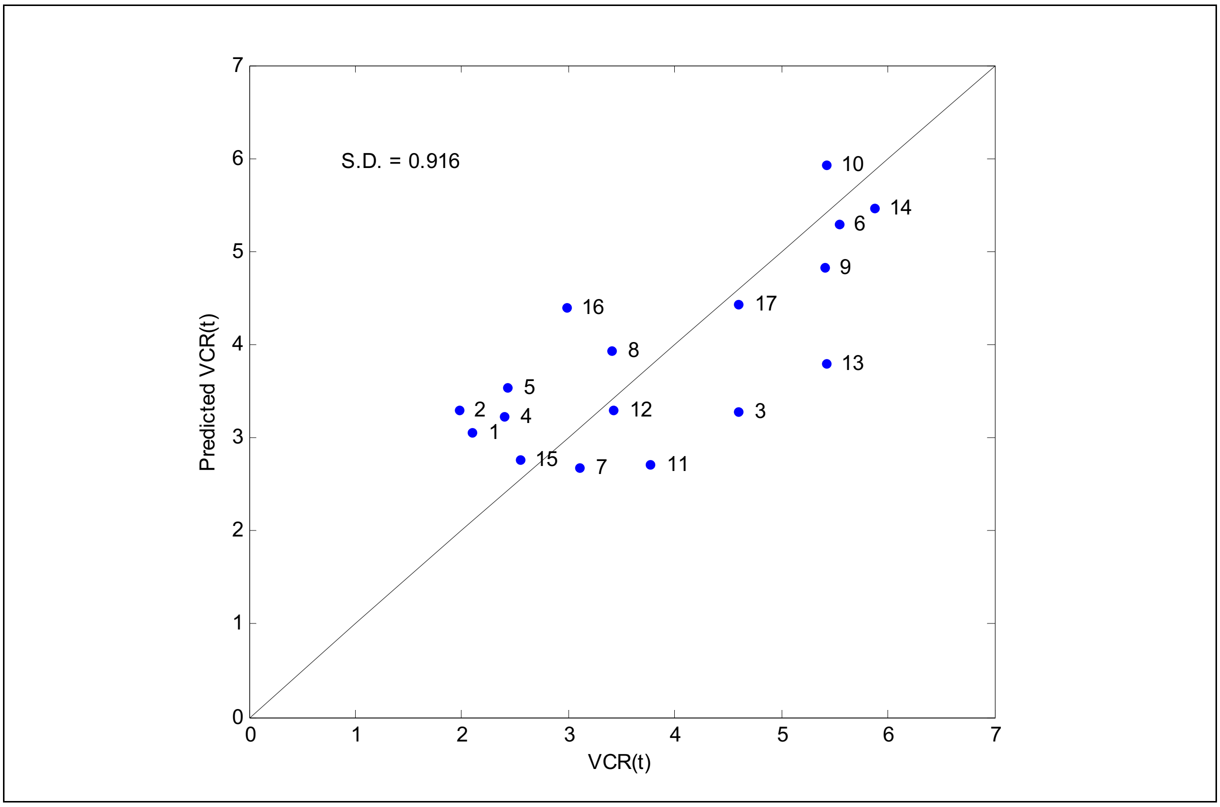


Figure 26 Prediction of VCR(t) based on *D*, α, β

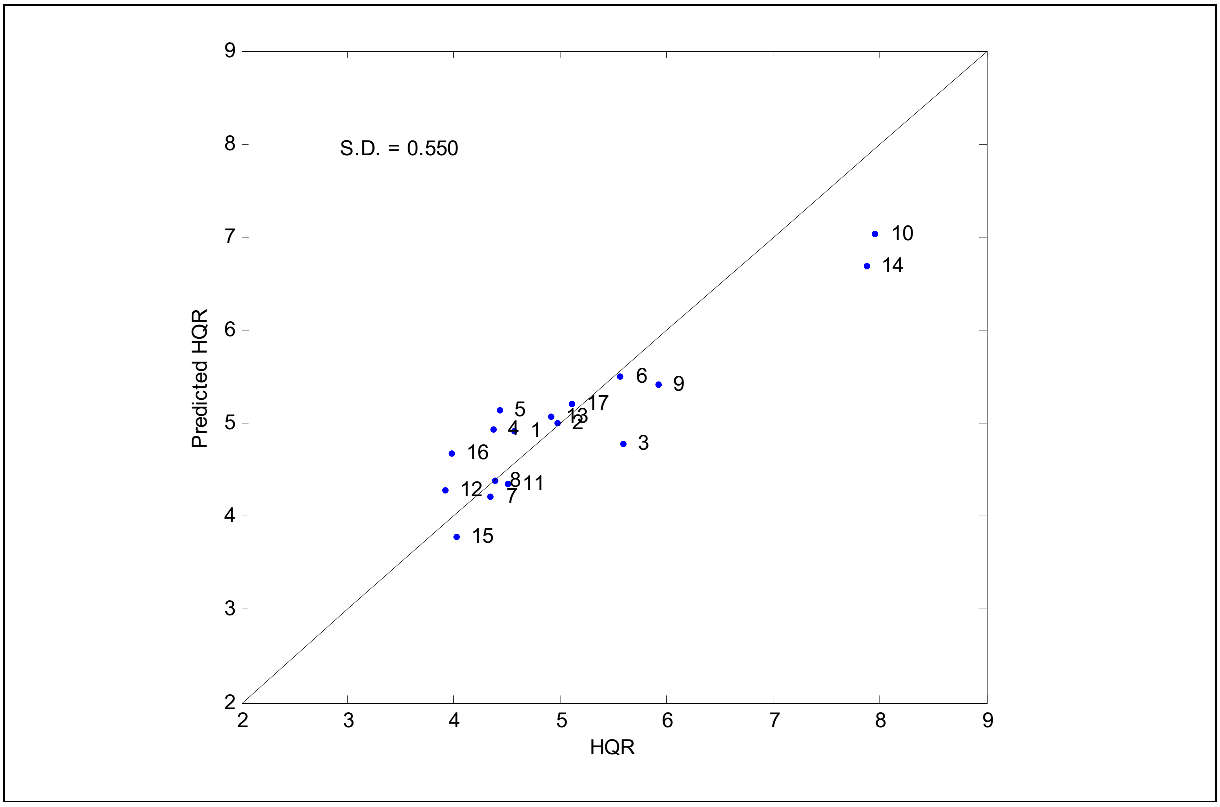


Figure 27 Prediction of HQR based on *D*, α, β

Figure 28 compares the pilot ratings (based on D, α, β) between the Basic, unstabilised helicopter configuration and the stabilised ACAH configuration. From inspection, the UCE, VCR (a) and VCR (t) ratings follow the same general tend whereas, as might be expected, the HQRs are significantly different for the two sets of results, i.e. HQRs for Basic are generally 1 rating poorer (higher) than those for ACAH. For VCR (a), the ratings for ACAH and Basic fall within ±1 of each other in all but one case, while for VCR (t) all but three ratings are within ±1. Similarly, all UCE values fall within ±1 one of each other. The corresponding images do not depend on the helicopter configuration, which implies that information in addition to the image metrics is required for a good prediction of HQRs, i.e. configuration state.

Configuration states are generally discrete and unordered, that is one configuration is not in all aspects better or worse than another, just different. In general it is not appropriate to represent this kind of data by a real number, and so it cannot be included as an extra independent variable in classic least-squares regression. Least squares regression can still be undertaken separately on each discrete configuration, but in this case a distinct set of coefficients would be fitted to each configuration state. In our example of unstabilised and stabilised helicopters 8 coefficients would be required: 4 for each configuration comprising one 'slope' for each fractal parameter D, α, β and a single 'intercept'. For many configurations the number of coefficients in the prediction model could be large, and there would be a danger of over-fitting the prediction model to the data. This type of regression would not take account of trends in pilot rating that are common to all states, as a separate model is being fitted to each configuration.

In the special case of helicopter stability, there are two features that enable it to be treated as a single real number:

- There is a reasonable expectation that the 'stabilised' state is overall better than the 'unstabilised' state, so there is a natural ordering.

There are only two states. In linear regression it does not matter what real numbers are assigned to each state (provided they are different); the same predictions will be made, but different 'slope' and 'intercept' coefficients will be fitted to derive this prediction. In this study helicopter stability has been represented as a binary variable with 0 denoting the unstabilised configuration and 1 denoting the stabilised configuration. These assignments are completely arbitrary choices. If there were more than two states it would be necessary to quantify the stability for the regression to be unambiguous.

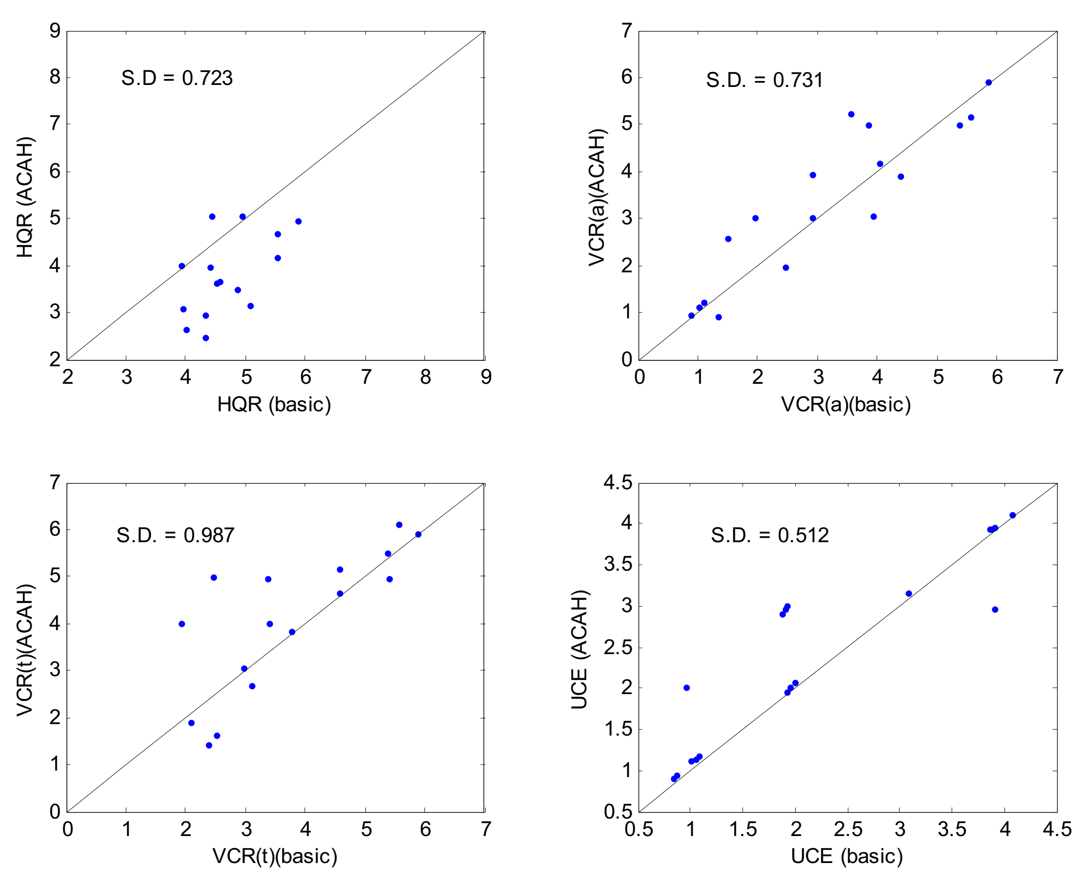


Figure 28 Pilot ratings for unstabilised (Basic) and stabilised (ACAH) helicopters

Figures 29 and 30 show the effect of using the additional stability variable on the prediction of HQR, the rating significantly affected by helicopter stability. The stability variable has improved the prediction by removing some of the bias within the data (sd = 0.818 without the stability variable and 0.645 with it). Not surprisingly, the actual HQR is on average significantly lower for the stabilised helicopter, reflecting the greater ease of undertaking manoeuvres. Without the stability variable, the predicted HQR is based on an average of the unstabilised and stabilised data, so the stabilised HQR is over-predicted and the unstabilised HQR is under-predicted (Figure 29; sd = 0.818). When the stability variable is included a negative correlation between stability and HQR is incorporated into the prediction, and so the bias is to some extent corrected (Figure 30; sd = 0.645).

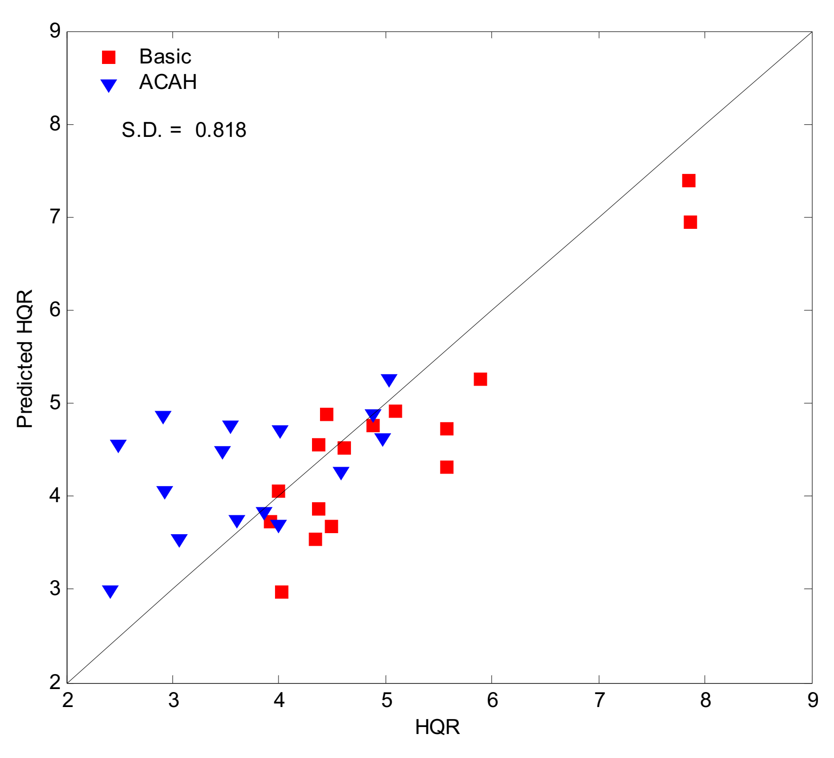


Figure 29 Prediction of HQR without helicopter configuration variable

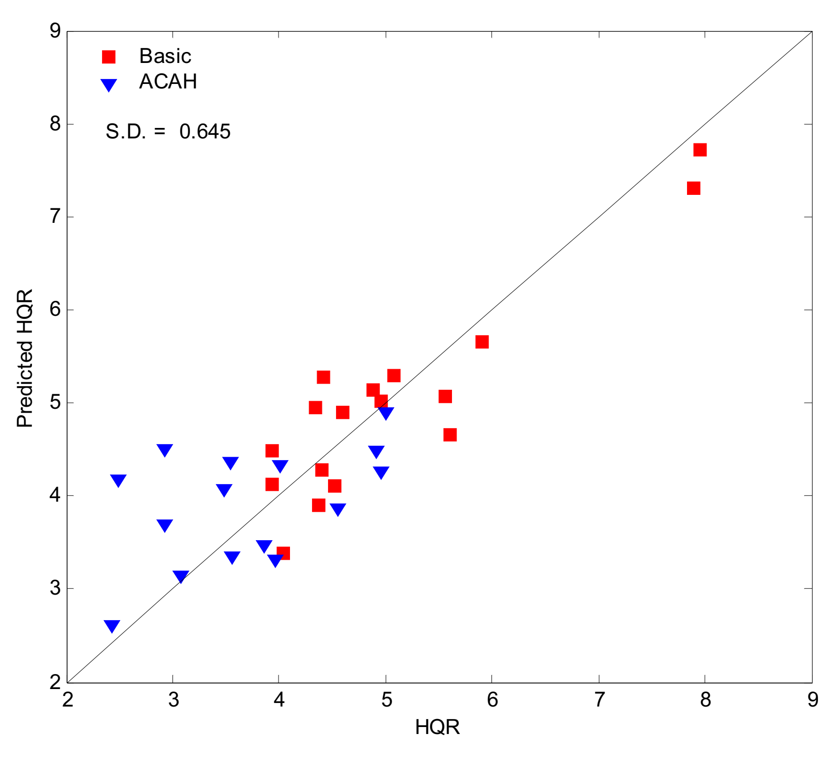


Figure 30 Prediction of HQR with helicopter configuration variable

Figures 31 - 36 show that the additional stability variable has little or no impact on the prediction of VCR or UCE. For UCE and VCR(a) this result might be expected because, as noted in the earlier discussion on Figure 28, these data are less affected by the stability variable.

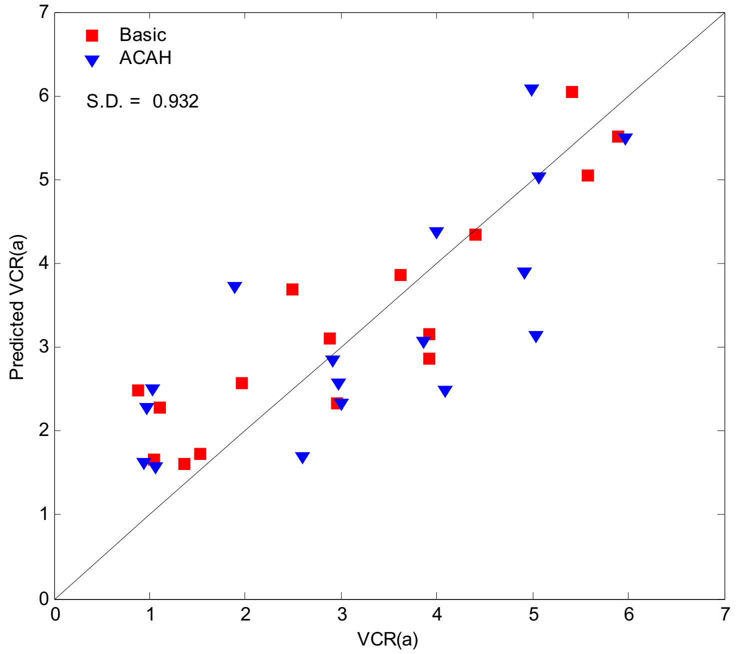


Figure 31 Prediction of VCR(a) without helicopter configuration variable

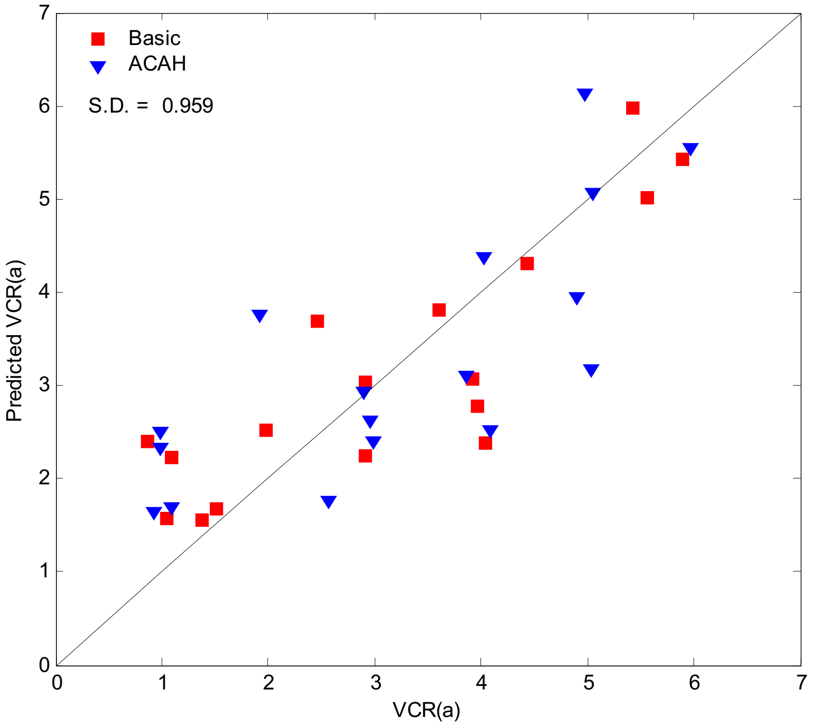


Figure 32 Prediction of VCR(a) with helicopter configuration variable

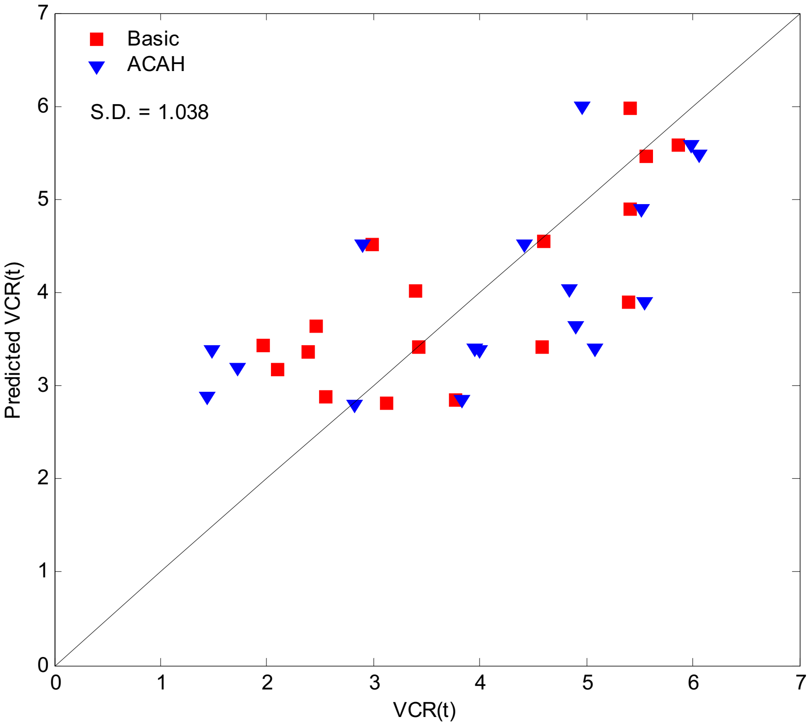


Figure 33 Prediction of VCR(t) without helicopter configuration variable

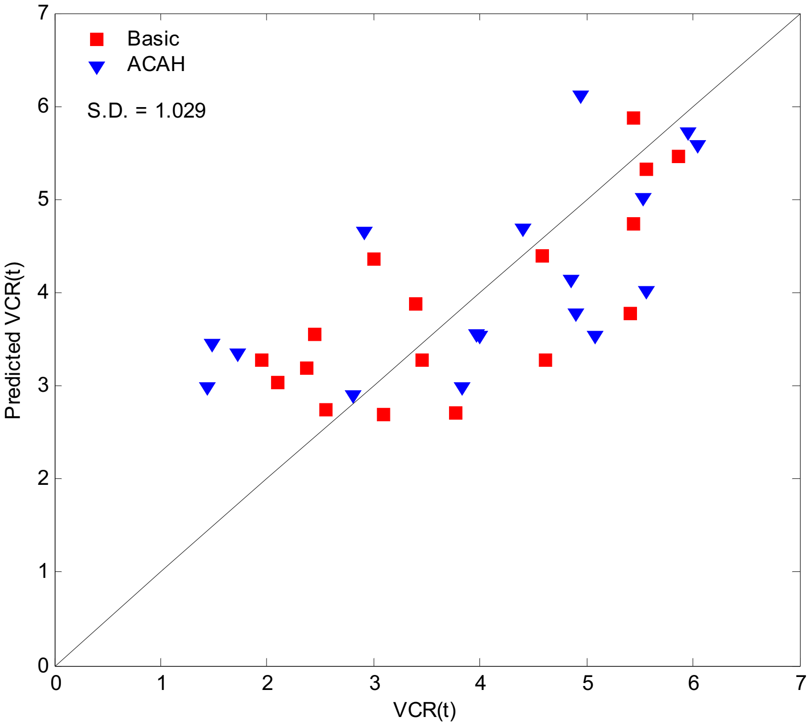


Figure 34 Prediction of VCR(t) with helicopter configuration variable

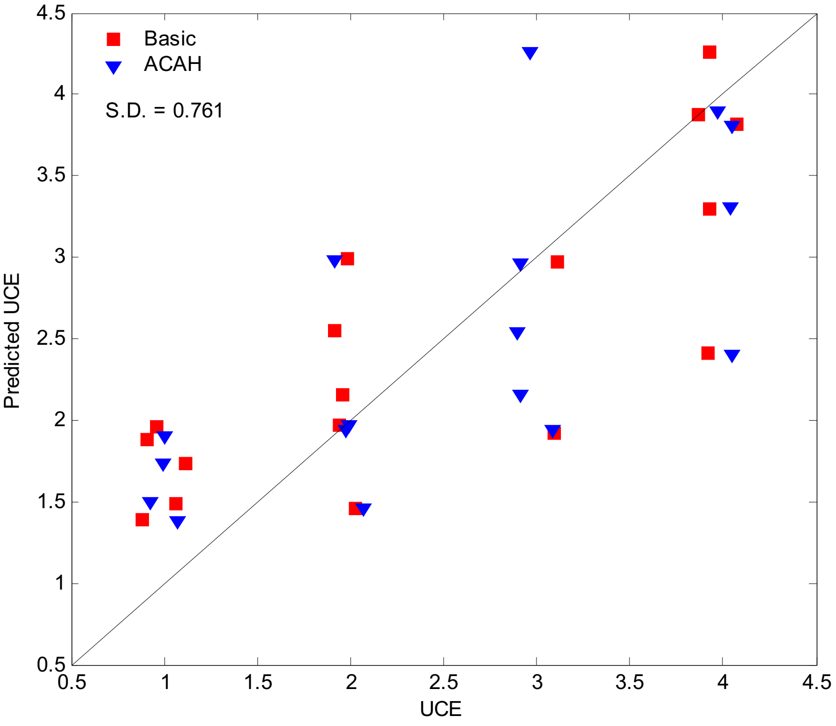


Figure 35 Prediction of UCE without helicopter configuration variabl

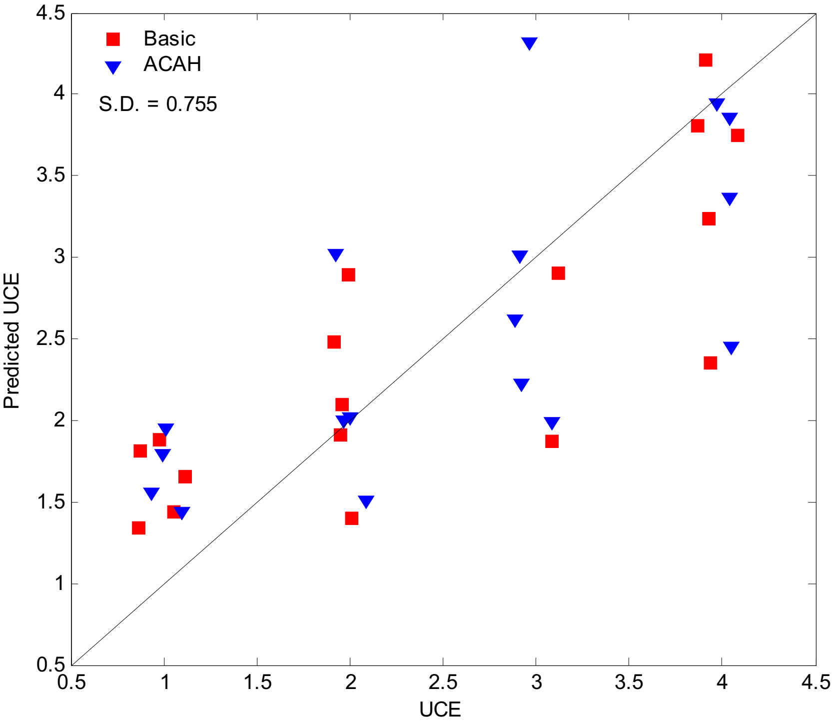


Figure 36 Prediction of UCE with helicopter configuration variable

4.2.5 Discussion

The results indicate that the fractal image metrics *D*, α and β are the most useful in predicting pilot handling qualities; the metric *k* adds little information. It follows that pilots' assessment of the quality of visual information in these cases depends primarily on uniformity (*D*), spatial density (α) and intensity (β) of the visual cues in the scene. Uniformity appears to be the most important factor for similar reasons to those given in the previous study [5], i.e. it is more difficult to identify reference points in an image if the visual cues are uniformly distributed (high *D*), and easier to distinguish between the cues when they are clustered or very non-uniform in intensity (low *D*).

Spatial density (α) and intensity (β) of visual cues appear to matter less than uniformity when the viewing conditions are good or fairly good. When the visibility is very poor, however, α and β become more significant because the pilot needs to have cues of sufficient brightness and quantity to interpret the scene at all. In the MoD CRP study [5], there were fewer scenes of extremely poor visibility so α and β were less significant. In this study it has been found that in very poor visibility the derivation of α and β using the conventional fractal model [16,17] is less stable than the derivation of *k* and *D*. A modification to this algorithm was developed (Section 4.2.3) that attempted to addresses this problem, but which did not significantly improve the prediction model's capability. A deeper examination involving a more detailed case study would be required to understand the reasons for this.

This analysis indicates that helicopter stability has a significant effect on HQR but very little effect on VCR or UCE, implying that for the data set analysed the latter were mostly governed by visual information. This is, perhaps, not surprising for, as noted in Sections 3.5.3 and 3.6.2, the UCE assessments were more dominated by translational rate effects rather than attitude stabilisation effects. Hence, it was found that including stability as an additional input variable in the least squares regression improves the prediction of HQR, but has little or no impact on VCR or UCE.

Overall, it is considered that a reasonable prediction of all the pilot handling metrics (UCE, VCR and HQR) has been demonstrated, i.e. in the majority of cases, the predicted values fall within +/-1 of the actual values. While this indicates a reasonable level of correlation between pilot handling metrics and the fractal image metrics, there are some cases where the prediction of the former from the latter is not so good, as discussed in the foregoing sections. Although the images are too few in number to form firm conclusions, it is thought that the remaining visual factors that are unaccounted for are concerned with more complex aspects of human vision, in particular certain aspects of geometrical alignment such as whether the main visual cues are collinear. Such additional factors could be measured and incorporated into models for pilot handling metrics, but considerably more training data would be required to validate the complex model that would result.

The accuracy of the current prediction of the pilot handling metrics is thought to be reasonable given the underlying simplicity of the model and the relatively limited data set on which it was developed. Further improvements would require access to a more extensive data set; in the first instance this could involve a more structured examination of the way that the image metrics are influenced by visual scene content, and factors such as atmospheric attenuation. This may help to explain and address some of the anomalies discussed in the foregoing.

4.2.6 Main findings

Based on the evidence of the results presented above the following conclusions are drawn:

a) Image analysis of EMOCUES2 visual scenes has illustrated how fractal image metrics can be used to measure the information contained within a given scene in relation to its visual cueing properties.

b) An image metric-based model for predicting HQRs, VCRs and UCEs has been successfully demonstrated using a process of calibration in terms of the pilot's ability to fly a given manoeuvre, i.e. as reflected by pilots' ratings.

c) The metrics D (uniformity), α (spatial density) and β (intensity) were found to be the most useful in predicting pilot handling qualities. Predictions of all the pilot handling metrics (i.e. VCR, UCE and HQR) have been demonstrated that, in the majority of cases, fall within one rating point of the actual values.

d) The results indicate that uniformity appears to be the most important factor probably because it is more difficult to identify reference points in an image if the visual cues are uniformly distributed (high D), and easier to distinguish between the cues when they are clustered or very non-uniform in intensity (low D).

e) The spatial density (α) and intensity (β) of visual cues appear to matter less than uniformity when the viewing conditions are good or fairly good but, when the visibility is very poor, α and β become more significant, because the pilot needs to have cues of sufficient brightness and quantity to interpret the scene at all.

f) It was found that including stability as an additional input variable in the model fitting process improved the prediction of HQR, but had little impact on predicted VCR or UCE.The accuracy of the current prediction of the pilot handling metrics is considered to be reasonable given the underlying simplicity of the model and the relatively limited data set on which it was developed.

g) Additional visual factors unaccounted for in the current model could improve the prediction capability, but this would require access to a more extensive data set and would likely result in a complex model.

4.3 Tau analysis

4.3.1 Method

The MoD CRP study [4,5,6] set out to establish a means of quantifying the necessary and sufficient visual information for safe flight in the DVE. A key premise was that the solution to reducing workload and maintaining the pilot's spatial or, more precisely, motion awareness lies in the integration of control and vision augmentation. If the UCE is poorer than Level 3, then the first challenge is to recover to UCE 3 or better through vision augmentation, then to achieve Level 1 handling qualities through control augmentation using the principles of ADS-33 [5,13] as illustrated in Figure 8.

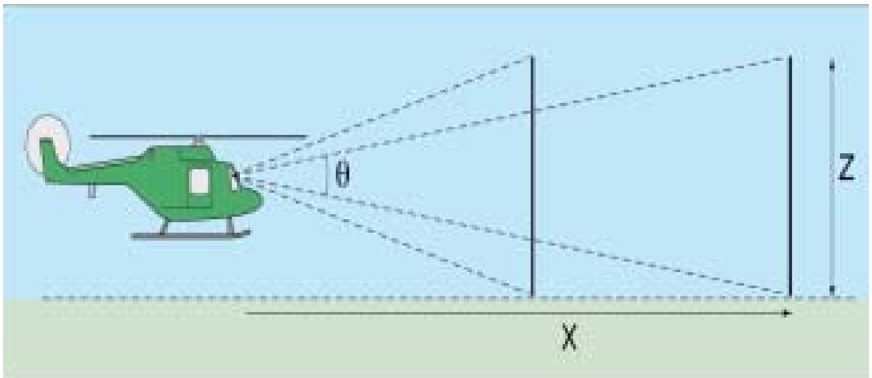


Figure 37 Optical looming when approaching an object

The problem of how to recover to UCE 3 was addressed in the CRP study using a technical approach, based largely on the application of tau-theory following the work of Lee [4,5,6]. According to Lee, the temporal variable of optical tau provides the natural information for judging motion, and is picked up by the looming of surfaces. As illustrated in Figure 37, optical tau is the instantaneous time to contact or encounter and is defined as the ratio of instantaneous distance to velocity, where:

$$\tau(t) = \frac{x}{\dot{x}} = \frac{\theta}{\theta} \qquad \dot{\tau}(t) = 1 - \frac{x\ddot{x}}{\dot{x}^2} \tag{4.1}$$

The research set out to investigate the optical variables that provide the natural inputs to a pilot's visual perception system to enable flight in good visual conditions, and the way in which this process is influenced by the available visual cues. Detailed analysis of an acceleration-deceleration manoeuvre gave rise to a general proposition that pilots seek out the visual cues that provide tau information from the optical flow on the surfaces over and around which they fly.

When this information is sufficiently prospective and remains consistent, then manoeuvres can proceed safely. When insufficient information is available to couple more than one motion tau, then a pilot can create a mental model of the prospective motion from which a tau-guide is activated that leads the pilot along a safe flight path. Flight safety is assured only if the pilot has sufficient information for coupling motion taus, or following (i.e. coupling the motion tau with) self-generated tau-guides. Hence, the question of what is necessary and sufficient in terms of scene content to provide a UCE 1, 2 or 3, can be determined indirectly in terms of tau-coupling models.

For the general case, it is hypothesised that the pilot's visual perception system introduces an intrinsic tau, tau-guide (τ_g), to guide the motion. For a simple manoeuvre that involves a change of aircraft flight path state (e.g. change from one constant speed state to another), tau-coupling of the motion tau, τ_m , with τ_g (i.e. an intrinsic tau-guide model) produces a guidance strategy that leads to an acceleration followed by a deceleration (or vice-versa), stopping after time T. In the case of a speed change, the motion-tau for speed, τ_v, couples with the tau-guide in constant ratio, where $\tau_v = k\ \tau_g$.

In the MoD CRP research, a case that involved acceleration from hover to a constant speed and deceleration back to a hover, over a distance *X* in time *T*, was examined. It was found that the pilot was applying a deceleration profile that followed a general tau-guide moving with a constant taudot (rate of change of tau with time). That is, the speed motion tau, τ_V, coupled with a tau-guide moving with a constant taudot given by the general expression:

$$\tau_v = k_g t + c \tag{4.2}$$

where k_g is the gradient (constant taudot) of τ_V over T, the time to complete the manoeuvre. The general case for this constant taudot model is $\tau_m = k_g t + c$.

This model was applied to the EMOCUES2 results taking into consideration the required control strategy and associated flight path parameters for the different test manoeuvres. For the Fly Away, Climb, and Approach manoeuvres the critical parameters are speed and height, where the aircraft is accelerated or decelerated from one constant speed state to re-establish at another, while changing height from one level to another. Hence, the motion taus of interest are τ_V, time to closure on the targeted speed, and τ_h, time to closure on the targeted height. For the Turn manoeuvre the flight path parameters include roll attitude when rolling into and out of the turn, and the change of heading during the turn. The motion taus of interest are τ_φ, time to closure on the targeted attitude, and τ_φ the time to closure on the targeted heading. Similarly, for the Hover Taxi the parameters include speed (i.e. the initial acceleration from rest to 25kn) and heading (i.e. during the turn to clear the buildings), the corresponding motion taus being τ_V, time to closure on the targeted speed, and τ_ψ, time to closure on the targeted heading. Values for τ_V (or τ_h, τ_ψ, τ_φ as appropriate) were derived for each time step for the experimental data using equation (4.1), and then k_g was derived by applying a linear least squares fit to the resultant time history for τ_V. Values of R^2 close to 1 (> 0.95) provide a measure of the 'goodness of fit' of this intrinsic tau-guide model.

An alternative strategy involves coupling between the motion taus for two different manoeuvre states (i.e. motion tau-coupling model), e.g. height and speed. In this case, the premise is that synchronisation is achieved by keeping the taus of motion gaps for the states in constant ratio where, for speed and height, $\tau_V = k_m \tau_h + c$. In this case, k_m is the gradient over time T, and is derived by applying a linear least squares fit to a cross plot of the time history data for τ_V and τ_h. Again, values of R^2 close to 1 (> 0.95) provide a measure of the 'goodness of fit' of this motion tau-coupling model.

A more detailed explanation of the method is given in the paper at Appendix D which was first presented at the American Helicopter Society Forum in 2001 [6]. For the CAA study, the aim was to apply this approach to the EMOCUES2 data and investigate the evidence for, and nature of tau guidance strategies applied by the pilot, and to examine the influence of the simulated visual conditions.

4.3.2 Results for intrinsic tau-guide model

The MoD CRP study approach was used to investigate the applicability of the intrinsic tau-guide model to the EMOCUES2 data. The first step was to derive appropriate motion taus for the five test manoeuvres, taking into consideration the required control strategy and associated flight path parameters. An example is shown in Figure 38 for the Climb manoeuvre. The critical parameters in this case are speed and height, where the aircraft is decelerated from one constant speed state to re-establish at another, while changing height from one level to another. Hence, the motion taus of interest are τ_V, time to closure on the targeted speed, and τ_h, time to closure on the targeted height. Data for these parameters can be derived using the equation (4.1), substituting X with either speed or height. The plots show sample results for the ACAH (Figure 38a) and Basic (Figure 38b) configurations for the Climb manoeuvre in the Day/DVE/Fog/Text visual condition.

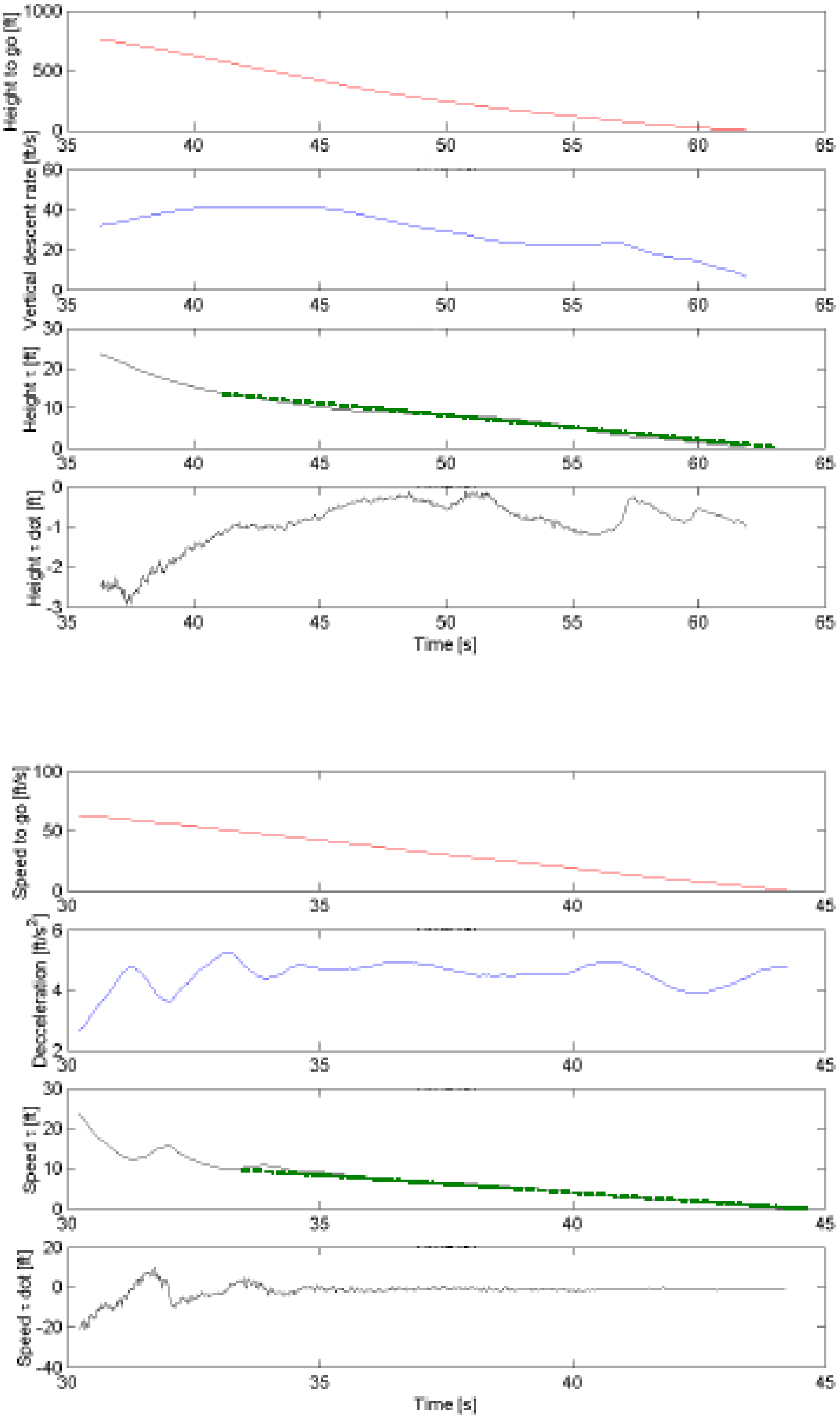


Figure 38a Tau data: Day/DVE/Fog/Text - Climb - ACAH

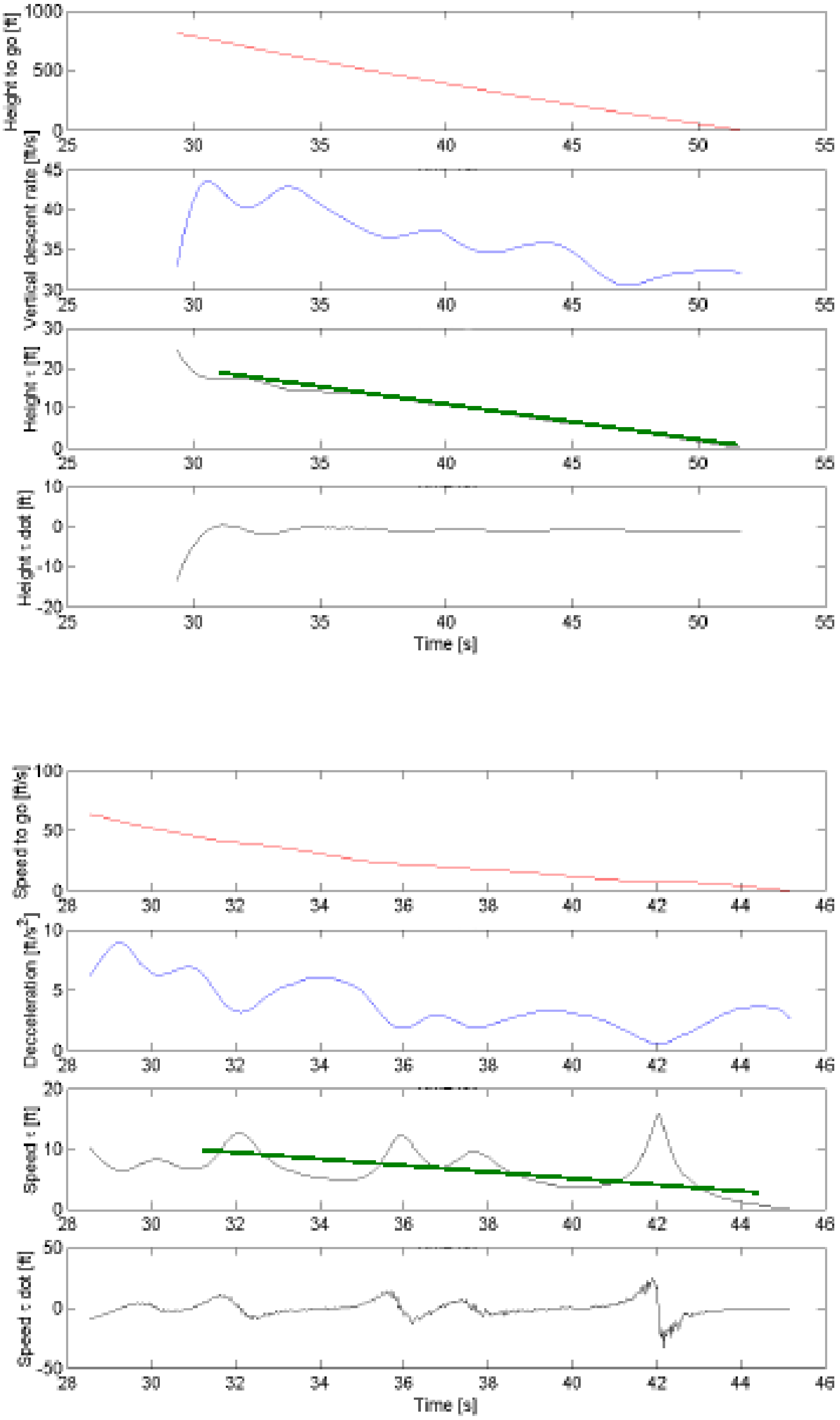


Figure 38b Prediction of HQR with helicopter configuration variable

From inspection of the data for τ_h and τ_V, as indicated by the dashed lines superimposed on the curves, it appears that for a significant portion of the manoeuvre the pilot was attempting to follow an intrinsic tau guide model with a constant taudot, i.e. as defined by equation (4.2). The relatively poor fit for τ_V in Figure 38b, reflects the poor attitude stability for the Basic configuration and control cross-coupling effects. In this case, the data indicate an underlying linear trend (the constant taudot strategy) over which the attitude control disturbance effects are superimposed. These results are typical of those for the Hover Taxi (τ_V and τ_ψ, time to closure on the targeted heading), Fly Away (τ_V and τ_h), Turn (τ_φ, time to closure on the targeted attitude, and τ_ψ) and Approach manoeuvres (τ_V and τ_h).

Overall results from assessment of the constant taudot values for the model using a linear least squares fit are summarised in Table 13, which shows the value of taudot and corresponding coefficient of regression, R^2, and the data length (time T) over which the linear regression was fitted, for each condition evaluated. For comparison the mean HQR for each case is also shown. Such trends that can be seen in the results are highlighted with an arrow. The duration T will be dependent on the time taken to execute a given manoeuvre element (i.e. to change speed and/or height) and the pilot's ability to apply the desired control strategy, i.e. constant taudot guide. It is of note that some difficulties were experienced in extracting these results because of the inherent variability of the tau data and the impact that this had on the duration (T) over which it was apparent that a constant strategy was applied.

Manoeuvre	Visual condition	Mean HQR	Height/heading			Speed/roll		
			Taudot	R2	Time(s)	Taudot	R2	Time(s)
Hover Taxi (Heading/ Speed)	Day/GVE	4	1.1088	0.9697	7	1.0328	0.9518	10
	Day/GVE/Fog	5	1.1885	0.9840	6	1.3448	0.8955	10
	Day/DVE/Fog/Text	5	0.5926 ↓	0.9145	6 ↓	1.0018	0.9476	10
Fly Away (Height/ Speed)	Day/GVE	4	1.1264	0.9851	10	1.0603	0.9711	15 ↑
	Day/GVE/Fog	4	0.9333	0.9272	10	1.0962	0.9259	17
	Day/DVE/Fog/Text	4	1.1421	0.9950	10	0.9729	0.9455	20
Turn (Heading/Roll attitude)	Day/GVE	4	1.2978	0.9947	14	1.7583	0.8527 ↑	9
	Day/GVE/Fog	4	1.2594	0.9751	25	1.7135	0.9568	2.5
	Day/DVE/Fog/Text	4	1.0422	0.9891	20	1.3491	0.9746	1.5
	Night/DVE/Fog/Text		1.2920	0.9103	23	1.1647 ↓	0.9358	0.6 ↓
Climb (Height/ Speed)	Day/GVE	2.5	0.9511	0.9917	30	0.8426 ↑	0.9822	10
	Day/GVE/Fog	5	0.9559	0.9900	20 ↓	1.05^1	-	17
	Day/DVE/Fog/Text	4	0.6878 ↓	0.9635 ↓	20	1.0730	0.9682	9
	Night/DVE/Fog/Text		0.8594	0.9867	18	1.0555	0.9103	7 ↓
Approach (Height/ Speed)	Day/GVE	2	0.7085 ↑	0.9969	20	0.8595	0.9472	20
	Day/GVE/Fog	4	0.9482	0.9143 ↓	30	0.7788 ↓	0.9285	8 ↓
	Day/DVE/Fog/Text	3	1.0483	0.6538	12 ↓	0.6018	0.9798	10

Table 12a Taudot and R^2 values - ACAH

1. Estimated values

Manoeuvre	Visual condition	Mean HQR	Height/heading			Speed/roll		
			Taudot	R2	Time(s)	Taudot	R2	Time(s)
Hover Taxi (Heading/ Speed)	Day/GVE	4	1.2952	0.7463	5	0.6821	0.9153	8
	Day/GVE/Fog	6	1.0223	0.6718	6	1.0444	0.9836	2
	Day/DVE/Fog/Text	7	0.52[1]	-	8	1.4379	0.699	10
Fly Away (Height/ Speed)	Day/GVE	4	1.0486	0.9740	7	0.7037	0.2963	8
	Day/GVE/Fog	5	1.3318	0.9872	24	0.9149	0.7766	15
	Day/DVE/Fog/Text	6	1.3826	0.9278	15	0.86[1]	-	25
Turn (Heading/Roll attitude)	Day/GVE	6	1.1202	0.8874	11	0.7872	0.9871	1.5
	Day/GVE/Fog	6	1.0865	0.6303	15	0.8625	0.9770	2
	Day/DVE/Fog/Text	6	0.99*	-	28	0.87[1]	-	0.7
	Night/DVE/Fog/Text	8	1.1378	0.6143	30	1.0375	0.9615	1
Climb (Height/ Speed)	Day/GVE	4	1.0129	0.9355	30	0.8621	0.9044	9
	Day/GVE/Fog	5	0.8565	0.9949	20	0.8355	0.6566	7
	Day/DVE/Fog/Text	6	0.8330	0.9928	20	1.0152	0.6450	4
	Night/DVE/Fog/Text	7	0.9801	0.9995	20	1.0156	0.9964	5
Approach (Height/ Speed)	Day/GVE	3	1.1863	0.8562	30	0.81[1]	-	10
	Day/GVE/Fog	4	0.7382	0.9759	30	0.9980	0.9479	5
	Day/DVE/Fog/Text	5	1.0926	0.5380	20	0.6184	0.9295	5

Table 13b Taudot and R^2 values - Basic

1. Estimated values

In some cases the nature of the data made the selection of the most appropriate data window over which to fit a curve somewhat arbitrary, and in others there were large discrete peaks or discontinuities in the derived tau data due to values of zero or close to zero in the X derivative. The latter problem mostly applied to the Basic configuration and is a true reflection of the difficulties experienced with that aircraft in the degraded visual conditions. As noted in the table, for these cases taudot was estimated from the general trend of the data and, although no R^2 value is given, the correlation can be taken to be very poor.

These problems are also reflected in the values of T shown in Table 13. It might be expected that T would be influenced by the quality of the visual cues and the pilot's ability to exploit them, and factors such as aircraft controllability, i.e. the flight path should be more controllable with a stable aircraft such as ACAH because of improved stability and cross-coupling characteristics. Hence, the expected trend was for T to reduce as the visual conditions degraded, and for relatively larger values for ACAH compared with those for Basic. However, from inspection of Table 13, these expected trends are only weakly observed at best (e.g. height control for ACAH in the Climb and speed control for Basic in the Climb) and there are many inconsistencies in the observed trends (e.g. height control for Basic in the Fly Away). In some cases the reverse trend is also shown (e.g. speed control for Basic and ACAH in the Fly Away).

Referring again to Table 13, taking the results as a whole, from inspection there does not appear to be a consistent correlation between the fitted taudot and associated R^2 values, the visual condition (as represented by simulated UCE) and pilots workload and performance (as represented by the HQRs). As a point to note, low R^2 values are indicative of poor correlation and in many cases low values were achieved due to large and discrete changes in the tau data noted above, for example, in Figure 38b. It is likely that, given the variability of the tau data for these cases and the resulting impact on extracting the linear regression data, the analysis has not captured the underlying taudot trends. The ACAH results for the Approach support this conclusion; this case was least influenced by variability in the tau data (i.e. easiest manoeuvre to fly, stabilised aircraft and low cross-coupling effects), and the extracted model values indicate that the constant taudot strategy was achieved less consistently for the DVE cases, i.e. there are significant differences between the results for the Day/GVE and Day/DVE/Fog/Text cases. To address this issue, further investigation would be required to develop a more detailed tau model to capture the more complex elements of the control strategy in relation to the control requirements for attitude stabilisation and cross-couplings.

4.3.3 Results for tau coupling model

Results from examination of the motion tau-coupling model (τ_v and τ_h) applied to the Fly Away, Climb and Approach manoeuvres showed that, in general, there was no firm evidence of a tau coupling between speed and height in these manoeuvres. Sample results are shown in Figure 39, which shows cross-plots of τ_v versus τ_h using data taken from the respective motion tau time histories for the Fly Away (Figure 39a), Climb (Figure 39b) and Approach (Figure 39c) manoeuvres. These examples represent typical results achieved for both model configurations and show that, in general, there does not seem to be any firm evidence of a tau coupling between speed and height (i.e. $\tau_v = k_m \tau_h$) in these manoeuvres. In the event, no attempt was made to derive fitted model data for these cases.

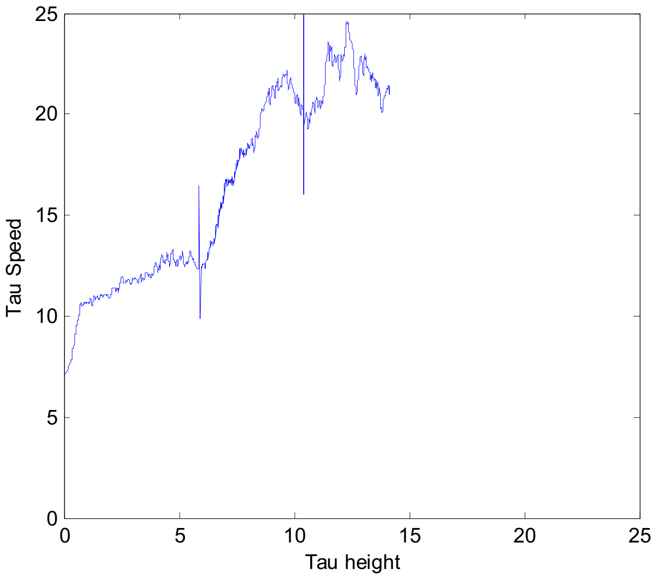


Figure 39a Approach - Day/GVE - ACAH

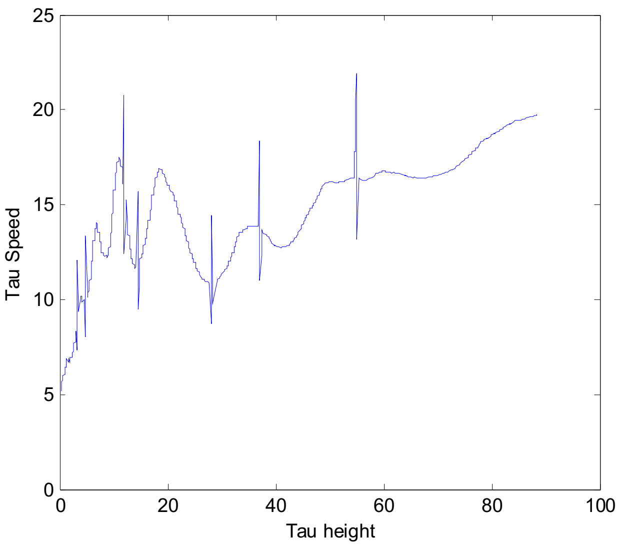


Figure 39b Fly Away - Day/GVE - ACAH

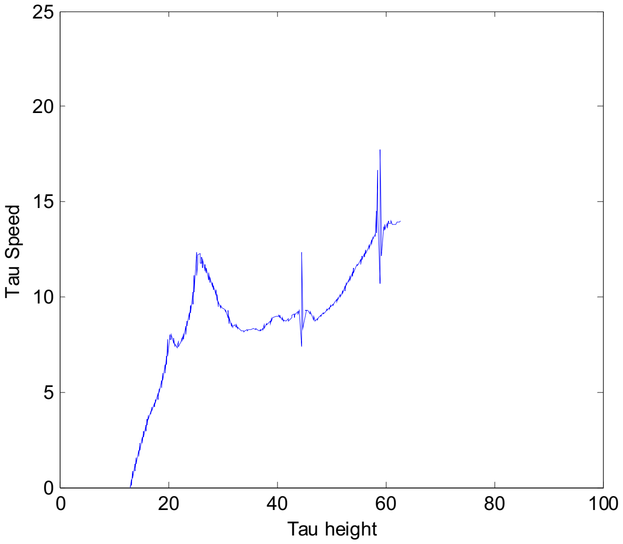


Figure 39c Climb - Day/GVE - ACAH

A key factor in this result is that speed and height changes tended to be initiated and completed at different points in time, where they were flown either as contiguous tasks or overlapping tasks. The probable reasons for this could be that the manoeuvre has specific speed and height targets so significant attention was required for the instruments, or simply that there were insufficient outside visual cues to allow the pilot to apply a speed and height motion tau coupling strategy. The results also suggest that there is a significant interference effect between the two tasks due to control cross-couplings, which would have added further to the difficulty of applying this strategy.

4.3.4 Discussion

Typically, the test manoeuvres flown comprise a number of control elements for a given aircraft change of state, e.g. increases in speed, height, or heading changes. Depending on duration, each of these changes involves an initial acceleration phase, a constant rate phase and final deceleration phase. It appears that three different tau strategies were applied for each of these phases and that there is little evidence to show that there was tau-coupling between the motion taus for the different manoeuvre components. However, commenting in general, the results such as illustrated in Figure 38 and Table 13 indicate that the pilots were able to apply a constant taudot strategy, at least for the constant rate phase of the manoeuvre components for all cases evaluated, where many of the slopes fitted to the tau data were close to one (i.e. supporting the case for a constant tau-guide model). This is supported by pilot comment to the extent that their general aim was to achieve a smooth and continuous change from one state to another (speed or height changes), as this presents the lowest workload, i.e. they can monitor and contain what is going on more easily.

As noted in the previous section, the fitted model parameter (constant tau guide) and correlation coefficient R^2 do not appear to be consistently correlated with visual condition. However, there is considerable variability in the results, which can be taken to indicate that the degraded visual cues did have a significant influence on the pilots' visual control strategy. The variability and trend of key manoeuvre parameters appear to be influenced by disturbance effects that interrupted the underlying constant taudot strategy. These disturbances were most likely due to inconsistent visual cues and control cross-couplings such as pitch-heave, roll-yaw etc., which caused strong interference effects between the control task elements (e.g. control of speed versus height), exacerbated for the Basic aircraft due to its poor stability characteristics. Discrete disturbances may also be the result of corrections applied in response to the instrument scan.

With these results in mind, at the outset of this investigation, it was noted that the exploratory nature of the work could possibly deliver some variability in the results. It was recognised that the relationship between the different forms of visual cues might be more complex than anticipated, and the ability to convert the levels of visibility degradation into the engineering, 'usable cue environment' (UCE), construct might be more challenging than expected. In the event, this seems to be the case and the application of tau analysis reported here has met with limited success. That is, the simple forms of models applied failed to identify a consistent, objective relationship between the degree of manoeuvre success (pilot workload and performance as represented by awarded HQR) and the level of degraded cues (simulated UCE). However, the results do support the case that the pilots were using tau information from the visual scene to enable them to control the aircraft in the manoeuvre cases evaluated.

Although the results clearly indicate that further work would be required in order to understand the full complexity of the tau guidance models applied, it is considered that the original premise for the work is still valid. Namely, that this approach can deliver a potentially high pay-off in the form of objective measures of UCE (i.e. the fitted tau model parameters) that are based on the fundamental relationship between the flight motion variables and optical variables input to the visual perception system. This will provide an improved understanding of the causal factors for accidents involving a loss of situation awareness by the pilot, and will support the development of design rules for pilot vision aids and the integration of vision and control augmentation. Furthermore, such objective measures could potentially be used to support the development of more 'intuitive' visual aids, which aim to take advantage of the natural skills and processes optimised in the human visual perception system.

4.3.5 Main findings

a) The results indicate that the pilots were following an intrinsic tau-guide model with constant taudot for all cases examined, including the relatively transient manoeuvre elements such as the roll in/out in the Turn and the heading change in the Hover Taxi.

b) The test manoeuvres comprise changes of state which have an initial acceleration phase, constant rate phase and final deceleration phase. The results indicate that three different tau strategies were applied for each of these phases, and that the constant taudot strategy was applied during the constant rate phase of the manoeuvre element for all cases evaluated. Detailed examination of the strategies applied during the acceleration and deceleration phases was not attempted as the MoD CRP research indicates that a more complex model than the simple taudot model described here would be required.

c) Examination of speed and height control in the Fly Away, Climb and Approach manoeuvres suggests that there is little evidence to show that the pilot was following a motion tau-coupling model.

d) There was significant variability in the tau data in many cases, most likely due to disturbances that interrupted the underlying constant taudot strategy. These disturbances probably resulted from inconsistent visual cues and control cross-couplings such as pitch-heave and roll-yaw, which caused strong interference effects between the task elements. These effects were more noted with the Basic configuration because of its inherent attitude instability.

e) Pilots were also able to apply the constant taudot strategy with the HDD turned off. However, without the HDD to provide datum state information, visual cues were too coarse/discrete to provide continuous support for the required visual control strategy, and pilots were generally unable to close on the targeted performance goals.

f) The cases analysed were treated as sequences of single axis control tasks. However, results from the CRP work, supported by the current findings, indicate that a multi-axis approach is required in order to achieve a good correlation between the level of task success and UCE.

g) Overall, it is considered that this application of tau analysis has met with limited success. Although it has failed to identify a consistent relationship between the degree of manoeuvre success and the level of degraded cues, the results do support the case that the pilots were using tau information from the visual scene to enable them to control the aircraft in the manoeuvre cases evaluated.

h) Further work would be required in order to understand the full complexity of the tau guidance models applied, but this approach could potentially deliver objective measures of UCE that would provide an improved understanding of the causal factors for accidents involving a loss of situation awareness by the pilot.

i) Such objective measures offer the potential for the development of design rules for more 'intuitive' visual aids, which aim to take advantage of the natural skills and processes optimised in the human visual perception system.

5 Review of civil regulations

5.1 Method

To conclude the Phase 2 work, the results from the simulation investigation and data analysis were compared with requirements from the civil regulations. To achieve this, a review of those civil regulations most pertinent to civil helicopter operations in degraded visual conditions was carried out. The objective was to identify any gaps or shortfalls, taking into consideration the earlier results and findings of Phases 1, 2/1 and 2/2, and make recommendations on how these might be addressed.

The documents reviewed included the following:

- *Joint Aviation Requirements JAR-27*[4] *(Small Rotorcraft)* and *29 (Large Rotorcraft)*.
- *Advisory Circulars AC 27-1B* and *AC 29-2C*.
- *ICAO ANNEX 14 Volume II Chapter 5 Visual Aids*.
- *ICAO ANNEX 6, Part III, Section 2, Chapter 3 Helicopter Performance Limitations*.
- *JAR-OPS 3 Subpart E All Weather Operations*.
- *JAR-OPS 3 Subpart E All Weather Operations – Acceptable Means of Compliance*.
- *JAR-OPS 3 Subpart K Instruments and Equipment*.
- *JAR-OPS 3 Subpart L Communication and Navigation Equipment*.

In addition, the CAA has issued a number of Flight Operations Department Communications (FODCOMs) in recent years which have endeavoured to address the problem of Public Transport/Commercial Air Transport helicopter accidents involving spatial disorientation. Those of most relevance to the research were taken into account by the review, and included the following:

- *CAA FODCOM 11/2001 VMC Public Transport Helicopter Flights at Night*.
- *CAA FODCOM 5/2002-1 Training and Checking Helicopter Night Qualification*.
- *CAA FODCOM 5/2002-2 Single Pilot VMC, unserviceable autopilot*.

The overall findings of the review are summarised in Appendix E and the principal points, including comparison with the study results, are summarised and discussed in the following sections.

5.2 Summary of main findings

The main points to arise from the review of the regulations are summarised below.

5.2.1 *JAR-27 and -29, Advisory Circulars AC 27-1B and AC 29-2C*

Subpart B – Flight Characteristics

JAR 27/29.141 General

- Civil regulations divide operations into either VFR or IFR categories, with no particular consideration given to DVE operations.
- No detailed requirements or explanatory material are given for night operations. It is considered desirable that further guidance be provided for operations in degraded visual conditions, both by day and by night.
- The AC should explain and develop the case for the consideration and application of the requirements to DVE operations.

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[4] It should be noted that JAR 27 and 29 have been renamed Certification Specification CS 27 and 29 following the formation of the European Aviation Safety Agency (EASA).

JAR 27/29.143 – 177

- In the accident cases considered, pilot workload was a key contributor driven by circumstantial factors such as vehicle stability, poor visual cues and division of attention. The JARs do not clearly address DVE and division of attention operations.
- The ADS-33 requirements for DVE, divided attention operations and UCE concept could help to deliver benefits to flight safety if applied to civil regulations.
- Flight Controls Mechanical Characteristics (FCMC) can have a direct impact on pilot workload, and it is considered appropriate to provide better guidance in the ACs on acceptable FCMCs for all civil operations to help eliminate configurations such as the EMOCUES2 Basic configuration.

Subpart D – Control Systems

JAR-27/29.671 – 695

- The clarity of this material could be improved by specifying the required handling qualities envelope in terms of desired levels of handling qualities as in ADS-33.

JAR-27/29 Appendix B Airworthiness Criteria for Helicopter Instrument Flight Paragraphs I – IX

- The EMOCUES2 ACAH configuration is likely to qualify for IFR operations, but the Basic configuration would be eliminated because of poor FCMCs and stability characteristics.
- Adoption of the JAR dynamic stability requirements for both VFR and IFR types would help to eliminate potentially accident-prone configurations such as Basic.

JAR-27/29.773 Pilot Compartment View

- The regulations do not address the need for an adequate visual reference for attitude cueing through the cockpit structure.

Subpart F – Equipment

JAR 27/29.1303 Flight and Navigation Instruments

- JAR-27 does not specify an attitude indicator for VFR operations, and it is considered desirable to amend the text so that an attitude indicator is required.

5.2.2 ***ICAO ANNEX 14 Volume II***

Annex 14 Volume II Chapter 5 Visual Aids

This document defines requirements for visual and approach aids for heliports.

- The requirements should provide greater clarity concerning the possibility of operations in DVEs.

5.2.3 ***ICAO ANNEX 6 PART III***

Annex 6 Part III Section 2, Chapter 3 Helicopter Performance Limitations

This document addresses operating conditions and minima for helicopters operating in performance Class 2 or 3.

- As with the JAR-OPS 3 requirements, the safety of operations will be dependent on factors such as the height that the aircraft is flying at and the available view over the nose of the aircraft. Hence, the comments given in the following section for JAR-OPS 3 are also applicable to this case.

5.2.4 *JAR-OPS 3 (Commercial Air Transportation (Helicopters))*

All Weather Operations

Parts 1 and 2 Sub-Part E

- The statistics indicate that accidents tend to occur to VFR operations en-route in unrestricted airspace when the operating conditions have deteriorated beyond those permitted under the rules.
- The continuing occurrence of accidents in unrestricted airspace suggests that the related requirements need to be reviewed and strengthened as necessary.
- For a given minima, the safety of operations will be dependent on factors such as the height that the aircraft is flying at and the available view over the nose of the aircraft. These considerations are not mentioned in the documentation.
- For example, at heights of 1000, 2000 or 3000 ft the look down angle for a minima of 800 m will be roughly 20, 40 and 50 deg respectively. With any degree of attenuation of the visual horizon, look down angles of more than 15-20 deg would mean that the pilot would be virtually flying on instruments due to lack of visual cues in the forward field of view.

Instruments and Equipment

Part 1 Sub-part K

- Small rotorcraft should also be required to be fitted with an attitude indicator to allow for inadvertent encounters with deteriorating visual conditions.
- IFR requirement for the chart holder should be extended to all operations at night.

Communication and Navigation Equipment

Part 1 Sub-Part L

- The regulations address the requirement for communications to provide appropriate navigation and meteorological information.
- Pilots can still become lost when navigating by visual references at night, even when such information is available. Hence, improved guidance and training for aircrew is needed to help prevent accident scenarios from developing.

5.2.5 *CAA FODCOMS 11/2001, 5/2002-1, 5/2002-2*

- FODCOMs address issues that are of general relevance to flight safety and have been issued principally for Public Transport operations. All three FODCOMs address issues that are of general relevance to flight safety in the case of an unexpected encounter with degraded visual cueing conditions en-route. Weather minima are specified to provide an operating margin so as to reduce the likelihood of occurrence of such situations, and the associated aircraft equipment fit and aircrew training requirements serve to mitigate the probability of an accident in the event that such encounters happen. In the case of an unexpected encounter with degraded visual cueing conditions en-route, the question of how to apply such measures more widely to all civil aircraft operations should be addressed.
- Other critical training issues that might be addressed more rigorously through such measures include transition from visual to instrument visual flight and divided attention operations when navigating by external references.

5.3 Comparison with previous study findings

This latest review of the regulations supports the findings from the earlier review of civil handling qualities requirements [13], that many of the requirements are too subjective and open to interpretation by manufacturers and qualification test pilots. In the follow-on decelerating approach to hover study [14], it was found that the ADS-33 attitude bandwidth and associated gust rejection criteria were applicable to that type of civil helicopter operation and, furthermore, provided a basis for flight test procedures to qualify aircraft types. The current study supports the case that the related criteria for DVE and divided attention operations [15] are similarly applicable to the civil helicopter operations under consideration.

By way of an example, if the Basic aircraft type from EMOCUES2 were to be formally assessed against ADS-33 criteria, then it might be expected that, by virtue of its response type, stability and control characteristics, it would be Level 2, Level 2-3 and Level 3 for UCE 1, 2 and 3 operations respectively. Correspondingly, because of its higher level of control augmentation and enhanced stability, the ACAH type would be Level 1, Level 1-2 and Level 2. The accident statistics show that it is likely that both aircraft types can encounter severely degraded visual conditions when operating VFR. In these situations, the pilot has to rely progressively on instruments as the visual conditions degrade, a situation where the Level 3 characteristics of the Basic type present a serious flight safety hazard, even for a pilot with a current IFR rating.

To reduce the probability of occurrence of accidents, it is considered that there is a need for criteria with appropriate qualification boundaries that will determine and eliminate potentially accident-prone configurations. Adoption of the JAR-27/29 dynamic stability requirements for all VFR types would be a step in the right direction.

The review of accident statistics demonstrated that, for both private and public transport operations, unexpected degradations of visual cues can and do occur for both night and day VMC operations, and are significant causal factors for civil helicopter accidents. In such cases, key factors include:

- Aircraft stabilisation and autopilot functions – lack of stabilisation, attitude-hold, or altitude and heading hold modes.
- Flight controls mechanical characteristics – inceptors without spring centring and trim functions.
- Navigation by visual references – loss of situational awareness.
- Pilot training – aircrew not rated for instrument flight.

The FODCOMS issued by CAA in recent years and the legislative changes introduced into ANO 2000, represent significant steps towards addressing these issues regarding public transport flights. There is now a need to review how these lessons can be applied more generally to both private and public transport flights.

6 Field of view study

6.1 Background

The field of view (FOV) study [10] was initiated at QinetiQ in 1995 by the CAA as part of its ongoing drive to improve standards of safety in civil helicopter operations; a copy of reference [10] can be found at Appendix F. Moreover, it was recognised that the visual scene and visual cueing become increasingly important considerations in maintaining safe operations as industry demand for low visibility operations increase.

The study noted that there are two main elements to the visual scene, its size (i.e. FOV) and its content (i.e. the available visual cueing), and its remit was to investigate FOV issues.

Three areas of investigation were covered including:

a) the extent of previous research in the area of visual cues for helicopter approach and landing;

b) collation of field of view data for a number of helicopters representative of the main types used in the UK; and

c) review and comparison of civil and military requirements.

With regard to the current study, the findings are of limited scope because the main focus of the FOV study was on the immediate take-off and landing phases of helicopter operations. However, it did raise some issues that are of more general applicability which are discussed in the following section.

6.2 Main findings

The conclusions reached as a result of the literature search and practical investigations are summarised below:

a) In good visibility conditions the basic FOV provided in helicopters does not seriously affect operational capability.

b) In many instances the actual FOV available to pilots is eroded by retrofitting additional equipment in the cockpit.

c) There are no minimum specifications for cockpit field of view in the civil industry, only advisory circulars showing acceptable methods for compliance with visual specifications (e.g. JARs).

d) If these methods of compliance were to be developed into a minimum specification and enforced, this would give a visual window (FOV) very similar to military aircraft and many of the associated problems would be solved.

e) During precipitation or in the presence of other contaminants, the wiper swept area becomes the only useable segment of the windscreen thereby significantly reducing the available field of view.

f) In low visibility situations, the view ahead of the helicopter becomes inadequate as pitch attitude changes are applied to perform the deceleration manoeuvre.

The principal message is that the basic FOV provision in civil helicopters is at least adequate for GVE operations provided that the AC guidance is followed. Nevertheless, it is clear that the regulations should be strengthened to make the advisory guidance mandatory, supported by limitations regarding the permissible encroachment on FOV of additional cockpit equipment.

Regarding the effects of precipitation (point (v)), it is perhaps surprising that this issue did not feature more prominently in the cases recorded in the MOR database as it is clear that for the type of scenario 2 and 3 cases that did feature, the pilots' difficulties would have been compounded by an obscured FOV. The study also concludes that external visual aids be developed to provide guidance in approach and landing operations that are tailored specifically to compensate for such circumstances. While this is supported, it is not immediately obvious how this approach could be extended to assist enroute and up and away operations.

Problems associated with pitch attitude changes in approach and landing manoeuvres are, however, of wider significance as evidenced by the problems encountered in the simulator noted in Section 3.3.5 and reference [8]. In addition, the points raised in Section 5.2.3 with regard to JAR-OPS 3 are also relevant. In this case, it is noted that acceptable visual minima should take account of factors such as aircraft height and associated view over the nose of the aircraft. The latter will also be adversely affected by aircraft (nose up) pitch attitude, and hence this is an additional factor that should be taken into account in determining acceptable minima.

7 Summarising discussion

7.1 General

The piloted simulation investigation demonstrated that, even without the use of flight instruments, a well-trained and capable pilot is able to continue to fly an aircraft with surprisingly little visual information. It should be noted, however, that pilot experience is inevitably a factor; both trials pilots were well qualified and experienced in VFR and IFR conditions. Significantly, though, as the visual cues degraded pilot workload did increase rapidly and the overall control strategy became more and more incoherent due to loss of situational awareness, with large error variations building in all axes (height, speed and heading). It is very likely that a less experienced, 'average' pilot would become disorientated and lose control under such conditions with the Basic configuration (i.e. a Scenario 3 situation).

With both aircraft types (Basic and ACAH) the pilot was able to stabilise and fly the aircraft, both with and without HDD, in straight and level and gentle manoeuvring flight, even in the most degraded scenarios tested. However, the results show that in such situations the probability of loss of control can increase if the pilot attempts to continue to navigate by visual references and gives insufficient attention to flight instruments, with subsequent loss of awareness of aircraft state. With the Basic aircraft, if speed was lost inadvertently or more moderate manoeuvres attempted, its inherent lack of stability gave rise to very high pilot workload and potential loss of control. This was not the case with ACAH, however, underlining the significant safety benefits of this configuration.

As noted above, the results illustrate the dangers associated with navigating by visual references in potential DVE situations. Loss of pilot situational awareness in relation to the navigation task can become a severe distraction from the attitude stabilisation and flight path guidance tasks, with inherent risks to flight safety. The case is argued that ACAH response types would help to minimise this risk by reducing the effort required for closed-loop stabilisation, allowing the pilot to concentrate on flight path guidance and navigation.

The visual scenarios evaluated during the trials demonstrated the way in which visual cueing conditions can vary significantly between the extremes of VMC and IMC, and the impact that this can have on the piloting task. The scenarios were based on the UCE concept introduced in ADS-33 and, in the following sections, a conceptual framework is presented which demonstrates the link between the assessed visual conditions and vehicle handling qualities. The case is made that this concept could be used to provide a framework within the civil regulations for guidance on attitude stabilisation, autopilot hold modes and FCMC requirements for DVE operations.

7.2 Conceptual application of results

Figure 40 illustrates the way in which the trial results shown in Figure 15 could be used as the basis for a conceptual framework onto which specific types of regulatory advice might be mapped concerning, for example, requirements for handling qualities, operational constraints, navigation aids and training. In this case aircraft configuration (i.e. level of attitude stabilisation), including ACAH, Rate Command (RC) and Unstabilised types, is shown along the X-axis. Section 4 discussed how objective measures of UCE might be determined potentially through correlation with the fitted model parameters determined using image and tau analysis. Hence, UCE is shown on the Y-axis, together with a normalised scale to represent either image or tau model metrics and, in this conceptual form, this scale is intended to represent UCE as derived from the prediction models. The UCE is shown linked to three categories of operations, VFR, DVE and IFR, and the figure illustrates what levels of handling qualities might be expected (taking account of ADS-33 criteria) for the three aircraft types for these types of operation and levels of UCE.

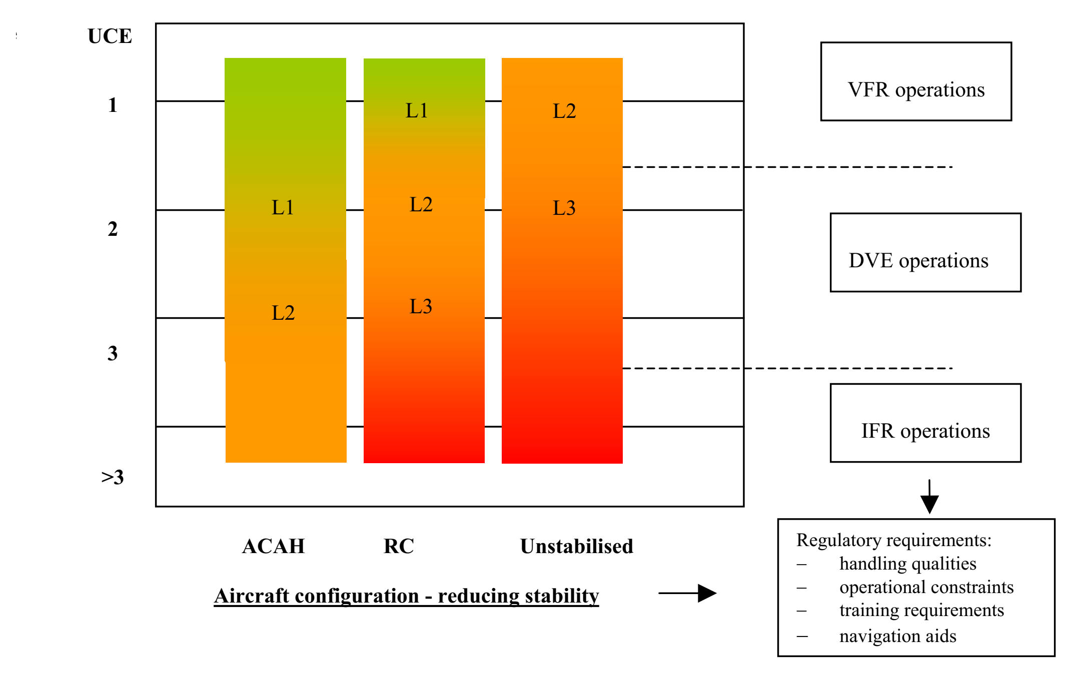

Figure 40 Conceptual framework for regulatory requirements

The purpose of this conceptual framework is to illustrate the strong inter-dependency between handling qualities and visual cues and the way that these impact civil operations and requirements and, ultimately, flight safety. In effect, the colour shading in the figures can be treated as a safety index for the aircraft type and the flight operations undertaken; red denotes the limiting case for permissible operations, amber a cautionary level with, perhaps, some appropriate operational constraints for speed, height and visual range, and green for unconstrained operations. These results support the case that the ADS-33 UCE and associated response type criteria [15] provide the basis for safer operations in the DVE and, specifically, that the ACAH response type is essential for these operations.

ADS-33 makes the point that control augmentation is essential to providing good handling in degraded visibility so that operations in the DVE can be conducted without compromising safety. To reinforce this, Figure 41 shows the original ADS-33 UCE data from which the Response Type/Handling Qualities relationships were derived, re-analysed in terms of the risk to flight safety when flying in the DVE with different response types [18]. The lines on Figure 41 show data trends for RC and ACAH response type aircraft as a function of visual cue rating. The attentional demand (AD) is derived from the handling qualities ratings (HQRs) and represents the percentage of the pilot’s workload capacity devoted to flight guidance and stabilisation. The riskrelates to the likelihood that poor handling qualities (and the associated high pilot workload) will lead to an accident. The data suggest that with a RC helicopter that is Level 1 in the GVE, the risk will increase from low to high as the UCE degrades from 1 to 2, with the attentional demands of flight control increasing from 30% to 60%. The ACAH helicopter, with Height Hold (HH), is also Level 1 (HQR = 3) in the GVE, but the risk remains low as the DVE degrades to UCE 2. Note ADS33 postulates that both RC and ACAH response types will provide Level 1 handling qualities in the GVE provided that the characteristics of the responses (e.g. bandwidth, control power) meet the criteria defined in ADS33. For comparison, a degraded Level 2_{GVE} RC response is shown on Figure 41 ($HQR_{GVE} = 4$), which induces additional attentional demand in GVE and DVE compared with the Level 1_{GVE} RC case, ($HQR_{GVE} = 3$).

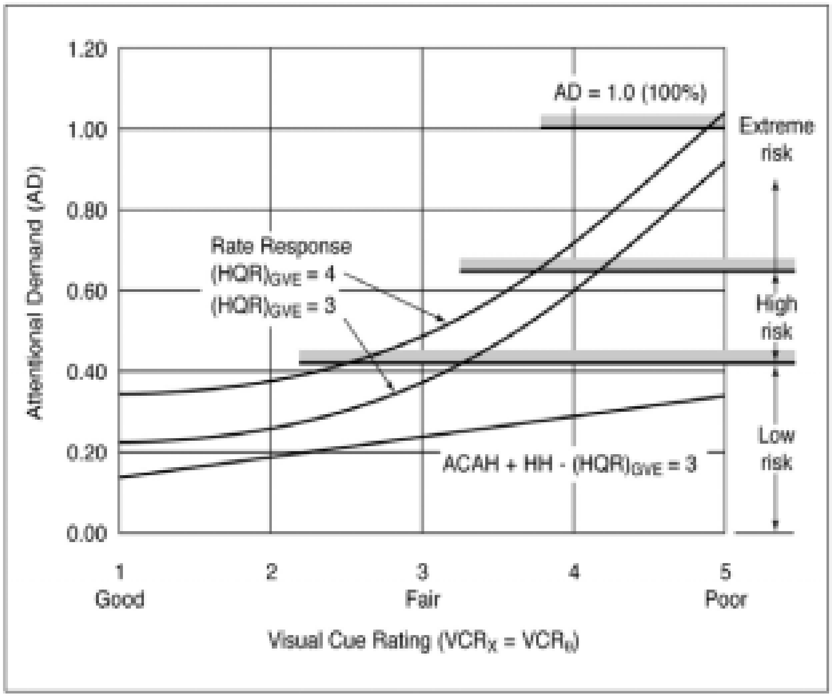

Figure 41 Relationship between Workload (attentional demand) and Visual Cue Ratings

At the heart of the argument for ACAH response types is the reduced workload they confer, which minimizes the effort required for closed-loop stabilisation and frees critical pilot attention for the outer loop guidance and navigation. ACAH does not stop the aircraft colliding with obstacles or the ground, but it does enable the pilot to concentrate on this guidance aspect of the flight.

7.3 The way ahead

The review of accident data has highlighted the significant numbers of accidents that have occurred involving fatalities where degraded visual cues were the primary causal factor, resulting in loss of situational awareness and spatial disorientation, i.e. Scenario 2 and 3 cases. Furthermore, analysis of the data indicates an increase in the number of accidents resulting from spatial disorientation in a DVE, despite recent advances in aircraft and equipment design or the mitigation measures adopted by the regulatory authorities. Between them, the Scenario 2 and 3 cases form the single largest cause of small helicopter fatal accidents, a reflection of the severe consequences of accidents involving CFIT or spatial disorientation.

It is clear that serious consideration must be given to the measures that need to be taken to reverse this trend. Moreover, it is considered that the crux of the problem of how to prevent accidents in degraded visual conditions is related to the way in which the civil requirements are polarised into IFR versus VFR categories, and the failure to address operations in the DVE, including the case of IIMC. Changing the operational requirements through FODCOM releases is essentially endeavouring to apply a retrospective fix for deficiencies in the JAR requirements. In effect, the two

EMOCUES2 configurations may be categorised as IFR and VFR qualified types and, not surprisingly, the IFR type (ACAH) fared better in the DVE evaluations.

The message is clear: if the regulations were to ensure that the aircraft is adequately equipped for DVE operations and that aircrew have received adequate training, the probability of accidents would reduce. Specifically, general adoption of the IFR rules for all types (i.e. equivalent to adopting the ADS-33 control augmentation and response type criteria for UCE 2-3) would significantly enhance flight safety for civil rotorcraft operations. However, it is recognised that unless the cost of equipping and qualifying IFR types were to reduce significantly, it is very unlikely that such changes would be accepted by the Industry. That being the case, other less radical solutions are given consideration in the following.

From the results presented in this report, including the review of the current regulations, there are a number of possible steps that might be taken as a package of measures to approach the problem.

a) The first of these is to consider what steps could be taken to tighten the existing regulations to take account of DVE conditions, which could include:

   i) Application of the IFR dynamic stability requirements as a general requirement for all operations, including VFR;

   ii) Introduction of appropriate requirements (or guidance) on criteria for DVE operations (based on consideration, but not full adoption, of all IFR requirements), including all night operations and operations in visual ranges of less than a specified [to be determined] minima;

   iii) Introduction of appropriate requirements (or guidance) on criteria for FCMCs;

   iv) Introduction of a general requirement for an attitude indicator flight instrument for all operations, including VFR.

   v) As discussed briefly in Sections 2 and 3, consideration should be given to the development of improved forms of instrumentation displays to cater for the IIMC case.

   Regarding the ‘specified minima’ noted above, as discussed in the review of regulations (Section 5.2.3), factors such as the height that the aircraft is permitted to fly at versus the available view over the nose of the aircraft should be taken into consideration when determining appropriate values. That is, simple geometry dictates that for a given cockpit view and permitted operating minima, the pilot’s view over the aircraft’s nose will diminish with increasing aircraft height. Look down angles of more than 15-20 deg (i.e. for heights greater than about 1000 ft) would impose severe restrictions on the available visual cues in the forward field of view.

b) Secondly, the FODCOM training requirements could be more generally adopted for all civil helicopter operations that fall into the DVE category specified above, i.e. all night operations and operations in ‘advised’ minima. For example, training could be provided to improve pilot awareness of divided attention operations when navigating by external references. Similarly, it would help mitigate the IIMC case if all pilots were to be trained in recovery from visual to instrument flight. There is also a more general need to raise pilot awareness of the problems associated with operations in the DVE and, in particular, the interaction between vehicle handling qualities and visual cueing conditions.

c) The third measure would be to endeavour to reduce the probability of pilots encountering DVE conditions, and particularly IIMC, by providing guidance on how to recognise potential DVE situations. It is possible that a simple probability index could be defined based on consideration of those factors that contribute to a high risk accident scenario, for example:

i) meteorological conditions (precipitation, cloud base etc.),

ii) visual conditions (time of day, fog/mist/haze conditions, visual range, acuity of the visual horizon etc.),

iii) aircraft configuration (navigation aids, flight instruments etc.),

iv) aircraft handling qualities (SAS, FCMCs).

Such an index could provide information to help pilots to make informed decisions on whether ‘to fly or not’ in marginal conditions, or when IMC conditions are developing enroute. The latter may be the result of reducing visibility or the fact that, despite good visual range (e.g. ≥1.5 km), the visual cues are inadequate to support flight by visual references (e.g. over the sea or remote moorland at night). Guidance in such cases could be supported by use of digital images of typical operating conditions such as the various visual images of the UCE conditions used from the simulator trial to perform the image analysis work (Section 4.2). This would relate the findings of the latter to practical visual scenarios.

8 Summary and Conclusions

8.1 Ego-motion and Optical Cues programme

A programme of research has been completed by QinetiQ for the CAA in collaboration with a MoD CRP study into how pilots use visual cues in the process of helicopter flight guidance and stabilisation. For the CAA, the aim was to identify and endeavour to mitigate the causal factors associated with accidents involving civil helicopter operations in degraded visual cueing conditions, such as aircrew loss of situational awareness, spatial disorientation and controlled flight into terrain.

In the initial phase of work, a review of accident statistics covering the period from 1975 to 2004 was carried out using the CAA's MORS database. The aim was to identify cases where loss of pilot situational awareness and spatial disorientation were primary causal factors. It was found that there has been a continuing incidence of such accidents, involving both private and public transport helicopter operations during this period. A primary set of 53 Scenario 2 (CFIT) and 3 (spatial disorientation) accidents and 1 Scenario 1 (obstacle/terrain strikes in low level flight) case was identified where degraded visual cues, poor pilot situational awareness and/or spatial disorientation were the primary causal factors. Between them, these accidents involved a total of 100 fatalities. Of note, Scenario 2 and 3 cases together form the single largest cause of small helicopter fatal accidents. Total occurrences per year increased over the period from 1975 to 2004 from 1 per year to approximately 2.5. From the mid-1990s onwards, the average number of Scenario 3 cases (1-2 cases) overtakes the number of Scenario 2 cases, which remains relatively constant at 1 per year. This result indicates an increase in the number of accidents resulting from spatial disorientation in a DVE. A detailed case study exercise (Section 2.3) was carried out on a sub-set of seven cases selected from the primary set, which was based on source material taken from appropriate AAIB reports and bulletins. Overall findings for this activity are given in Section 2.5.

In follow-on piloted simulation experiments using QinetiQ's RTAVS simulator, two test pilots evaluated a matrix of manoeuvres and visual conditions that was based on the details extracted from the sub-set of accident case studies. The experiments were designed specifically to investigate the applicability of the ADS-33 UCE concept and response type criteria to civil operations. The trial met its objectives and was successful in demonstrating how pilot situational awareness can be eroded in VFR operations as visual conditions degrade, a key factor being the division of attention between the attitude stabilisation, flight path guidance and navigation tasks. Overall findings for this activity are given in Sections 3.6 and 3.7.

Data from the simulation experiments were subjected to deeper examination by applying two special analytical procedures, image analysis and tau analysis, which had been developed under the MoD CRP programme. The objective was to investigate how pilot control strategy, task performance, workload, and ultimately flight path safety were influenced by the UCE. For image analysis, the application of a prediction model based on image metrics was successfully demonstrated as a means of predicting pilot's HQRs, VCRs and UCE. Tau analysis was used to demonstrate successfully the applicability of the intrinsic tau-guide model (with taudot constant) to the test cases evaluated in EMOCUES2. Results from examination of the motion tau-coupling model showed that, in general, there was no firm evidence of a tau coupling between speed and height in the Fly Away, Climb and Approach manoeuvres. Overall findings for these activities are given in Sections 4.2.6 and 4.3.4.

A review of civil regulations has also been carried out where the aim was to identify any deficiencies and omissions concerning DVE operations, taking account of the results and findings from the earlier research activities. Documents reviewed included JAR-27/-29 and ACs, the relevant parts of JAR-OPS 3 and ICAO Annexes 6 and 14 and various CAA FODCOMS. The overall findings of this activity are summarised in Section 5.2.

The findings of an earlier field of view (FOV) study carried out in 1995 by QinetiQ for the CAA were also taken into consideration. The purpose of the study was to examine the influence of issues concerning the visual scene and visual cueing on safety for low visibility operations. Three areas were covered by the study including: previous research concerning visual cues for helicopter approach and landing; field of view data for representative types of helicopters used in the UK; review and comparison of civil and military requirements. It was found that with regard to the current study, the findings are of limited scope because their main focus is on the immediate take-off and landing phases of operations. However, those issues that were found to be of more general applicability are summarised in Section 6.2.

In Section 7, the overall findings of the review have been discussed and measures identified which may help to reduce the likelihood of civil helicopter accidents in conditions of poor visibility. The discussion has taken into account the findings of an earlier CAA sponsored review of pilot FOV issues. A conceptual framework is also presented which illustrates the strong inter-dependency between handling qualities and visual cues, and the way that these impact civil operations and requirements and, ultimately, flight safety. The mapping of the EMOCUES2 trials results onto this framework supports the case that the ADS-33 UCE and associated response type criteria provide the basis for safer operations in the DVE and, specifically, that the ACAH response type is essential for these types of operations.

Conclusions on the overall programme and its activities are summarised in the following section.

8.2 Overall findings

8.2.1 Accident data

a) A primary set of 53 Scenario 2 and 3 accidents and 1 scenario 1 case was identified where degraded visual cues, poor pilot situational awareness and/or spatial disorientation were the primary causal factors.

b) These Scenario 2 and 3 accidents involved a total of 100 fatalities. And together form the single largest cause of small helicopter fatal accidents.

c) Total occurrences per year over the period from 1975 to 2004 increase from 1 per year to approximately 2.5, largely due to increasing numbers of accidents resulting from spatial disorientation in a DVE, i.e. Scenario 3 cases.

d) During the period 2000-2004 there were 4 fatal accidents involving private flights, representing 50% of the relevant private cases identified and resulting in 8 fatalities. They all involved spatial disorientation as a probable causal factor (Scenario 3 cases).

e) Serious consideration must be given to the measures that need to be taken to reverse this trend, taking into account improvements to regulations, operating procedures and requirements or pilot training requirements.

8.2.2 Simulator investigations

a) A conceptual framework has been presented, which illustrates the strong inter-dependency between visual scene and handling qualities as represented by level of UCE and handling qualities according to ADS-33 Level 1, 2, 3 criteria.

b) The way in which the framework can be linked to civil requirements for handling qualities, operational constraints, training and navigation aids has also been illustrated. HQR evaluations from EMOCUES2 show good correlation, qualitatively, with the conceptual case for both the ACAH and Basic configurations.

c) The underlying argument on which the framework is based is that ACAH response types confer reduced workload, which minimises the effort required for closed-loop stabilisation. This frees critical attention to enable the pilot to concentrate on the guidance aspect of flight management.

d) Regarding stability, types similar to Basic are likely to be Level 2, Level 2-3 and Level 3 for UCE 1, 2 and 3 operations respectively, but ACAH would be Level 1, Level 1-2 and Level 2.

e) The Level 3 characteristics of the Basic type are likely to present a serious flight safety hazard in DVE situations such as IIMC.

f) Associated handling problems will be exacerbated by poor/inappropriate FCMCs. Hence, the impact of FCMCs on pilot workload should be taken into account, and better guidance is needed concerning acceptable FCMCs for all civil operations.

g) The results support the case that adoption of the ADS-33 UCE and associated response type criteria would lead to significant safety benefits for civil helicopter operations in the DVE and, specifically, that the ACAH response type should be mandatory for DVE operations.

8.2.3 Civil regulations and requirements

a) Civil regulations and requirements in the area of handling qualities are very subjective and open to interpretation by manufacturers and qualification test pilots.

b) The regulations divide operations into either VFR or IFR categories, with no consideration given to DVE operations, e.g. there are no detailed requirements or guidance given for night operations.

c) In the accident cases considered pilot workload was a key contributor, driven by circumstantial factors such as vehicle stability, poor visual cues and division of attention. The JARs do not clearly address DVE or division of attention operations, suggesting that greater clarity is required concerning the possibility of such circumstances.

d) There is a need for objective criteria with appropriate qualification boundaries that will determine and eliminate potentially accident-prone configurations such as Basic; adoption of the JAR dynamic stability requirements for both VFR and IFR types would meet this need.

e) Military criteria such as the ADS-33 attitude bandwidth and associated gust rejection criteria, and the related criteria for DVE (response type versus UCE) and divided attention operations could provide advisory material to improve JARs.

f) JAR-27 does not specify an attitude indicator for VFR operations; small rotorcraft should be required to be fitted with an attitude indicator to allow for inadvertent encounters with DVE conditions.

g) The JAR-OPS 3 requirement for the chart holder for IFR operations should be extended to all operations at night.

8.2.4 Aircraft and equipment design issues

a) The regulations do not address the need for an adequate visual reference for attitude cueing through the cockpit structure; this is essential for operations in poor visual conditions.

b) The advisory guidance concerning cockpit FOV should be made mandatory, supported by limitations regarding the permissible encroachment on FOV of additional cockpit equipment.

c) Consideration should be given to the development of improved forms of instrumentation displays to cater for the IIMC case.

8.2.5 Operational issues

a) Statistics based on the CAA's MORS database indicate that accidents tend to occur for VFR operations en-route in unrestricted airspace; this suggests that requirements (minima) need to be reviewed and strengthened as necessary.

b) When addressing requirements for visibility minima, factors such as the height that the aircraft should be permitted to fly at versus the available view over the nose of the aircraft should be taken into consideration. For a given cockpit view, the pilot's forward view diminishes with increasing aircraft height, and look down angles associated with heights of greater than 1000 ft (i.e. greater than 15-20 deg) would impose severe restrictions on the available visual cues. The likely effect of aircraft pitch attitude on pilot view should also be taken into account.

8.2.6 Pilot training issues

a) The regulations address requirements for communications to provide appropriate navigation and meteorological information, but pilots still become lost when navigating by visual references at night. Improved guidance and training for aircrew is needed.

b) FODCOMs attempt to address issues such as those noted at x) and y), but such measures need to be more widely applied to all civil aircraft operations. Critical training issues that might be addressed more rigorously through such measures include: recovery from visual to instrument visual flight and divided attention operations when navigating by external references.

c) Pilots should be better trained to make informed decisions on whether 'to fly or not' in marginal conditions, or when IMC conditions are developing enroute. This might be achieved by developing a probability index based on factors that contribute to a high risk accident scenario (e.g. meteorological conditions, visual conditions, visual range, acuity of the visual horizon, aircraft configuration, aircraft handling qualities).

d) IIMC can occur due to reduced visibility and/or an insufficiency of visual cues to support flight by visual references, e.g. over the sea or remote moorland at night. Pilot training and awareness for such cases could be supported by use of digital images of typical operating conditions such as the various visual images of the UCE conditions used from the simulator trial to perform the image analysis work. This would relate the findings of the latter to practical visual scenarios.

8.3 Concluding remarks

Helicopters are difficult to fly at the best of times, i.e. in good visual conditions with plenty of outside world references and with stability augmentation. In such circumstances a pilot is able to use the optical parameter tau, the time to contact, to guide motion control, adopting what the proponents of tau-guidance theory suggest is the most natural form of perception to maintain adequate safety margins. As visual conditions degrade, control becomes complicated (workload increases) by the interaction between stabilisation and guidance functions, and it becomes more difficult for the pilot to utilise tau cues coherently.

The results of these simulator investigations have highlighted just how precarious the balance between performance and safety is, and how small the safety margin can get, as visual conditions degrade. The accidents reviewed [7] also reflect this precariousness and the vulnerability of the 'average' pilot to the consequences of loss of spatial awareness. Hence, it is of concern that analysis of the data shows that the number of accidents resulting from spatial disorientation in a DVE is increasing, and that between them, the Scenario 2 and 3 cases form the single largest cause of small helicopter fatal accidents. As noted previously, it is clear that timely consideration must be given to the measures that need to be taken to reverse this trend, including the recommendations given in the following section.

9 Recommendations

Taking account of the foregoing conclusions, the following recommendations are offered:

a) Introduction of the IFR dynamic stability requirements as a general requirement for all operations, including VFR.

b) Introduction of appropriate requirements (or guidance) on criteria for DVE operations, based on consideration, but not full adoption, of all IFR requirements for:

   i) Night operations.

   ii) Operations in visual ranges of less than a 'specified' minima, which takes account of permitted aircraft height and associated view over the nose. Look down angles associated with heights of greater than 1000 ft (i.e. greater than 15-20 deg) would impose severe restrictions on the available visual cues.

c) Introduction of specific requirements (or guidance) on criteria for FCMCs.

d) Introduce a requirement for an attitude indicator flight instrument for all operations, including VFR.

e) Specification and adoption of FODCOM training requirements for all civil helicopter operations that fall into the DVE category specified at (2).

f) Appropriate steps should be taken to raise pilot awareness of the problems associated with operations in the DVE, i.e. the interaction between vehicle handling qualities and visual cueing conditions.

g) Address the probability of pilots encountering DVE conditions by providing guidance on whether 'to fly or not' in marginal conditions with the potential for DVE encounters. This could be achieved using a simple probability index based on consideration of those factors that contribute to a high risk accident scenario, including:

   i) meteorological conditions (precipitation, cloud base etc.),

   ii) visual conditions (time of day, fog/mist/haze conditions, visual range, acuity of the visual horizon etc.),

   iii) aircraft configuration (navigation aids, flight instruments, cockpit view and layout etc.),

   iv) aircraft handling qualities (SAS, FCMCs).

h) Pilot training and awareness should be supported by use of digital images of typical operating conditions such as the various visual images of the UCE conditions used from the simulator trial to perform the image analysis work. This would relate the findings of the latter to practical visual scenarios.

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11 Abbreviations

AAIB	Air Accidents Investigation Branch
AC	Advisory Circular
ACAH	Attitude Command Attitude Hold
ADS-33	Aeronautical Design Standard 33
AGL	Above Ground Level
ANO	Air Navigation Order
CFIT	Controlled Flight Into Terrain
CRP	Corporate Research Programme
CS	Certification Specification
DVE	Degraded Visual Environment
EMO	Ego Motion and Optical
EMOCUES	Ego Motion and Optical Cues (Trial name)
FCMCs	Flight Controls Mechanical Characteristics
FODCOM	Flight Operations Department Communication
GVE	Good Visual Environment
HDD	Head Down Displays
HQR	Handling Qualities Rating
HUD	Head Up Display
ICQ	In-Cockpit Questionnaire
IFR	Instrument Flight Rules
IIMC	Inadvertent [entry into] Instrument Meteorological Conditions
JARs	Joint Aviation Requirements
L1	Level 1 – Cooper-Harper handing qualities ratings 1 to 3
L2	Level 2 – Cooper-Harper handing qualities ratings 4 to 6
L3	Level 3 – Cooper-Harper handing qualities ratings 7 to 9
MORS	Mandatory Occurrence Reporting System
OTW	Out The Window
OVCs	Outside Visual Cues
RC	Rate Command
RTAVS	Real Time All Vehicle Simulator
SAS	Stability Augmentation System
TRC	Translational Rate Command
UCE	Useable Cue Environment
VCR	Visual Cue Rating
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

12 Glossary of terms

D	Image clutter uniformity
k	Image smoothness
α	Image clutter density
β	Image clutter strength
y	Threshold value
N_y	Number of edges exceeding the threshold value, y
sd	Standard deviation
X	Horizontal displacement
$\dot{X}$	Horizontal velocity
$\ddot{X}$	Horizontal acceleration
θ	Elevation angle
$\dot{\theta}$	Rate of change of elevation angle
τ	Instantaneous time to contact or encounter
$\dot{\tau}$	Rate of change of τ
τ_g	Intrinsic tau guide
τ_m	Generic motion tau
τ_h	Height motion tau
τ_v	Velocity motion tau
τ_θ	Roll attitude motion tau
τ_ψ	Heading motion tau
k_g	Gradient of τ_g over time T, $\dot{\tau}_g$ constant
k_m	Gradient of τ_m over time T, $\dot{\tau}_m$ constant

Appendix A Detailed Accident Case Studies

1 Case 1 (SA355/199604787)

1.1 Synopsis

1.1.1 **Overview**: The aircraft was en-route with one pilot plus four passengers on-board. The flight was carried out at night in visual contact with the ground, and the accident occurred during the execution of a climb to a higher altitude. During the climb, the pilot was deprived of external visual references, the aircraft entered an unintentional steep, nose-up attitude and lost airspeed. This manoeuvre developed subsequently into a fast, spiral descent from which the aircraft did not recover; it crashed into a field and all occupants were killed.

1.1.2 **Background**: The aircraft was twin-engined certified for single pilot operations. It was restricted to VFR operations because it had no auto-pilot/auto-stabilisation equipment, the cyclic stick did not have force trimming or spring centring, and it did not have a flight director, only an artificial horizon, altimeter and ASI. Hence, the flight was conducted under special flight rules for VFR within controlled airspace, which provide a dispensation 'to operate an IFR flight in similar way as day VFR by remaining in visual contact with the terrain'. The pilot, who was not instrument flight rated, was responsible for navigating the aircraft and maintaining clearance from weather and terrain, but received advisory heading information from local radar control. The weather was reported as fine with good visibility with winds of around 10 kn. Natural light levels were in accordance with the time of day (2150 hrs) and there was an 83% moon. There was a broken cloud layer with a base of 1200 ft and tops at 1500 ft agl, and an upper layer of broken cloud with base at 2-2,500 ft and tops at 3,500 ft. Visibility below cloud was 10 km. The AAIB report concluded that the weather conditions were regarded as acceptable for the flight in relation to visibility, cloud and terrain separation.

1.1.3 **Accident details**: Prior to the accident, the flight was conducted at a cruise speed of around 100 kn and at a height just below the lower layer of cloud. Several course changes were made for navigational purposes, with advisory direction from the radar controller, in order to maintain a 'minimum safe en-route altitude' (MSA). The aircraft did not follow the planned route and encountered cloud conditions that would have compromised the MSA. The pilot elected to climb from 1600 ft to 3000 ft in order to ensure clearance of local high ground (elevation circa 1200 ft amsl); the AAIB report surmised that he elected to do this through a break in the clouds. Radar returns show that the aircraft commenced a climb through some 1000 ft but that the airspeed reduced to below 50 kn for about 25 s, to a minimum of 30 kn around the apogee. At around this point the pilot reported that he had entered inadvertent IMC and thought that the aircraft was descending, although ground-based observers of the accident subsequently reported that the aircraft did not enter cloud. The radar plot shows that the aircraft subsequently entered a dive with what is described as an erratic flight path.

1.1.4 **AAIB analysis**: Analysis of the accident identified a number of factors that may have influenced the situation. Firstly, although there was good visibility, because of the cloud cover and the lack of background lighting from the sparsely lit rural locality, the visual horizon was poorly defined. This would have created difficulty in discerning aircraft pitch attitude and bank angle using only the outside visual scene. The pilot's workload would have been high due to the demands of flying the aircraft, together with the navigation and communications tasks. This may have resulted in the aircraft being off the intended track and below the MSA and subsequent encounter with a heavier cloud layer. During the climb, it is surmised that the aircraft achieved an excessive nose up attitude, which lead to loss of speed and of visual references, and in the pilot becoming spatially disorientated. Paraphrasing from the AAIB report, '…Given the aircraft's sensitivity in pitch and lack of cyclic stick force feedback cues, it is entirely possible that the stick was moved aft to initiate the climb, but the pilot failed to stabilise the required climb angle. The aircraft could have continued pitching upwards, with airspeed reducing and no feedback cues to the pilot, other than that given by the attitude instruments. The source of disorientation would arise from the difference between the pilot's mental sensation and expectation of the attitude condition and the indicated attitude indicator reading…'.

1.1.5 **Visual cueing aspects**: From subsequent flight tests carried out by the AAIB in the locality of the crash site, under night conditions with excellent visibility, no cloud and a full moon, it was ascertained that the following visual cueing factors would have played a role in the accident:

- After astronomical twilight there may be no true horizon.
- Minor terrain features could not be seen from the air from 1500-2000 ft above ground level.
- Optical perception of the horizon plane is provided by an illuminated ground plane.
- Unlit features such as rivers and roads were hard to see and follow and motorways provide the best line features.
- The vicinity was unexpectedly dark because of the limited artificial lighting outside of towns.

1.2 Relevant causal factors and conclusions

- The pilot's workload in marginal conditions was excessive.
- The pilot probably lacked recent experience of recovering the helicopter from an unusual attitude using flight instruments.
- The pilot was unable to control the aircraft by sole reference to flight instruments when external references were lost.
- The helicopter had no autopilot or autostabilisation equipment and was not approved for IMC operations.
- The flight had to operate below an overcast cloud layer, which was below the MSA.
- The flight had to avoid obstacles by detouring around them.
- The weather conditions were acceptable for attempting the flight.
- The lack of visual horizon was likely to become a problem where the cloud cover was overcast and the ground lighting was sparse.
- Immediately prior to the accident, the aircraft was in view of the ground and did not enter cloud.
- The helicopter adopted a steep, nose-up pitch attitude during the climb, during which the speed fell from 105 to 33 kn in 30 s.
- The excessive pitch attitude deprived the pilot of visual ground references and he subsequently became disorientated through losing external attitude references.
- Safe recovery from unusual attitudes depended on the pilot's instrument flying skills.

- The pilot was probably not looking for visual references at the time they became available during the later stages of recovery, and he was probably still disorientated when the aircraft struck the ground.
- Current regulations governing VMC flight at night do not require the existence of a visible true horizon and there is no method of predicting its existence.

2 Case 2 (SA355/199805910)

2.1 Synopsis

2.1.1 **Overview**: The aircraft was involved in police air support operations (PAS), with one pilot plus two observers on-board. The flight was planned as a night flight in visual contact with the ground and the accident occurred during take-off and transition from the air support unit's landing pad. During the transition, the aircraft encountered a bank of fog, which rapidly deprived the pilot of external visual references. He attempted to recover the aircraft using flight instruments but the aircraft crashed following contact with trees near to the pad; the aircraft was subsequently destroyed and one observer killed.

2.1.2 **Background**: The aircraft was twin-engined certified for single pilot operations and was fitted with auto-pilot/auto-stabilisation equipment. It had standard flight instruments including an artificial horizon indicator, altimeter, compass and ASI; subsequent AIB investigations revealed that the main attitude indicator lighting was sub-standard and made the instrument more difficult to read than normal. Pilots involved in PAS operations are not required to have an instrument flight rating, but have to maintain an instrument capability to allow for sudden and inadvertent IMC. This entails a six-monthly system of check flights involving flight by sole reference to instruments, and includes recovery from unusual attitudes and high power/low speed situations. The weather was reported as fine with good visibility (up to 10 km) with low winds of around 5 kn; the pilot noted that the sky was clear above the landing pad and that stars were visible. Natural light levels were in accordance with the time of day (2305 hrs). However, the AAIB report noted that conditions were conducive to the formation of mist and fog.

2.1.3 **Accident details**: The pilot took-off from the pad and climbed the aircraft to a low hover. He then initiated the standard procedure for a visual departure from the pad, which involved a transition to forward flight and a gentle turn to the right to head for open ground. At an estimated height of around 30-35 ft and speed of 20-25 kn the aircraft suddenly entered a bank of fog. The pilot attempted to continue flight through reference to flight instruments. He made cyclic and pedal corrections for bank and side-slip excursions to maintain wings level, balanced flight, and applied full power (maximum torque demanded). However, he reported that the aircraft felt out of balance; this was probably because the aircraft continued to yaw throughout the transition. The pilot made no mention of reference to the compass in his post-accident report. After an estimated 10-12 seconds into the transition, the aircraft struck trees and subsequently crashed.

2.1.4 **AAIB analysis**: The AAIB report concluded that the pilot became disorientated because of sudden and unexpected loss of external visual cues. In this situation, it is likely that it would have taken longer to achieve an 'orderly transition to flight by sole reference to instruments'. The difficulty may have been increased by the additional effort required to read the main AI. It was further concluded that the pilot probably never became fully established on flight instruments and did not detect changes to aircraft motion, the yaw acceleration in particular. These factors would have created uncertainty as to the aircraft's position until impact with the trees. It was also noted that, because of increased instability effects and the need for reliance on external visual references, IFR approval is prohibited for hover and low speed flight. For this aircraft, the minimum IFR airspeed was 55 kn. Hence, the circumstances encountered would have resulted in high pilot workload, the problem being compounded by the need to transition from visual to flight using instruments.

2.1.5 **Visual cueing aspects**: The most significant factor was the sudden loss of all external visual references and the time needed to transition from visual to instrument flight. From the point of encounter with the fog to contact with the trees, continued flight was only possible using flight instruments. In these circumstances, the pilot had no external visual references to warn him of the aircraft's continued change of heading.

2.2 Relevant causal factors and conclusions

- The pilot was in current flying practice for night flying and had received instrument flight training, including recovery from unusual attitudes.
- The pilot expected that he would be able to complete a visual transition and departure from the pad.
- A bank of fog was encountered which gave rise to a sudden and unexpected loss of external visual references.
- The sudden loss of visual references probably extended the time taken for orderly transition to instrument flight and the problem may have been compounded by the non-standard attitude indicator lighting.
- The pilot probably never became fully established on flight instruments.
- The airspeed was below the aircraft's minimum limit for IFR flight and the pilot's workload would have been extremely high.
- The pilot did not detect changes in aircraft motion, particularly the yaw acceleration, and would have been unsure of the aircraft's position.
- The pilot became disorientated after losing external visual attitude references and was unable to control the aircraft by sole reference to flight instruments.

3 Case 3 (SA355/199800372)

3.1 Synopsis

3.1.1 **Overview**: The pilot had taken-off from a private landing pad to carry out a practice approach at night. During the climb and transition, the aircraft flew into a layer of low lying mist at 200-300 ft AGL. The pilot became disorientated and the aircraft subsequently entered a dive at around 30 deg nose down, which continued until the aircraft struck the ground, with wings level, a pitch attitude of approximately 23 deg nose down and a speed of 100 kn. The pilot was killed in the crash.

3.1.2 **Background**: The aircraft was twin-engined certified for single pilot operations and was fitted with auto-pilot/auto-stabilisation equipment. It was also fitted with an Automatic Voice Alert Device (AVAD), which gave audio warnings at 100 ft and a pre-set height using a Radalt bug (set at 110 ft prior to the accident). The pilot was rated for night flying but not for instrument flying. Prior to the accident, he had undergone continuation training for night flying under the guidance of an instructor at a local airfield and possibly continued practice following return to his home base. The accident occurred during climb out and transition from the landing pad. The weather was reported as fine, with light winds and the possibility of local mist patches.

Visibility was generally at 3km but locally down to 1.2 to 1.5 km. Natural light levels were in accordance with the time of day and year (1852 hrs, January). There was a high cloud base at 25,000 ft, which would have obscured moon and star light. The AAIB investigation revealed that the area in the vicinity of the accident was very dark due to lack of background lights and that the visual horizon was indistinct.

3.1.3 **Accident details**: The accident report surmises that the pilot elected to continue practice approaches on return to his home base. The aircraft made an initial approach to the landing pad from the north, touched down briefly and then took off to make a standard departure from the site heading to the west. Eyewitness accounts suggest that the maximum height achieved during the departure was around 200-300 ft. The aircraft was subsequently seen descending at a steep angle of about 30 deg and then seen to impact the ground.

3.1.4 **AAIB analysis**: Analysis of the accident identified the possible causes. Examination of the wreckage showed that the aircraft struck the ground at an attitude of about 23 deg nose down and a speed of 100 or more knots. Actuator positions indicated close to maximum collective demand with cyclic stick slight right and forward of neutral. Witness accounts indicated that the area of the crash was very dark due to lack of ground lights and that there were light mist patches. A post-accident statement on flight conditions also noted that the visual horizon was indistinct. From the available information, the AAIB report determined a probable sequence of events:

- There was a strong possibility that the pilot levelled the aircraft during the climb out after encountering a layer of mist or fog.
- The pilot subsequently became disorientated through inadvertently flying into the mist and losing sight of the ground and a visual horizon.
- The pilot's disorientation may have been compounded by the act of levelling out of the flight path and a downward repositioning of the aircraft's landing light.
- The disorientation may have led the pilot to push the stick forward to compensate for a perception that the aircraft was pitching nose up.
- Corrective action was subsequently inadequate in preventing collision with the ground.

3.1.5 **Visual cueing aspects**: The pilot became disorientated because of degraded visual cues, most likely caused by an encounter with a layer of mist and subsequent loss of sight of the ground. Other significant factors include the indistinct visual horizon and the darkness of the local environs. The visual impression created by repositioning the landing light may also have been a contributory factor. The report also considered that lights from a nearby motorway could have created a compelling false horizon, further adding to the pilot's spatial disorientation.

3.2 Relevant causal factors and conclusions

- The pilot was in current flying practice for night flying but did not have a rating for instrument flight.
- The aircraft encountered a layer of mist, which gave rise to a loss of sight of the ground.
- The pilot most likely became disorientated after losing external visual attitude references.
- Disorientation was compounded by the indistinct visual horizon, the darkness of the local environs and false horizon cues created by lights from a nearby motorway.

- The pilot may also have been influenced by the sensory effects of levelling the aircraft and the visual impression created by a repositioning of the aircraft's landing light.

4 Case 4 (Enstrom F28/199702041)

4.1 Synopsis

The AAIB report gives only a brief description of this case, but it is included here because it is representative and very relevant to the visual cueing study. It is summarised in the following.

The aircraft was a single engined type on a VFR transit flight during the daytime, with pilot and one passenger on-board. The weather was fine with variable wind of 5-10 kn, visibility of 3.5 km with haze and varying amounts of cloud. The transit was underway at a height and speed of 6-700 ft and 78 kn, when the aircraft entered a layer of cloud embedded within the haze layer. Initially, the pilot was able to maintain visual contact with the ground, but he then decided to attempt a 180 deg turn to leave the cloud. During the turn, he lost his visual references, allowed the speed to decay and a high rate of descent to develop. The aircraft broke through the cloud very close to the ground; the pilot managed to level the aircraft attitude but it struck the ground heavily and rolled over, causing extensive damage. The pilot concluded that he had become disorientated due to inadvertent IMC and lack of instrument flying practice, and inappropriate control inputs had further compounded the problem.

5 Case 5 (Sikorsky S61/198301880)

5.1 Synopsis

5.1.1 **Overview**: The aircraft was on a scheduled VFR flight in daylight over the sea with three crew and 23 passengers on board. Whilst on approach to its destination airport, the aircraft gradually descended and flew into the water approximately 1.5 nautical miles out to sea. Prior to this, the aircraft had descended 250 ft from its intended height without either pilot noticing it. The aircraft partially broke-up on impact and sank; there were only six survivors.

5.1.2 **Background**: The aircraft was twin-engined and fitted with conventional dual flying controls (pilot plus co-pilot) and a three-axis (pitch 10%, roll 7.5% and yaw 5% authority) automatic flight control system (AFCS), with attitude and heading holds. Both pilot stations were also fitted with ASIs and flight directors, which provided roll and pitch attitude information, and a radio altimeter for height readout. The flight was carried out under VFR in visual contact with the sea. The general weather was reported as fine, with visibility 1-4 km and winds of around 10 kn, there was low level cloud (8/8 stratus, surface to 200 ft) and the possibility of sea fog, with dense fogbanks reducing visibility to 500 m and less than 100 m locally. Prior to take-off weather at the destination was reported as 1200 m visibility and cloud cover of 3/8 at 500 ft, compared with the laid down minima of 900 m and 200 ft cloud ceiling for day VFR operations. Natural light levels were in accordance with the time of day and year (1130hrs, July).

5.1.3 **Accident details**: The flight proceeded after the crew had checked that the weather en-route conformed to the mandatory VFR minima. Following a normal departure, the aircraft established a cruise at a height and speed of 2000 ft and 110 kn. At 18 miles from the destination, height was reduced to 500 ft in anticipation of low cloud. At around this point, the crew reported that they continued to have visual contact with the surface, that there was no cloud or fog but a thick haze restricted forward visibility with no discernible horizon, and that there was a flat calm sea. At 6 miles the aircraft descended to 250 ft radio height, with speed still at 110 kn. During the decent the pilot continued to fly primarily using external visual references. At 250 ft, the pilot stated that he was primarily looking outside but at the same time monitoring instruments (AI, Radalt and ASI). The co-pilot was concentrating on navigation and keeping a look-out for local shipping. Prior to the accident, the pilot commenced a deceleration to a speed of 90 kn, intending to maintain height at 250 ft, by reducing collective and use beep trim to adjust nose-up pitch attitude. At this point, the pilot decided to fly on external visual references and attempted (unsuccessfully) to establish a visual horizon and to sight a landfall ahead. At the same time he continued to decelerate the aircraft using the collective and cyclic beep trim. The aircraft hit the water unexpectedly at 1.5 miles from the coast, in a straight and level attitude and probably at an airspeed of less than 90 kn.

5.1.4 **AAIB analysis**: The AAIB report concluded that the accident falls into the category of a collision with the water in controlled flight. The aircrew were under the impression that the aircraft was at 250 ft and were unable to explain how the accident occurred. They were also sure that VFR conditions prevailed throughout the flight and reported that at the time of the accident, they were in contact with a flat calm sea, in haze with no discernible horizon, but with greater than 900 m visibility. From the available evidence, this claim was supported by the accident report, but it was also concluded that the conditions made assessment of height and attitude difficult using only external visual references. Moreover, the conditions also led the pilot to be deceived into believing that the visual cues were adequate. The analysis surmises that the loss of height that led to the accident must have been gradual and did not result from large changes to attitude or power. However, the situation probably arose as a result of small discrepancies in both torque and pitch attitude while the pilot was attempting to decelerate the aircraft. The level of accuracy required to maintain level height during this manoeuvre would have been difficult to achieve in the given visual conditions without reference to flight instruments. Hence, it was likely that whilst looking ahead, the pilot had insufficient visual cues to realise that imprecise co-ordination of collective and cyclic control strategy had resulted in a power and attitude combination that gave rise to a gradual and continuous loss of height.

5.1.5 **Visual cueing aspects**: The accident report gives an assessment of the difficulties faced when flying by external visual references when flying over the sea, and of relevance to the accident. It was concluded that any visual horizon created by the haze would have been inadequate for control of attitude, and that this would have been exacerbated by the lack of surface texture on the surface of the sea. At the same time, the vestibular system could not be relied upon to detect rates of attitude change or to detect any resultant changes of attitude. Regarding altitude, it was considered that the horizon information would have been of little use in deriving height information. Furthermore, given the apparent lack of texture and structure on the sea surface, the edge rate and looming cues needed for detecting changes in height and height rate would not have been adequate.

5.2 Relevant causal factors and conclusions

- The accident was caused by an unobserved and unintentional descent into the sea when the pilot was attempting to fly by external references only in conditions of poor and deceptive visibility.
- The pilot was justified in planning a VFR flight and the weather throughout the flight was above the laid down minima.

- During the initial approach to the destination, the pilot alternated his scan between flight instruments and external visual cues.
- The pilot subsequently changed to flying by external visual references at about the time he commenced a deceleration to reduce airspeed.
- The loss of height probably occurred because the pilot did not correctly co-ordinate power and attitude to maintain level height.
- The pilot did not notice the final descent because of inadequate external visual cues and lack of reference to flight instruments.

6 Case 6 (Bell 212/198102469)

6.1 Synopsis

6.1.1 **Overview**: The aircraft was en-route to a destination platform in the North Sea following departure from another platform, with one pilot plus thirteen passengers on-board. The flight was planned as a VMC daytime operation in visual contact with the sea. The accident occurred following an encounter with an area of very poor visibility and subsequent decision to return to the point of departure. During the turn, the pilot became disorientated because of a loss of external visual references. Control of the aircraft was lost after the aircraft pitched 20 deg nose up and climbed to 300 ft, losing airspeed. The aircraft yawed rapidly to the right, descended and struck the sea in a level attitude; there was one fatality and 13 survivors.

6.1.2 **Background**: The aircraft was twin-engined certified for single pilot operations. It was fitted with stability augmentation in roll, pitch and yaw and had an attitude hold type of autopilot. A collective-yaw inter-link was also provided for main rotor torque compensation. The transmission was fitted with a torque limiting system to prevent exceedance of the torque limit of 104%. The flight was conducted as a VMC operation and, although not a legal requirement, the pilot held an instrument flight rating. The operator’s policy was to train all its pilots to full instrument rating, but this training tended to be largely of a procedural nature and did not include recovery from unusual attitudes. The weather at the start of the flight was reported as over-cast at around 1500 ft with 10 km visibility, with winds of around 20 kn. Natural light levels were in accordance with the time of day for the region and time of year (0430hrs, August). During flight en-route, foggy conditions were reported at the destination and within 1.25 miles local conditions deteriorated such that the pilot was forced to reduce height and speed to stay in visual contact with the surface. Following the accident, conditions were described as patchy fog with visibility at times down to 150 m and a cloud base of 100 ft.

6.1.3 **Accident details**: Following take-off the flight proceeded at normal inter-rig transit height and speed of 500 ft and 100 kn. A band of drizzle was encountered and height was reduced to 200ft. The weather improved after clearing this band, but within 5 miles of the destination, there was a sudden deterioration in visibility and speed was gradually reduced to 65 kn. The aircraft was clear of cloud at 200 ft but the poor visibility necessitated cross-checking of external references with flight instruments. The flight continued in visual contact with the sea until within 1.25 miles of the destination when a decision was made to turn back. A left turn was initiated at a height and speed of 200 ft and 65 kn, with a torque setting of 70%. During the turn, flight instruments indicated a pitch attitude of 10 deg nose-up and airspeed decreasing through 20 kn. The pilot attempted to correct this, but the aircraft climbed to 300 ft and reached a pitch attitude of 20 deg, with zero airspeed. At this point, the pilot reported that he was disorientated in cloud and unsure as to position; the aircraft then yawed right and began to descend until it finally hit the sea surface. The pilot was unable to control the aircraft in the descent apart from maintaining a level attitude using the AI.

6.1.4 **AAIB analysis**: The investigation of the accident showed that the visual conditions were a primary causal factor. Rescuers reports indicated that visibility was variable, down to a minimum of 150 m. It was also noted by the rescue helicopter that the surface of the sea was calm with little surface texture and that at times, visual references for hovering were barely adequate. Following analysis of the various reports, it was concluded that the accident was caused by loss of control due to pilot disorientation while attempting to fly in visual contact with the sea in conditions of very poor visibility. It was surmised that the probable sequence of events was as follows:

- While in a left turn the aircraft was allowed to pitch nose-up such that airspeed reduced to zero and height increased from 200 to 300 ft.
- External visual cues were further degraded by the increased height and pitch attitude and, at the same time, the stabilising influence of airspeed was lost and the torque reaction began to yaw the aircraft to the right.
- The aircraft began to descend and rotation to the right increased as power was applied to arrest the rate of descent.
- The torque limit was reached but blade over-pitching resulted in main rotor rpm decay to a minimum of at least 85%, with an associated reduction in main rotor power.
- Recovery was then not possible without considerable loss of height and the aircraft consequently hit the sea.

6.1.5 **Visual cueing aspects**: Degraded visual cues were a key feature of the accident. In the first instance, fog severely reduced visibility leading to the decision to turn back. The information available suggests that there was no visual horizon and few visual references from the appearance of the sea surface. It would seem that the pilot became disorientated because he attempted to turn the aircraft flying on external visual references and flight instruments. As the manoeuvre developed, visual cues were degraded further because the aircraft pitched nose-up and climbed. Aircraft stability would have decreased also as the speed reduced, making control more difficult with the poor visual cues available.

6.2 Relevant causal factors and conclusions

- The pilot held a valid instrument rating but lacked recent flying practice; standard training requirements did not include basic instrument flying manoeuvres or recovery from unusual attitudes.
- The accident was caused by loss of control due to pilot disorientation while attempting to fly in visual contact with the sea in conditions of very poor visibility.

7 Case 7 (Agusta 109/200401275)

7.1 Synopsis

7.1.1 **Overview**: The pilot was flying a visual approach to a regional airport in poor weather at night following a Special VFR clearance at approx.1500 ft. The pilot declared that he was visual with the airport but, shortly afterwards at a range of 1 – 1.5 NM from the airfield the aircraft turned through about 540° before striking the ground, fatally injuring both the pilot and the passenger.

7.1.2 **Background**: The Agusta 109E helicopter was fully equipped for operation under the Instrument Flight Rules (IFR) with an Electronic Flight Information System (EFIS), an autopilot and standby flight instrumentation. The pilot held an ATPL/H but did not hold a UK Instrument Rating and had flown 78 hrs on type with 15 hrs of night flying in the accident aircraft.

7.1.3 **Accident details**: The Air Traffic Controller recalled that the pilot transmitted "Just becoming visual this time" when the aircraft was about 1 to 1.5 NM from the airport. At about the same time the aircraft entered a descending turn to the left. It reached a minimum height of 400 feet after the first 180° of the turn and then climbed back towards 1,000 feet as the aircraft continued the left turn. Having completed a turn of approximately 360° the aircraft continued turning left through a further 180°, whilst continually descending until the height readout was lost on the radar. During the final moments of the flight the low rotor RPM warning was recorded. The ground impact features indicated that the aircraft struck the ground whilst descending in a steeply banked turn to the left.

7.1.4 **AAIB analysis**: An occluded front was passing over the area and the associated weather was overcast and misty with outbreaks of light rain and drizzle; the surface visibility was generally 5 to 6 km deteriorating to 1,500 to 2,500 metres in any precipitation. There were areas of broken stratus cloud with a base of 600 to 1,000 feet and a further layer of strato-cumulus cloud which was broken to overcast with a base at 1,700 feet. The available radar data indicates that the pilot had flown the transit from the departure point at constant altitudes and headings consistent with the clearances given. The regular nature of the flight path suggests that the altitude and heading hold modes of the autopilot were being used. From the point at which the aircraft appears to have commenced the left descending turn, an approach angle of 7.5 – 9 ° was required to the runway threshold. Therefore, when the pilot became visual he would have recognised that he needed to lose height. To achieve this, the pilot would have had to de-select the height and heading hold modes and initiate a positive descent by rapidly lowering the collective control. Without appropriate intervention, the helicopter would have yawed and rolled to the left and the nose would have dropped. No technical defect was established which contributed to the accident and the AAIB concluded that the accident occurred when the pilot encountered a significant deterioration of the weather in the immediate area of the airfield, and, during the final stages of the approach, the pilot probably became disorientated due to a loss of visual references when attempting to fly by sole reference to his flight instruments or limited ground lights or a combination of both.

7.1.5 **Visual cueing aspects**: Whilst the airfield approach lights and airfield lighting would have provided good visual references, the area to the east and northeast of the airfield was dark and featureless with virtually no external visual references discernible in the prevailing visibility. In addition, the reported surface visibility was probably further reduced by rain on the cockpit windows. There would also have been no discernable horizon and the only cultural lights visible would have appeared well below the true horizon giving false visual cues to the pilot.

7.2 Relevant causal factors and conclusions

- The pilot's limited instrument flying background did not equip him to cope with the difficult situation in which he found himself.
- The accident occurred when the pilot encountered a significant deterioration of the weather during the final stages of the approach and subsequently probably became disorientated due to a loss of visual references.

Appendix B Visual Images from EMOCUES2 Scenarios

1 Introduction

The images shown in this appendix are taken from the visual database used for the EMOCUES2 evaluations. Examples shown include the following cases:

1 Day/GVE - Hover Taxi, Fly Away, Turn, Climb, Approach.

2 Day/DVE/Fog/Text - Hover Taxi, Fly Away, Turn, Climb, Approach.

3 Night/DVE/Fog/Text - Turn, Climb.

As noted in the main report, the examples shown for the degraded visual conditions, i.e. cases (2) and (3), are to some extent unrepresentative, because some of the surface textures apparent in the simulator visuals have been lost in the reproduction process. This problem does not affect the actual images used for the analysis exercise as these were translated into digital format in the image capture process.

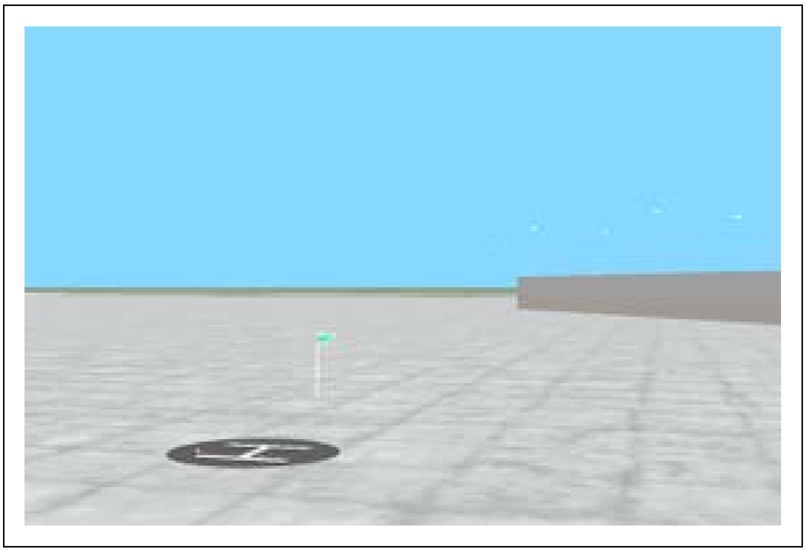

Figure 1 Hover Taxi - Day/GVE

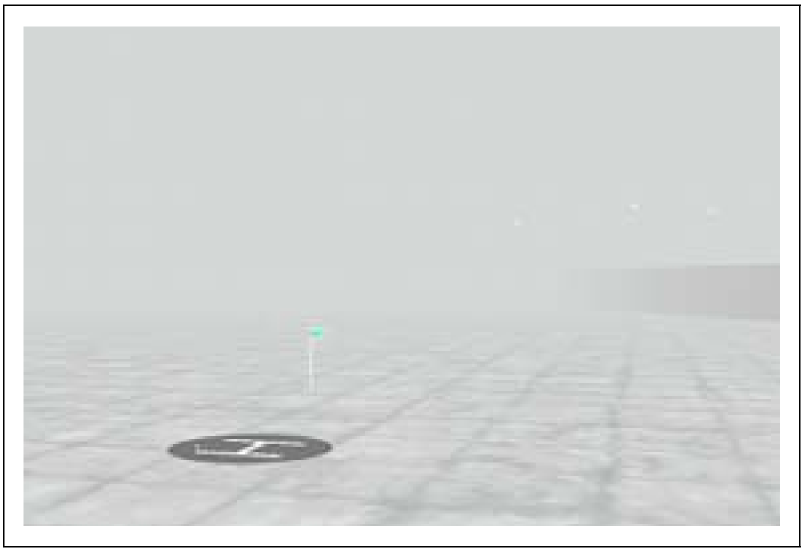

Figure 2 Hover Taxi - Day/GVE/Fog

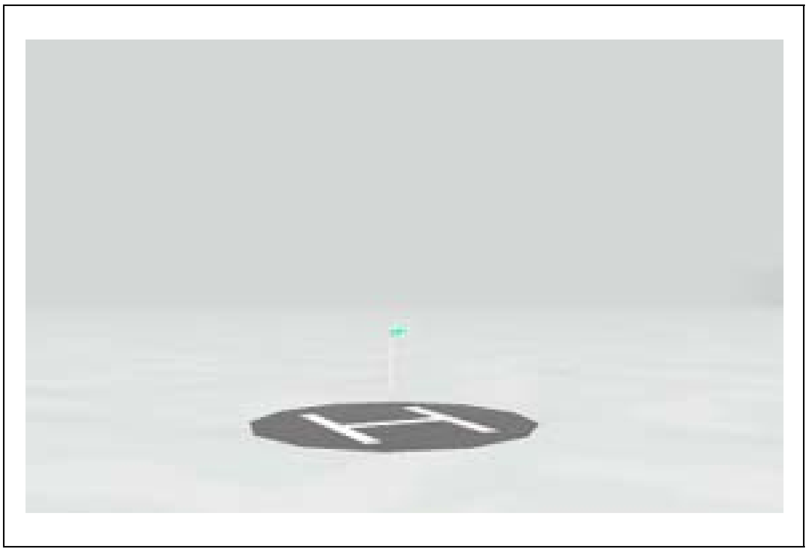

Figure 3 Hover Taxi - Day/DVE/Fog/Text

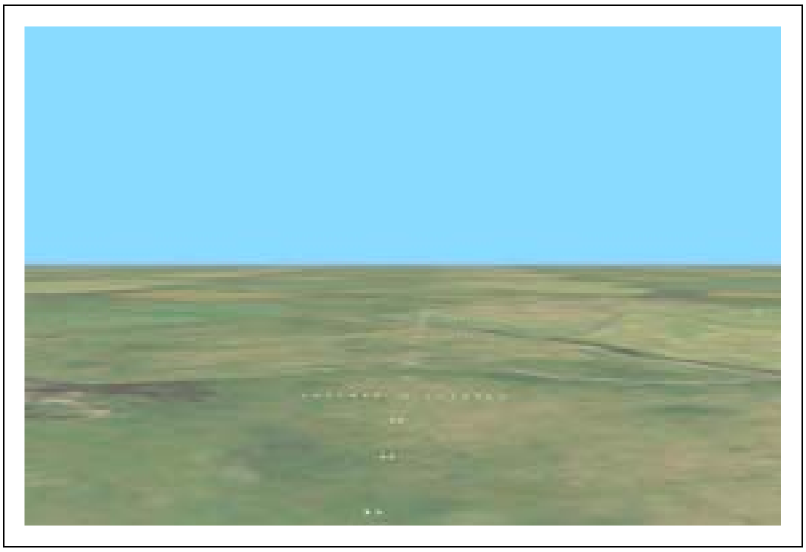

Figure 4 Fly Away - Day/GVE

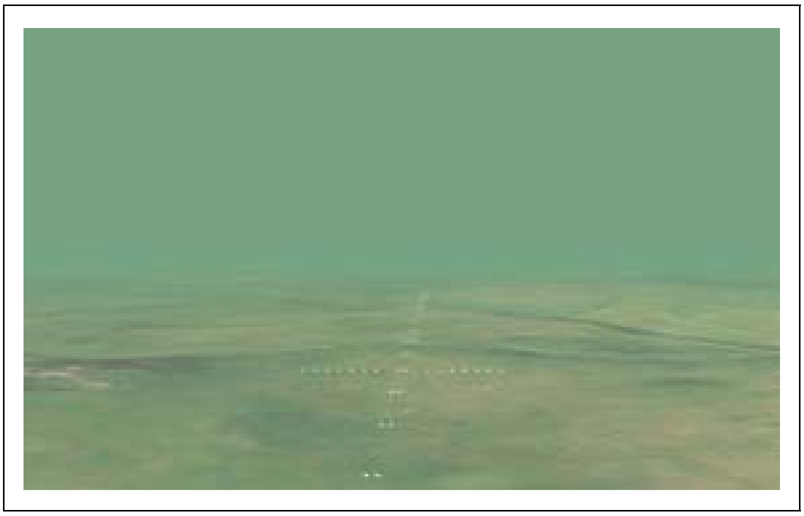

Figure 5 Fly Away - Day/GVE/Fog

Figure 6 Fly Away - Day/DVE/Fog/Text

Figure 7 Turn - Day/GVE

Figure 8 Turn - Day/GVE/Fog

Figure 9 Turn - Day/DVE/Fog/Text

Figure 10 Turn - Night/DVE/Fog/Text

Figure 11 Climb - Day/GVE

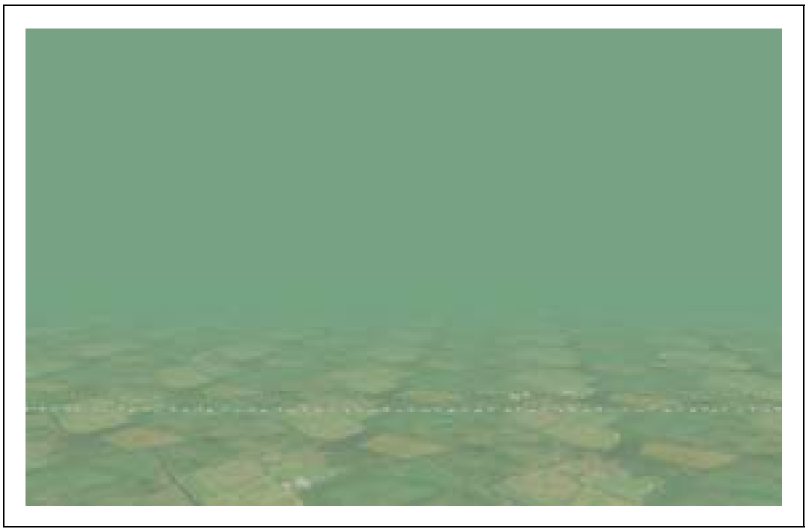

Figure 12 Climb - Day/GVE/Fog

Figure 13 Climb - Day/DVE/Fog/Text

Figure 14 Climb - Night/DVE/Fog/Text

Figure 15 Approach - Day/GVE

Figure 16 Approach - Day/GVE/Fog

Figure 17 Approach - Day/DVE/Fog/Text

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Appendix C Background to Image Analysis

1 Introduction

For the pilotage task, images of the environment determine how easy it is for a pilot to perceive information to determine helicopter position and attitude etc. Obviously, if the image is completely blank (such as in thick fog) there will be no information on which to base these estimates. On the other hand, if there is too much information, for example uniformly distributed clutter from sea glint, the pilot may also find it difficult to fixate on landmarks. Ideally there should be image structures that are sufficiently non-uniform to be identified instantly and are sufficient in number to act as reference points for all parts of the scene. The number and distribution of image structures are not the only potentially important criteria; their size and contrast (edge strength) is also important for them to be seen easily, and this is dependent on factors such as weather (visibility) and sensor noise.

Visual perception is a very complex and as yet poorly understood process. Images themselves are also very complex and varied. The relationship between the images received in the cockpit and mission outcome is therefore likely to be very complicated and also dependent on the mission. For example, a blank background will usually aid target detection, but would hinder navigation. Given these considerations, the approach undertaken in this investigation was to define a small number of generic image metrics from which functions could be derived that could potentially be used to predict the sufficiency of a scene and its optical cueing properties (e.g. tau, optical flow) to support pilotage.

For the applications under consideration ‘sufficiency’ is commensurate with attainment of desired task performance, acceptable levels of pilot workload and situational awareness. Hence, the aim is to establish quantification of the image, or level of sufficiency, through a calibration of relevant image analysis parameters against appropriate pilot performance data, including performance, workload and situational awareness measures. The calibrations then form the basis for a performance prediction model as a function of image analysis parameters, which can provide a means for assessing and quantifying the quality of visual imagery in relation to its ability to support pilotage tasks.

2 Image metrics

It is difficult to encapsulate all of the information within an image that might be relevant to pilotage because a typical image contains a vast amount of data (typically in excess of a million colour pixels), and because of the complexity of human visual perception. Generic metrics are generally sought in order to encapsulate information relevant to a wide variety of tasks. In this study the following information has been incorporated:

- Contrast (edge strength)
- Scale (size or resolution)
- Orientation
- Density (number of features per unit area)
- Uniformity (clustering of features)

These present a considerable amount of information to incorporate into a few metrics, so summary statistics of these quantities are usually applied. Previous research has led to the development of statistical models of signal and image natural backgrounds, which incorporate the above information. For the CRP investigation it was decided, therefore, to use one of the simplest of these models that is based on fractal geometry and from which four, fundamental image metrics can be derived. The aim was to use these metrics as a basis for predicting pilot performance through calibration with trials data.

Fractal geometry concerns the relationship between different scales in a signal or image. The underlying concept is *self-similarity*; an image is self-similar if it can be equated with a part of itself that has been magnified. Natural images are rarely exactly self-similar, but are often statistically self-similar, that is magnification does not affect statistical distributions of image structure such as brightness or edge strength. Examples of statistical self-similarity are in images of clouds, mountains, coastlines and trees; for example, a coastline looks similar over a wide range of magnifications.

The basic fractal model used is called a monofractal, in which the statistical distribution of edge strength is independent of scale (magnification) except for a scale-dependent multiplier. The full statistical model is as follows:

$$\log\left(\frac{N_y s^D}{\alpha}\right) = -\frac{y}{\beta s^k} \tag{1}$$

where N_y is the number of edges whose strength (contrast) exceeds a given threshold y and Equation (1) predicts N_y as a function of y. This model has four parameters which serve as the four specified image metrics:

- A measure of overall clutter strength, β. This is similar to average edge strength, but emphasises the strongest edges and is scale-normalised. It is the strongest edges that most affect the difficulty of object recognition in clutter.
- A measure of image smoothness (spatial correlation) called the self-similarity parameter, k, which also describes how edge strength varies with scale (the size and smoothness of the edge). The dominant edges in a smooth image (large k) have larger scales, whereas rough (uncorrelated) images have dominant small-scale structure.
- A measure of overall clutter density, α. This is related to the average number of edges in the image, but is scale-normalised. It indicates how many edges there are in the image, rather than their average strength (intensity), β.
- A measure of clutter uniformity called the fractal dimension D, which shows whether edges are distributed uniformly within the image, or whether there are some regions that are relatively more densely populated. In the latter case edges tend to form local clusters, which in turn comprise other, smaller clusters, and so on down to the smallest scale. D is a measure of how the number of edges depends on their scale. In a completely uniform image the number of edges is inversely proportional to their area, or scale raised to the power of 2, so $D = 2$. In images with a lot of clustering the variation of this number with scale is less extreme; for example the number might be inversely proportional to scale raised to the power of 1.5, in which case $D = 1.5$.

The above metrics are based on the implicit assumption that Equation (1) is a good predictor of N_y as a function of y; whilst this is true for many natural backgrounds, it is not true when there are a small number of unusual objects in the scene with different statistics, for example a few roads and buildings in a rural scene, or a few trees in a desert. In these cases N_y plotted against y is no longer a continuous curve, but has one or more steps, and the prediction of N_y will be less accurate. In this study, however, the aim is not to predict N_y, but to predict pilot performance, so it is more important to give a summary indication of edge strength, density and uniformity. The above model, when calibrated appropriately, serves this purpose even when the scene contains statistical outliers.

The four fractal parameters are derived from each image by fitting Equation (1) to the measured distributions of N_y against y. Two stages of least-squares regression are used: the first stage fits an exponential curve to the distribution N_y at each scale and the second stage fits power-law distributions to the slopes and intercepts of the exponential curves. When modelling backgrounds only, each point in the distribution is given equal weight. This approach works because it is insensitive to statistical outliers (such as the roads, trees and buildings mentioned above), as they are relatively few in number. In the current application, these outliers are an important influence on pilot performance so they require a stronger weighting in the model regression. To this end, non-uniform weights are used such that their theoretical distribution with respect to y rather than N_y is uniform, so that edges are given priority according to their strength (intensity) rather than number. Because the theoretical distribution of N_y is exponential (see Equation (1)), this implies that the cumulative distribution of the weights should be logarithmic, which in turn implies that the weights themselves are the reciprocal of N_y.

Equation (1) does not explicitly involve orientation or colour; these attributes are represented by applying the model with different edge filters and to different colour components (or bands in any multispectral imagery). For the CRP investigation the image data had three colour components, so the fractal parameters were calibrated independently for each component. A wide variety of edge filters are available, but in the interests of simplicity three filters were considered: a radially-symmetric 'blob' filter, a horizontal edge filter (which would respond to structures like the horizon) and a vertical edge filter. Thus in total 4x3x3 = 36 metrics were computed for each image.

3 The calibration process

The procedure for calibrating simple image models using pilot performance metrics is described in the following. The general principle involves application of a training data set to calibrate the model, which is then applied to a second data set to test its predictive capability. The underlying model is a multivariate linear function:

$$y = \sum_k a_k x_k + b \qquad (2)$$

where y is the pilot performance metric (or other attribute of interest) and x_k are the image metrics (36 in all, but a subset is usually considered). The classical calibration method of least-squares regression is used because this is computationally efficient and numerically stable. A linear model is used for simplicity, and which also reduces the risk of over-fitting the training data.

Over-fitting is a common problem when there is limited training data and typically occurs when the number of degrees of freedom in the model (in this case up to 37) is too large compared to the number of values of y to fit. Over-fitting usually results in a good (sometimes perfect) prediction of y *for the training data*, but a poor prediction for any new data. In the case of a linear model it is usually possible to find a perfect fit when the number of degrees of freedom equals or exceeds the number of training examples, but such a fit would not necessarily predict future behaviour well. However, most non-linear models have an even greater number of degrees of freedom and, thus, have not been considered.

Appendix D Background to Tau Analysis

The background to tau analysis is covered in this appendix by the paper entitled: *How Do Pilots Know When to Stop, Turn or Pull-up? Developing Guidelines for Vision Aids*, authored by G D Padfield et al and originally presented at the 57th AHS Annual Forum, Washington DC, May 2001.

How Do Helicopter Pilots Know When to Stop, Turn or Pull Up? *(Developing guidelines for vision aids)*

*Paper Presented at the American Helicopter Society 57th Annual Forum,
Washington, DC, May 9-11, 2001.*

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Abstract

The title of this paper, posed as a question, reflects the current interest in gaining an improved understanding of visual perception in flight control to inform the development of design guidelines for future pilot vision aids. The paper develops the optical flow theory of visual perception into its most recent incarnation, tau-coupling, where tau is the time to closure to surfaces at current velocity. General tau-theory posits that the closure of any type of gap, using any form of sensory input, is guided by sensing and constantly adjusting the tau of the gap. According to the theory, and contrary to what might be expected, information about the distance to obstacles or the landing surface, for example, and about the speed and deceleration of approach, are not necessary for precise control of landing or stopping. Analysis is presented that supports the importance of tau-coupling in flight control. Results from simulation trials conducted at DERA and at The University of Liverpool demonstrate the considerable power of what we describe as tau-guides, that lead the pilot to adopt a prospective flight control strategy.

Introduction

Helicopter pilots make use of nap-of-the-Earth (NoE) flight to increase stealth and mission security. Such tactical flight, close to the ground and amongst the surrounding obstacles, is characterised by the pilot making continuous corrections in speed, height and heading, guided by a mental model of where his or her aircraft will be in the future. The pilot uses what can be described as ‘prospective control’ to evolve a safe trajectory, or skyway, based on perception of the aircraft’s changing velocity and direction from instant to instant. How far into the future this mental model needs to project is a central question for research into vision aids, the answer to which depends on the task being flown and, critically, on the aircraft’s performance and handling qualities. For NoE tasks suggested by the title of this paper - turning through a terrain-gap, stopping in a clearing or climbing over a hill - the question reflects the requirements for an adequate flight safety margin.

In engineering terms, the positional states and motion velocity and turn rate describe the flight control task. The pilot effectively transforms perceived motion in the optical frame of reference into relative motion in the inertial frame-of-reference and applies feedback regulation to minimise errors between the commanded and perceived motion. In an alternative, active psychophysics framework, flight control can be described in terms of pilots picking up information generated by motion over terrain and around obstacles, through variables in the optical flow-field from the surfaces in their field of vision (Ref 1). Optical flow rate can, for example, provide the pilot information on ground speed in eye-heights per second (Ref 2) or surface slant (Ref 3). Differential motion parallax can guide way-finding in a cluttered environment (Ref 4). Another optical variable, introduced by Lee (Ref 5), is that which specifies time to contact or close to an obstacle or surfaces at the current closing rate - tau. Tau provides a temporal scaling of the external environment and, like other flow-field variables, provides pilots with instinctive information about their motion relative to external surfaces. More recent developments of tau theory have hypothesised that purposeful motion is guided by couplings arising from either external or internal sources (Ref 6). This hypothesis features as a central theme in the paper and suggests a major new paradigm for safe flight, to be discussed later.

In terms of a visual guidance strategy we can say that the overall pilot's goal is to overlay the optical flow-field over the required flight trajectory – the chosen path between the trees, over the hill or through the valley – thus matching the optical and required flight motion. With this approach, it is argued that the pilot has no requirement to 'transform' the flow variables into motion variables, as such. The pilot's perception system works directly with the raw optical flow variables.

Learning to fly close to the ground and in a cluttered environment, a pilot naturally uses the same rapid and efficient processes that he or she uses every day to walk, run or jump. However, ultimately a pilot has to effect control of the aircraft through the flight motion variables in an inertial frame of reference (e.g. when landing). When there are consistent, unambiguous, one-to-one mappings between the frames of reference, accurate flight control will follow from the direct perception of the optical variables. When the relationships, the mappings, become blurred, then the pilot may experience flight control problems through a degraded spatial awareness. The blurring, in a general sense, defines a degraded visual environment (DVE). A key question relating to the design of pilot vision aids is how best to represent the world when the natural optical information begins to degrade.

At first sight the engineering and active psychophysics approaches can appear conflicting and yet they surely must overlap and ultimately be complementary descriptions of the same control function, viewed from different perspectives. Making the link between the two approaches should improve our understanding of both and ultimately stimulate ideas on how to provide effective aids to pilots when the prime source of information for flight control, through optical variables, begins to degrade. The amount and form of what is necessary to be displayed for the pilot to be able to fly safely is the driver for vision system requirements. The prospect of enhanced and synthetic vision systems calls for a re-examination of the design guidelines for primary flight display formats, and the stimulus for exploring the efficacy of more natural optical flow components. This is the subject of the present paper and is derived from research conducted by the authors in collaboration with scientists at the Defence Evaluation and Research Agency.

The paper is structured as follows. First, the nature of visual perception in flight control is discussed and the key optical variables used in the paper are introduced in the context of NoE helicopter manoeuvring. Second, the concept of tau-coupling is introduced and applied to test data captured on the DERA and Liverpool Flight Simulators. Some thoughts on the implications of the current research for the design of vision aids are then discussed before the paper is brought to a conclusion.

Visual Perception in Flight Control; Optical Flow

The use of the term prospective control emphasises that flight tasks are essentially temporal, within a spatially ordered environment. When flying close to the ground or obstacles, the reliability of the pilot's mental model of the future is particularly critical. In a good visual environment the pilot is able, arguably by definition, to pick up sufficient information to make sense of motion from the optical flow-field on the surfaces in the visual scene. The optical flow-field defines the way in which points in the visual scene move from instant to instant relative to the pilot's viewpoint. The visual perception system that picks up and organises this information has, necessarily, to be very robust and efficient. Figure 1, derived from Ref 3, illustrates the optical flow-field seen by the pilot when flying horizontally over a surface at 3 eyeheights per second. The figure shows the projection onto a plane perpendicular to the direction of flight. This corresponds to fast NoE flight - about 50 kn at 30 feet height, giving the same visual impression as experienced by a running person. The eye-height scale is useful in visual perception research because of its value to deriving body-scaled information about the environment during motion. Each optical flow vector in Figure 1 represents the angular change of a point on the ground during a 0.25 second snapshot. Inter-point distance is one eyeheight. The scene is shown for a limited field-of-view window, typical of current helmet-mounted-displays. A 360 deg perspective would show optical flow vectors curving around the sides and to the rear of the aircraft. The centre of optical expansion is on the horizon.

The length of the optical flow vectors in Figure 1 gives an indication of the motion information available to a pilot; they decrease rapidly with distance. If we consider the median plane, the angular velocity, $\frac{d\theta}{dt}$ of a point on the ground distance x in front of the pilot is given by,

$$\frac{d\theta}{dt} = -\frac{dx}{dt}\left(\frac{z}{x^2 + z^2}\right) \tag{1}$$

where θ is the elevation angle, $\frac{dx}{dt}$ is the horizontal velocity, and z is the height of the observer. Velocity (i.e. the length of the vector) is seen to fall off as the square of the distance from the observer. In Ref 3, Perrone suggests that a realistic value for the threshold of velocity perception in practical complex situations is about 40 min arc/sec. According to eqn 1, this corresponds to information being sub-threshold at about 15-16 eyeheights distant from the observer for the case shown in Figure 1. To quote from Ref 3, "*This is the length of the 'headlight beam' defined by motion information alone. At a speed of 3 eye-heights/sec, this only gives about 5 seconds to respond to features on the ground that are revealed by the motion process.*"

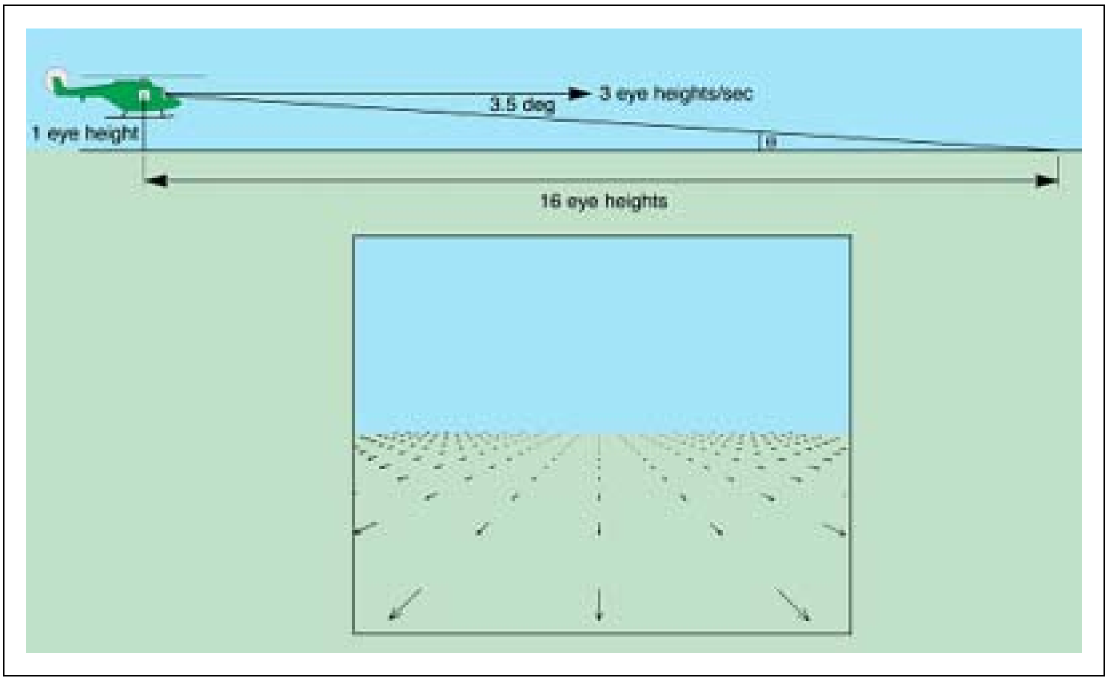


Figure 1 Optical Flow-field for Motion over a Flat Surface

The velocity in eye-heights per second is given by,,

$$\dot{x}_e = \frac{dx}{dt}\frac{1}{z} \tag{2}$$

Transforming eqn (1), we can write,

$$\frac{d\theta}{dt} = \frac{\dot{x}_e}{1 + x_e^2} \tag{3}$$

where x_e is the pilot's viewpoint distance ahead of the aircraft scaled in eye-heights. When $\dot{x}_e$ is constant, then the optical angular velocity is also constant; they are in effect measures of the same quantity. However, the simple linear relationship between $\dot{x}_e$ and the ground velocity given by eqn (2), is disrupted by changes in altitude. If the pilot descends while keeping forward speed constant, $\dot{x}_e$ increases; if he climbs, $\dot{x}_e$ decreases. A similar effect is brought about by changes in surface layout, e.g. if the ground ahead of the aircraft rises or falls away. Generalising eqn (1) to the case where the aircraft has a climb or descent rate ($\frac{dz}{dt}$) relative to the ground we can write;

$$\frac{d\theta}{dt} = -\frac{\frac{dx}{dt}z - \frac{dz}{dt}x}{x^2 + z^2} \tag{4}$$

We can see from eqn (4) that the relationship between optical flow rate and the motion variables is not straightforward. Flow rate and ground speed are uniquely linked only when flying at constant altitude.

A related optical variable comes in the form of a discrete version of that given by eqn (2) and occurs when optically specified edges within the surface texture pass some reference in the pilot’s field of vision. This optical edge rate is defined as (Ref 2);

$$e_r = \frac{dx}{dt}\frac{1}{T_x} \tag{5}$$

Here, T_x is the spacing between the surface edges. A pilot flying at 50 ft/sec over a network of 50 ft square grids would therefore experience an edge rate of 1/sec. Flying over a uniform surface the simple linear relationship between the flight motion and optical variables holds. Unlike optical flow rate, edge rate is invariant as altitude changes. However, as noted in Ref 2, when ground speed is constant, edge rate increases as ground texture becomes denser, and decreases as it becomes sparser.

Time to Contact; Optical tau

When x_e>>1 (or x>>z), we can simplify eqn (1) and (3) to the form;

$$\dot{\theta} = \frac{\dot{x}_e}{x_e}\theta = \frac{\dot{x}}{x}\theta \tag{6}$$

The ratio of distance to velocity is the instantaneous time to reach the viewpoint, which we designate as $\tau(t)$, hence,

$$\tau(t) = \frac{x}{\dot{x}} = \frac{\theta}{\dot{\theta}} \tag{7}$$

This temporal optical variable is important in flight control. A clear requirement for pilots to maintain safe flight is that they are able to predict the future trajectory of their aircraft far enough ahead that they can stop, turn or climb to avoid a hazard. This requirement can be interpreted in terms of the pilot’s ability to detect motion ahead of the aircraft. In his explorations of temporal optical variables in nature (Refs 5-7), David Lee makes the fundamental point that an animal's ability to determine the time to pass or contact an obstacle or piece of ground does not depend on explicit knowledge of the size of the obstacle, its distance away or relative velocity. The ratio of the size to rate of growth of the image of an obstacle on the pilot's retina is equal to the ratio of distance to rate of closure, as conceptualised in Figure 2, and given in angular form by eqn (7). Lee hypothesised that this 'looming' is a fundamental optical variable that has evolved in nature, featuring properties of simplicity and robustness. The brain does not have to apply computations with the more primitive variables of distance or speed, thus avoiding the associated lags and noise contamination. The time to contact information can readily be body scaled in terms of eye-heights, using a combination of surface and obstacle $\tau(t)$’s thus affording animals with knowledge of, for example, obstacle heights relative to themselves.

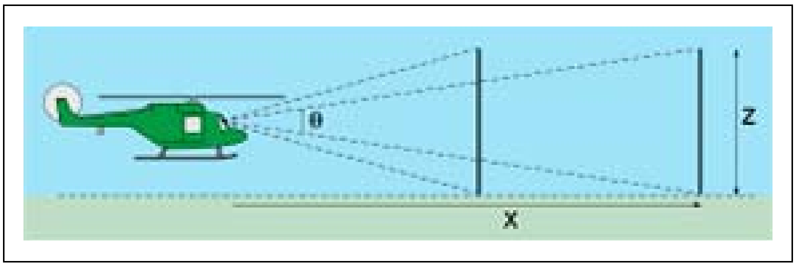


Figure 2 Optical Looming when approaching an Object

Tau research has led to an improved understanding of how animals and humans control their motion and humans control vehicles. A particular interest is how a driver or pilot might use τ to avoid getting into a crash state (or animals alight on objects). A driver approaching an obstacle needs to apply a braking (deceleration) strategy that will avoid collision. One collision-avoid strategy is to control directly the rate of change of optical tau, which can be written in terms of the instantaneous distance to stop (x), velocity and acceleration in the form;

$$\dot{\tau} = 1 - \frac{x\ddot{x}}{\dot{x}^2} \tag{8}$$

With x<0, then $\dot{\tau} > 1$ implies accelerative flight; $\dot{\tau} = 1$ implies constant velocity, while $\dot{\tau} < 1$ corresponds to deceleration. With constant deceleration, $\ddot{x}$ the stopping distance from a velocity $\dot{x}$ is given by,

$$x = -\frac{\dot{x}^2}{2\ddot{x}} \tag{9}$$

Hence a decelerating helicopter will stop short of the intended hover point if;

$$\frac{-\dot{x}^2}{2\ddot{x}} < -x \quad \text{or} \quad \frac{x\ddot{x}}{\dot{x}^2} > 0.5 \tag{10}$$

Using eqns (7) and (8) this condition can be written more concisely as,

$$\frac{d\tau}{dt} < 0.5 \tag{11}$$

A constant deceleration results in $\dot{\tau}$ progressively decreasing with time and the pilot stopping short of the obstacle, unless $\dot{\tau} = 0.5$ when the pilot just reaches the destination. The hypothesis that optical τ and $\dot{\tau}$ are the variables that evolution has provided humans and animals with the ability to detect and rapidly process, suggests that these should be key variables to guide the design of vision augmentation systems. In Ref 8, Lee extends the concept to the control of rotations (angular τ) related to how athletes ensure they land on their feet after a somersault. For helicopter manoeuvring, this can be applied to control in turns, providing a direct connection with the heading component of flight motion. With heading angle and turn rate, we can write the angular tau as:

$$\tau(t) = \frac{\psi}{\dot{\psi}} \tag{12}$$

A combination of angular and linear tau's, associated with physical gaps, needs to be successfully picked up by pilots to ensure flight safety. The requirement for combining tau's to perform more complex manoeuvres has led to the development of a more general theory of tau-coupling.

Tau-Coupling in Helicopter Flight – a Paradigm for Safety in Action

General tau theory posits that the closure of any type of gap, using any form of sensory input, is guided by sensing and constantly adjusting the tau of the gap (Ref 6). The theory shows, for example, that information solely about $\dot{\tau}_x$ is sufficient to enable the gap x to be closed in a controlled manner, as when making a gentle landing. According to the theory, and contrary to what might be expected, information about the distance to the landing surface and about the speed and deceleration of approach are not necessary for precise control of landing.

The theory further shows how a pilot might perceive τ of a motion gap by virtue of that τ being proportional to the τ of a gap in a sensory flow-field. The example of decelerating a helicopter to hover over a landing point on the ground serves to illustrate the point. The τ of the gap in the optic flow-field between the image of the landing point and the centre of optical outflow (which specifies the instantaneous direction of travel) is equal to the τ of the motion gap between the pilot and the vertical plane through the landing point. This is always so, despite the actual sizes of the optical and motion gaps being quite different (see Figure 3). The same applies to stopping at a point adjacent to an obstacle (Figure 4).

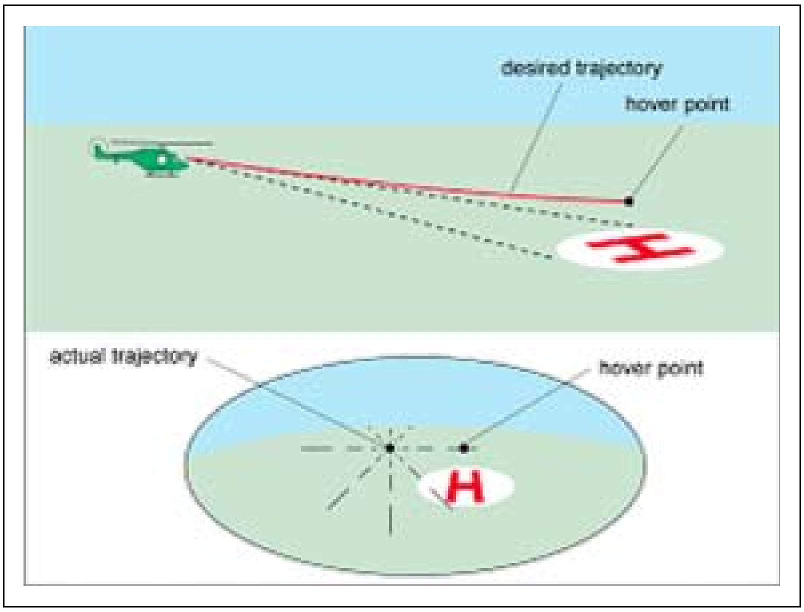


Figure 3 Tau-gaps for Helicopter approaching a hover point above Landing Pad

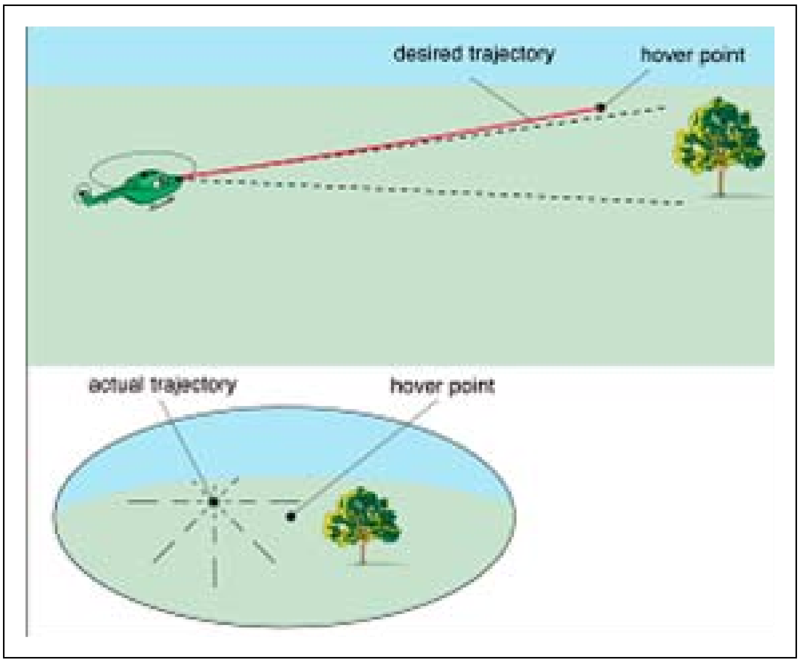


Figure 4 Tau-gaps for Helicopter approaching a hover point adjacent to an Object

Often movements have to be rapidly co-ordinated, as when simultaneously making a turn and decelerating to stop at a goal position or flying parallel to a line feature. This requires accurate synchronising and sequencing of the closure of different gaps. To achieve this, sensory information about several different gap closures has to be picked up rapidly and continuously and applied to guiding the action. Tau theory shows how such movement co-ordination might be accomplished in a simple way by τ-coupling, that is, by keeping the τ's of gaps in constant ratio during the movement.

Evidence of tau-coupling in action is presented in Refs 8 and 9 for experiments with echo-locating bats landing on a perch and infants feeding. In the present context, if a helicopter pilot, descending (along z) and decelerating (along x), follows the tau-coupling law,

$$\tau_x = k\tau_z \tag{13}$$

then the desired height will automatically be attained just as the landing pad itself is reached. The kinematics of the motion can be regulated by appropriate choice of the value of the coupling constant k.

General tau-guidance principles can also be used to hypothesise how pilots might perceptually guide their craft through the other two manoeuvres of current interest – turning and terrain following. To simplify the analysis, and without losing much generality, we consider planar motion only. Turning to fly parallel to a vertical feature (e.g. line of trees) might follow the guidance rule of coupling tau for the heading with tau for the distance to the line feature. However, since the heading itself may be difficult to perceive, an alternative would be to follow the principle of keeping,

$$\tau_x = k\tau_y \tag{14}$$

where x and y are the distances respectively to the centre of outflow (instantaneous direction of travel) and to a point ahead where the pilot naturally directs his or her gaze (Figure 5). Manoeuvring around an obstacle on the inside of the turn could be guided by controlling tau of the angle between the instantaneous trajectory and the direction of the tangent to the obstacle (Ref 6).

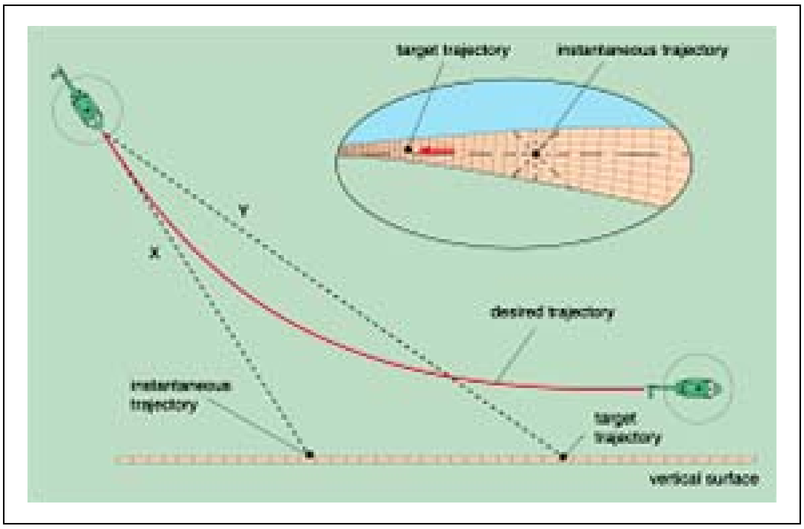


Figure 5 Tau-gaps for Helicopter Turning along a Line Feature

The scenario in Figure 5 could equally well apply to control of motion when approaching a horizontal surface (e.g. the ground). The visual cues available from the cockpit are different in the horizontal and vertical cases, of course, determined partly by the different orientation of the pilot's head to the outside world. Obscuration of visual cues by the cockpit frame, and the potential complexity introduced by the orientation of the optical frame of reference to the inertial frame, both clearly influence the available optical tau's.

Figure 6 illustrates the final case of interest with the scenario of a helicopter approaching rising ground and manoeuvring up and over a crest. As for the previous case, the pilot can potentially couple the tau's associated with a point on the ground along the instantaneous direction x (centre of optical expansion) with a point further up the hill moving at a rate consistent with the required climb rate.

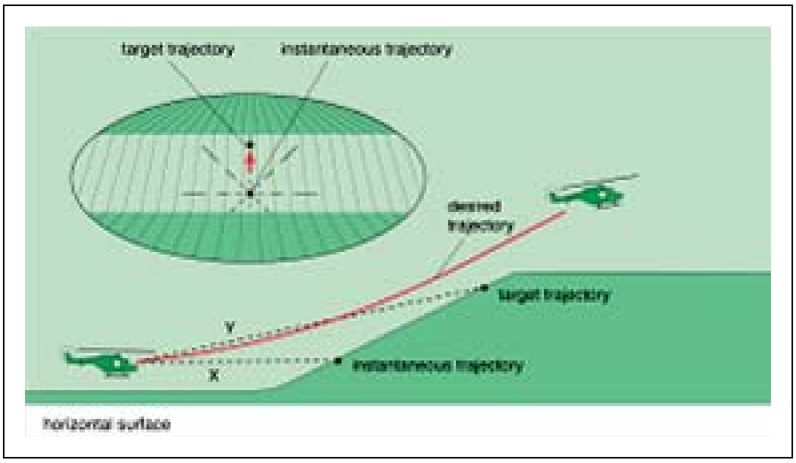


Figure 6 Tau-gaps for a Helicopter approaching Rising Ground

The basis of the general hypothesis for the 'turning' manoeuvres described above certainly needs to be tested, but there is evidence that such coupling can be exploited successfully in vision aids. For example, the system reported in Ref 10 exploited such tau-coupling through the matching of a cluster of forward directed light beams with different look-ahead times. Such a system was designed as an aid in situations where the natural optical flow was obscured.

Intrinsic Motion Guides

In the above examples, the tau's of two motion gaps are coupled to achieve the overall action. However, in many movements such as drumming a rhythm and self-paced reaching, there is only one motion gap basically to control (e.g., between the hand and drum). And yet the kinematics of controlled closure of motion gaps is similar, whether there are two coupled motion gaps or just one. Such findings led to the hypothesis that the closure of a single motion gap is controlled by keeping the tau of the motion gap (e.g., between hand and drum) coupled onto an intrinsically-generated tau-guide τ_g (Ref 6). It may be assumed that simple, robust control processes have evolved, rather than unnecessarily complex ones. Therefore it is reasonable to hypothesise that the simplest form of intrinsic tau-guide will have evolved that is adequate for guiding movements, such as reaching, through the normal phases of acceleration followed by deceleration. In the context of helicopter NoE flight any of the classic hover-to-hover re-positioning manoeuvres fit into this category of motions. The hypothesised intrinsic tau-guide corresponds to a time-varying quantity, perhaps related to the flow of electrical energy in neurons, that changes in value from a rest or constant velocity level to a goal level at a constantly accelerating rate. It should be noted, however, that tau-coupling onto this intrinsic guide does not, in general, generate a motion of constant acceleration, but rather generates one with a (non-constant) accelerative phase followed by a (non-constant) decelerative phase. The equations describing the changing τ_g take the form:

$$\tau_g = \frac{1}{2}\left(t - \frac{T^2}{t}\right) \dot{\tau}_g = \frac{1}{2}\left(1 + \left(\frac{T}{t}\right)^2\right) \qquad (15)$$

where T is the duration of the aircraft or body movement and t is the time from the start of the movement. Coupling a motion-gap tau, τ_x (e.g., from hand to drum or hover to hover) onto an intrinsic tau-guide, τ_g, therefore involves following the equation,

$$\tau_x = k\tau_g \qquad (16)$$

for some coupling constant *k*. The intrinsic tau-guide, τ_g, has a single adjustable parameter, *T*, its duration. The value of *T* is assumed to be set by the nervous system, either to fit the movement into a defined temporal structure, as when moving the hand in time with a musical rhythm, or in a relatively free way, as when reaching for an object. In the case of a helicopter flying from hover to hover across a clearing, we can hypothesise that time constraints are mission related and the pilot can adjust the urgency through the level of aggressiveness applied to the controls. The kinematics of a movement can be regulated by setting the coupling constant, *k* in eqn (16), to an appropriate value. For example, the higher the value of *k*, the longer will be the acceleration period of the movement, the shorter the deceleration period, and the more abruptly will the movement end. We describe situations with *k* values > 0.5 as hard stops (i.e. where peak velocity is pushed close to the end of the manoeuvre) and situations with *k* < 0.5 as soft stops.

When two variables (e.g. the motion x_m and the motion guide x_g) are related through their tau-coupling in the form of eqn (16), then it can be shown that they are also related in one of the most prevalent ways in nature, through the power law,

$$x_m = Cx_g^{1/k} \tag{17}$$

where *C* is a constant. Reference 5 expands on the implications of this relationship in terms of the overall kinematics of the motion and the associated motion gaps. We continue this paper with an application of tau-analysis during helicopter stopping manoeuvres.

Tau in Action during Stopping Manoeuvres

A common manoeuvre used by helicopter pilots to fly from cover to cover across open ground is colloquially known as the acceleration-deceleration or quick-hop (Ref 12). As part of an exercise in simulation validation, 'accel-decels' were flown both in flight and on the DERA Advanced Flight Simulator (AFS) using a Lynx helicopter (Ref 13). The layout of the manoeuvre, showing the basic ground markings, is sketched in Figure 7. Pilots were required to fly the manoeuvre according to prescribed performance standards in terms of track, height, level of aggressiveness and terminal position constraints.

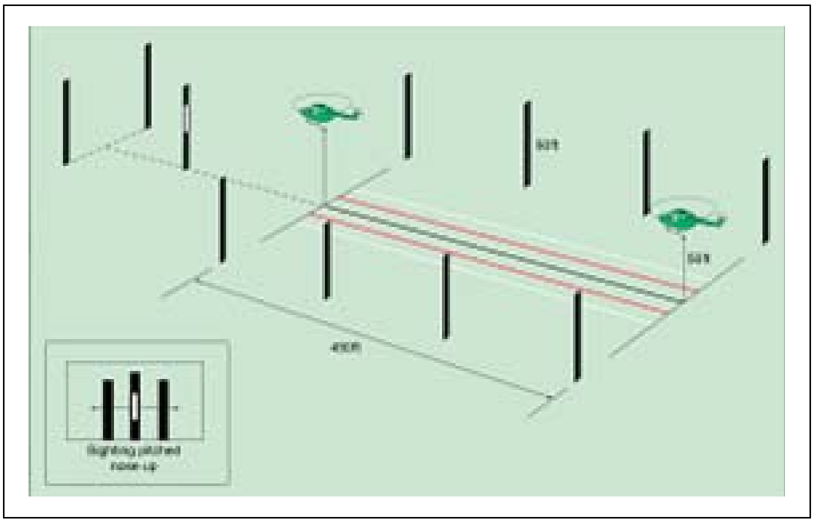


Figure 7 Course Layout for CONDVAL Acceleration-Deceleration Manoeuvre

A typical set of results from the AFS simulation trial for three levels of pilot aggressiveness is shown in Figure 8. The pilot accelerates the aircraft by commanding a nose down pitch attitude, accelerates to a maximum speed (approximately 40, 50, 65 ft/sec for the three aggression levels), reverses the pitch to initiate a deceleration, coming to a stop at a range of about 450 ft (150 m).

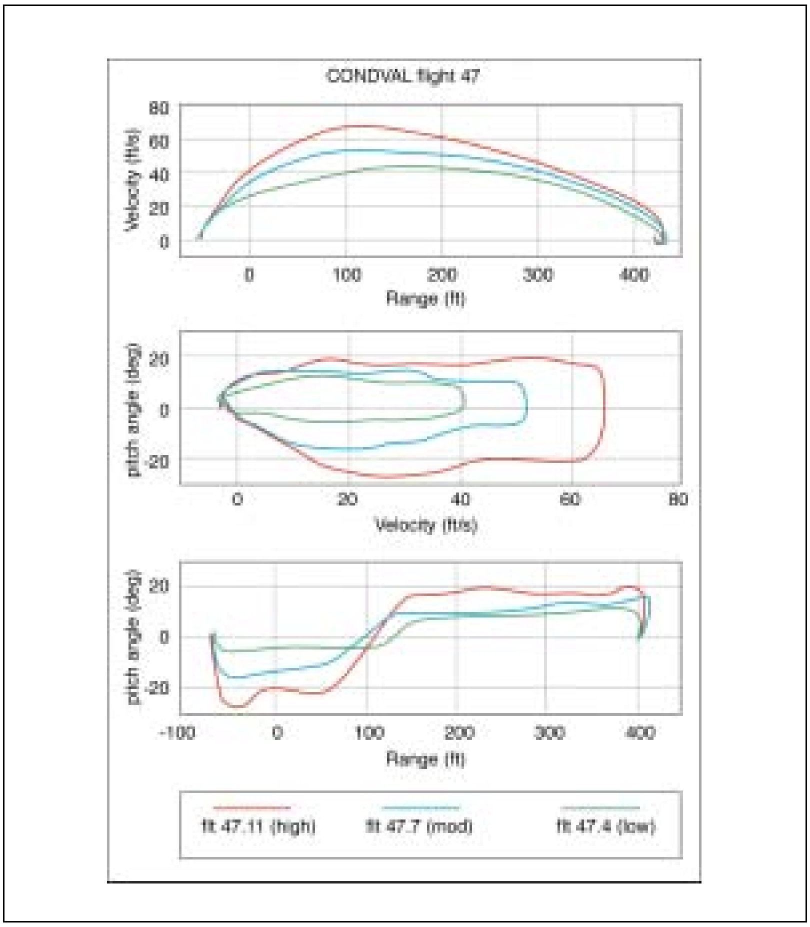


Figure 8 Typical set of Accel-decel results from the AFS CONDVAL Trial

The course markings on such manoeuvres are designed to provide sufficiently good visual information that the pilot can perceive whether the achieved performance is within the desired or adequate standards. Fifteen accel-decels were flown by three test pilots, at three levels of aggressiveness – low, moderate and high.

In the following analysis the relationship between the motion of the aircraft and the intrinsic guides introduced above is explored. The basic modelling technique adopted will establish the linear correlation between the motion tau, τ_m, the time t, and the guide tau, τ_g. Figure 9 shows a typical profile for the velocity and displacement as a function of manoeuvre time (36.2 = Flight 36, run 2). For the correlation analysis, the manoeuvre was assumed to begin when the velocity reached 10% of the peak velocity and to end when it had subsided to 10% of peak. The distance along the track is designated as X_s, to differentiate with the distance to go, X.

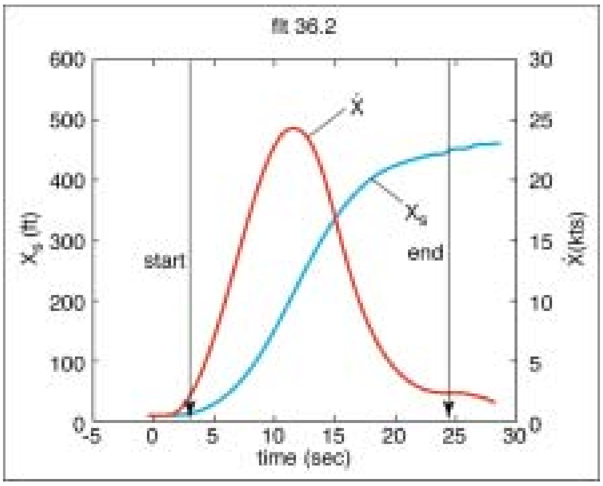
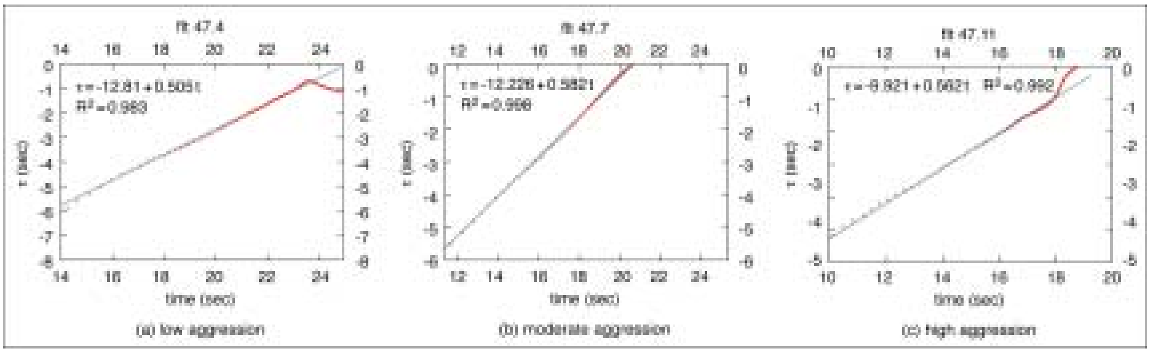


Figure 9 Typical Displacement and Velocity Profiles in the CONDVAL Accel-Decel (Flt 36.2)

Constant $\dot{\tau}$ Guides; Building on the previous tau-analysis for stopping scenarios, we begin with a study of the deceleration phase of the manoeuvre and an examination of the strength of the motion coupling with the constant $\dot{\tau}$ intrinsic guides. Figs 10a, b and c show the regression fit of the motion tau with time for flight cases, 47.4, 47.7 and 47.11, corresponding to pilot O flying with low, moderate and high aggressiveness.



(a) low aggression (b) moderate aggression (c) high aggression

Figure 10 Regression fit of Motion Tau vs Time – Deceleration Phase

The values of the coupling, in this case corresponding to the guiding $\dot{\tau}$, are 0.51, 0.58 and 0.56, with the correlation coefficients R^2 of about 0.99. In all three cases the fit degrades during the final few moments of the stopping.

As a guide to interpreting these results, Figure 11 illustrates the deceleration profile against time (normalised by initial τ under constant velocity) for a general tau guide moving with constant $\dot{\tau}$ (Ref 8).

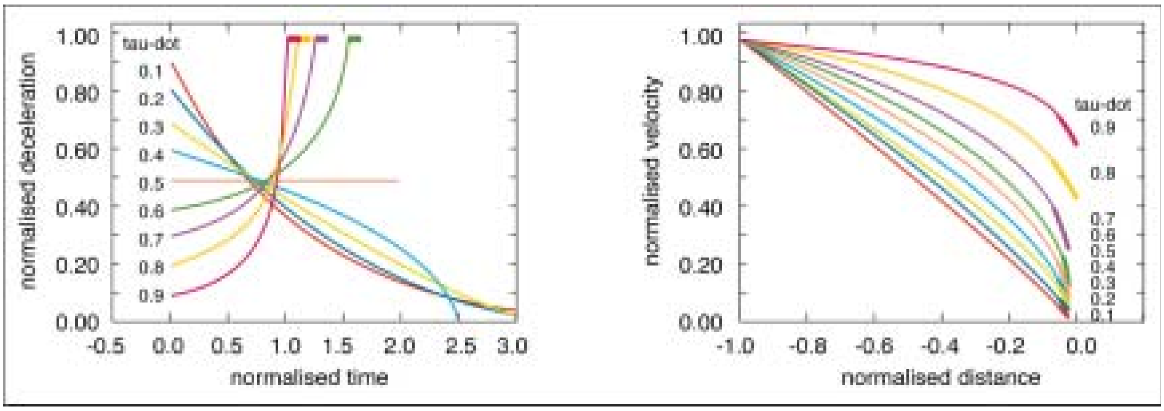


Figure 11 Kinematics of the Constant τ guide (from Ref 8)

All three cases in Figure 10 follow a profile for $\dot{\tau}$ between 0.5 and 0.6, showing how the deceleration (or pitch attitude) of the aircraft increases as the stopping point is reached. The degraded match close to the hover is hypothesised to arise from the need for the pilot to fly the final positioning with a reduced pitch attitude and different control strategy. The close correlation of the motion tau and guide tau during the deceleration phase suggests that the pilot is able to pick up visual information from the course layout that enables this close coupling to be maintained until close to hover, despite the high nose-up pitch attitude.

Constant Acceleration Guide; Maintaining constant $\dot{\tau}$ will only work as a guiding strategy when performing a stopping manoeuvre. To treat the whole accel-decel we need to examine the efficacy of the constant acceleration guide described by eqn (15). If we normalise the kinematics, then a motion which couples onto this motion guide through the relation $\tau_m = k\tau_g$, will take the form given in Figure 12 (a) – (d) (from Ref 6).

The bell-shaped profile of the velocity distribution and sigmoid profile of the displacement are reminiscent of the helicopter motion shown in Figure 9. The comparison of the helicopter motion tau and guide motion tau for the case Flt 36.2 is shown in Figure 13. Within a few seconds of the launch, the tau's show a consistent correlation through to the hover point. We can imagine the motion guide as a ball, initially at the same location as the helicopter and following the constant acceleration profile to the hover point, where it again meets the helicopter. The helicopter tau is always less than the tau of the ball. One can imagine the pilot developing the mental model of the aircraft motion as he or she rides in the ball, remaining behind the helicopter until they become one at the hover point.

Figures 14 - 16 show the graphs of τ_m vs τ_g and the comparison of the test data with the linear fit. Also shown are the velocity and displacement profiles of the test runs. For all 3 cases about 97% of the accel-decel data was used; only the first couple of seconds of the acceleration were truncated, when the pilot is settling into the manoeuvre (below 10% Vmax threshold).

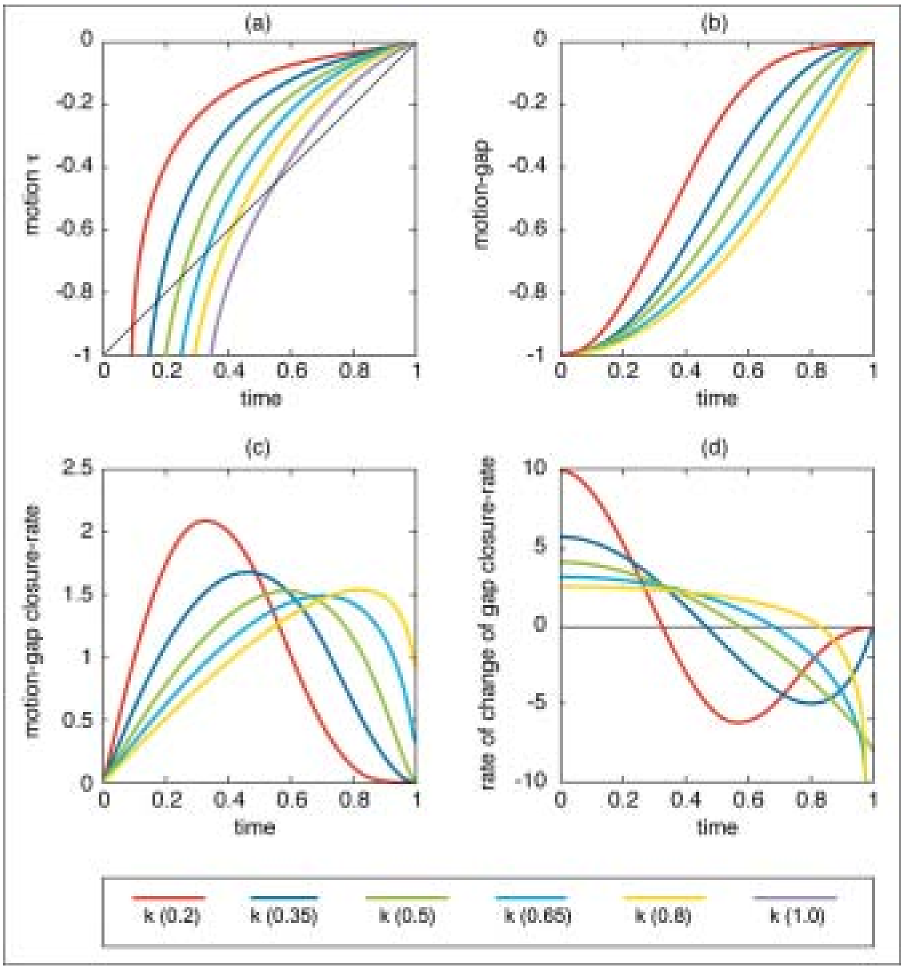


Figure 12 Kinematics of the Constant Deceleration Motion Tau (from Ref 6)

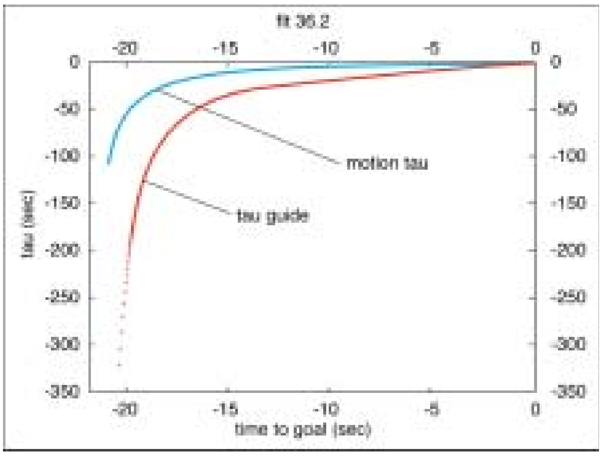


Figure 13 Comparison of Helicopter and Guide Tau's for Flt 36.2

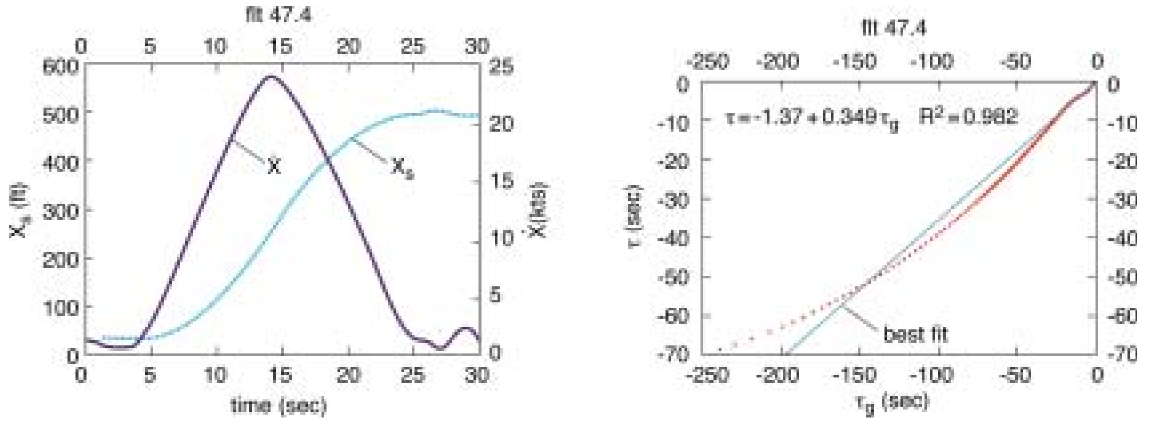


Figure 14 Correlation of Motion Tau with Guide tau; Flt 47.4 - low aggression

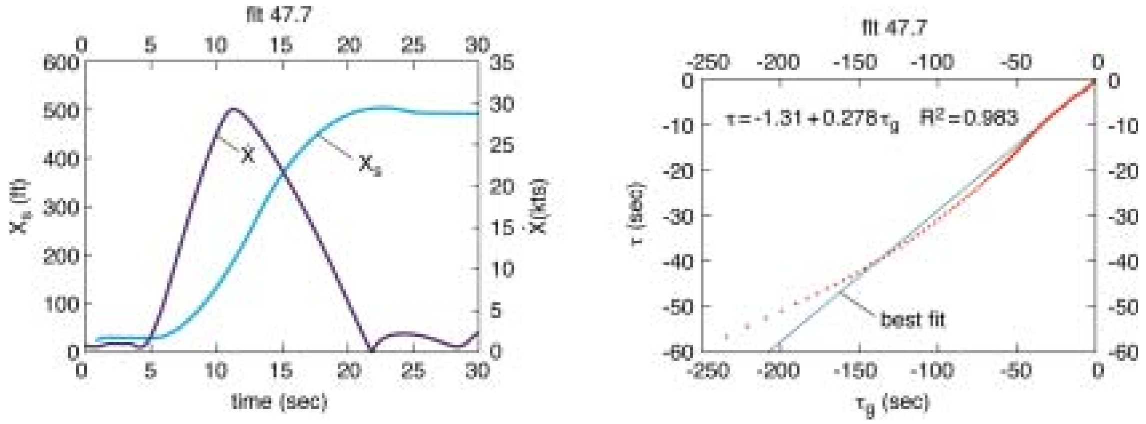


Figure 15 Correlation of Motion Tau with Guide tau; Flt 47.7 - moderate aggression

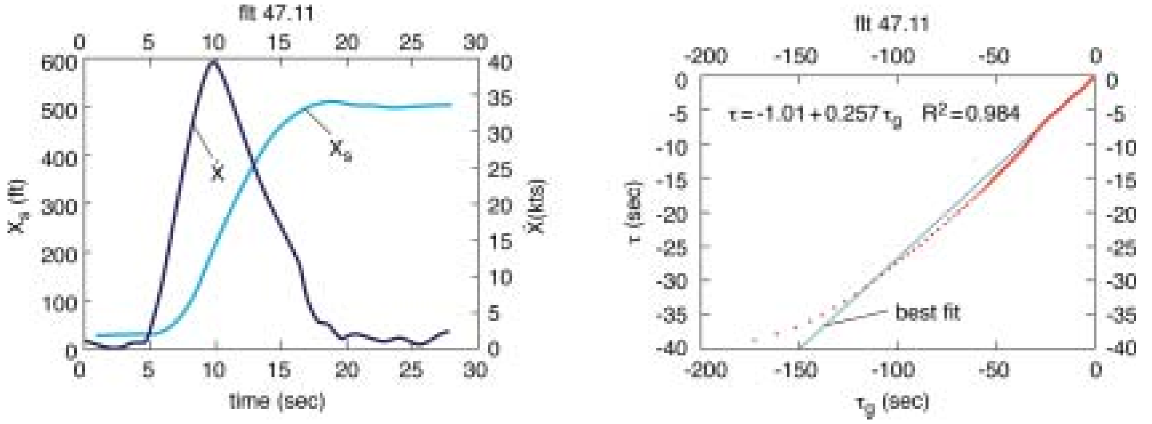


Figure 16 Correlation of Motion Tau with Guide tau; Flt 47.11 – high aggression

The coupling constant *k* varies between 0.26 (high aggression case) and 0.35 (low aggression case). The correlation coefficient is greater than 0.98 for all cases and the velocity profiles show consistency with the general guide profile in Figure 12, i.e. the later the velocity peak, the larger the coupling constant. If we consider all 15 accel-decels then the mean values of *k* follow the expected trend (low aggression, *k*=0.381; moderate aggression, *k*=0.324; high aggression, *k*=0.317). As the aggression level increases, the pilot elects to initiate the deceleration earlier in the manoeuvre; low aggression at 10 sec (0.5T into manoeuvre); high aggression at 4 sec (0.4T into manoeuvre). The pilot is more constrained during the deceleration phase. Figure 8 shows the pilot limiting the nose up attitude to about 20 deg at high aggression, even though attitudes of greater than 30 deg were possible purely from a performance standpoint.

The tau-coupling principle hypothesises that the pilot seeks features in the visual flow-field that provide consistent and continuous information on motion and allow the intrinsic tau-guide to be activated. The results from the CONDVAL simulation trial provide fairly compelling evidence that such a coupling is present and that sufficient optical information was available on the test course for the pilot to fly the manoeuvres safely. The handling qualities results reported in Ref 13 indicate that the desired performance was achieved. Handling qualities ratings (HQRs) of 4/4/5 were given for low/mod/high aggression cases respectively by pilot O. The pilot commented on the task 'cues' (Ref 13); "Overall visual cues were good but better in the acceleration compared to the deceleration phase. The tramlines gave good positional cueing and the poles gave good peripheral height cueing. The forward field of view was restricted compared to the Lynx, which might make the task a little easier in the real aircraft. At high nose up attitudes the large poles in the forward window provide a general idea of lateral and heading position and the poles in the side window gave a good indication of longitudinal position. However as aggression increased cueing was compromised by the degree of divided attention between the windows."

As noted in passing above, task 'cues' are introduced in stylised course layouts to ensure that the pilot has an equivalent visual scene content to what would be expected in the real world when flying such a manoeuvre. The process at arriving at such equivalence needs to have a sound engineering basis. This, and the related fundamental question of what information a pilot needs to guide and stabilise the aircraft, is at the heart of developing guidelines for pilot displays and synthetic vision systems. We continue the paper on this theme.

Developing Guidelines for Vision Aids and Synthetic Vision Systems

The collaborative research described in this paper aims to inform the development of guidelines for the requirements-capture and design of future display systems for low level tactical flight. An important aspect of such requirements is the level of stability augmentation in the host aircraft. The handling qualities performance standard, ADS-33E introduced the Usable-Cue-Environment (UCE) as a construct from which the stability augmentation requirements to achieve Level 1 handling qualities can be established. The design of any vision aid influences the UCE and hence we have a clear and important link between display and control augmentation. The UCE scale is illustrated in extended form in Figure 17. To achieve Level 1 performance when flying in UCE 1, a conventional rate response type will suffice. As we move through UCE2 to UCE 3, so increased augmentation in the form of attitude and velocity response types are required to enable the pilot to focus on guidance, rather than the workload-sapping stabilisation tasks. UCE 3 corresponds to conditions where the pilot is unable to achieve precision when flying tasks with any level of urgency, but the conditions are not so degraded that the surface and surrounding obstacles are not visible.

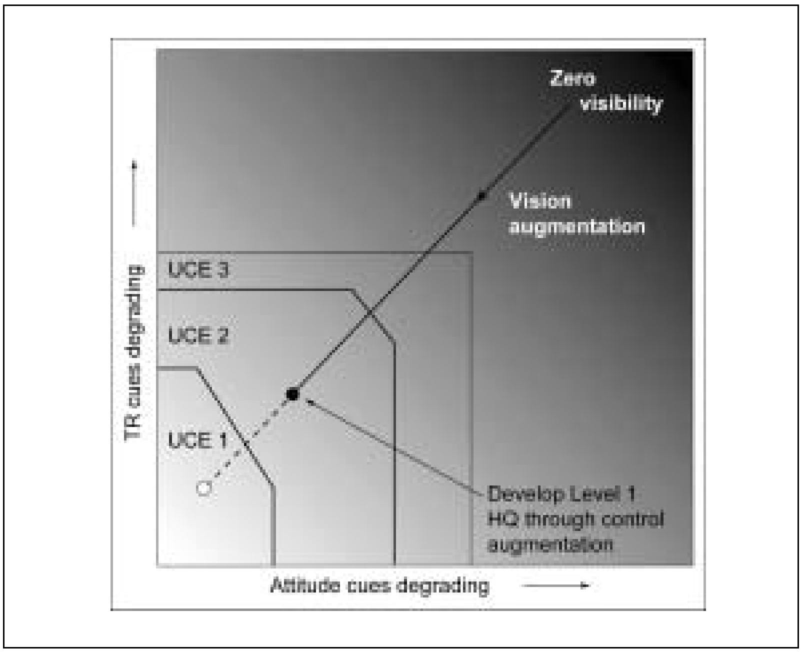


Figure 17 The Extended UCE Scale

The extended UCE scale in Figure 17 conceptualises that beyond UCE, conditions continue to degrade through to zero visibility. Free flight at NoE heights can only be conducted safely in these conditions through a synthetic vision system. Leaving aside the maturity of the technologies that will make such a system practicable, for it to be functional it must, arguably, provide a pilot with a consistent model of the outside world throughout the range from UCE2/3 to zero visibility. The vision augmentation system that brings the UCE into the 2/3 range on Figure 17, must essentially be complementary to any system that enhances the pilot's real outside world view with, for example, overlaid symbology. In addition, such vision augmentation needs to harmonise and be integrated with control augmentation. The fundamental requirement for such an integrated system is that it should allow the pilot to construct and maintain an accurate mental model of the future flight trajectory that is sufficiently prospective for safe flight. The nature of such an integrated prospective flight control system, its functions, failure modes and how it interfaces with the pilot needs to be investigated in research, and clearly there is considerable scope for innovation.

One of the conclusions from the exploratory analysis presented earlier in this paper is that tau-coupling offers a robust approach to the design of a synthetic vision system. The first stage in developing requirements for a tau-based prospective system is to quantify what visual information pilots use for performing manoeuvres like climbing, turning and stopping. Such a synthesis leads to a second stage where we examine how pilots cope when visual components are removed, through to conditions where insufficient information is available for safe flight, i.e. beyond UCE 3. Such degradation in spatial awareness and task performance will, in theory, be reflected in the correlation between the tau's of motion gaps or perhaps the pilot's inability to track an intrinsic motion guide through the poor visibility. A third stage takes us to the design of the re-constructed or synthetic world where the tau-coupling is restored and once again coherent. This 3-stage approach is being taken within the current UK research. In the first stage, a series of experiments have been initiated on the new moving base flight simulation facility at The University of Liverpool. The single seat cockpit pod is mounted on a 6-axis, hexapod, high-bandwidth motion system (Figure

18) and contains 5 outside-world visual channels presented to the pilot in the arrangement shown in Figure 19.

The first phase of this work included very simple tasks with limited flight degrees of freedom, guided to an extent by concurrent NASA research reported in Ref 15. Figure 20 illustrates the stopping area for a decel-to-stop manoeuvre over a flat surface. The task involves decelerating the helicopter from a defined initial speed to stop over the line, 2 grid squares in front of the vertical poles, which themselves were 2 grid squares ahead of a vertical wall. The visual information available to the pilot included the surface grid, and the vertical wall, poles and stop line. The grid size was either 50ft or 100 ft. Flying at a speed of 50 ft/sec at a height of 50 ft over the 50 ft grid gives exactly the same visual impression as flying over the 100ft grid at a height of 100 ft and velocity of 100 ft/sec.

Figure 18 The Liverpool Flight Simulator

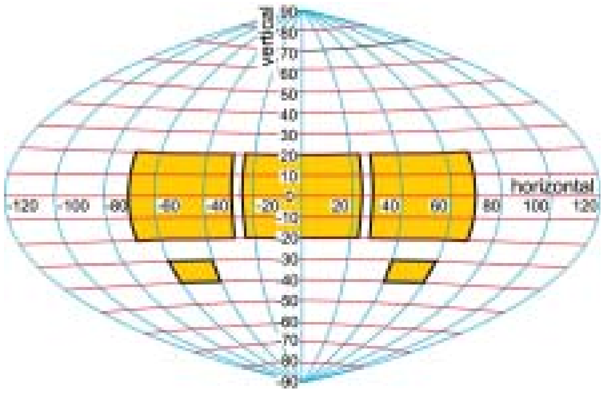


Figure 19 Cockpit Field of View in Liverpool Flight Simulator

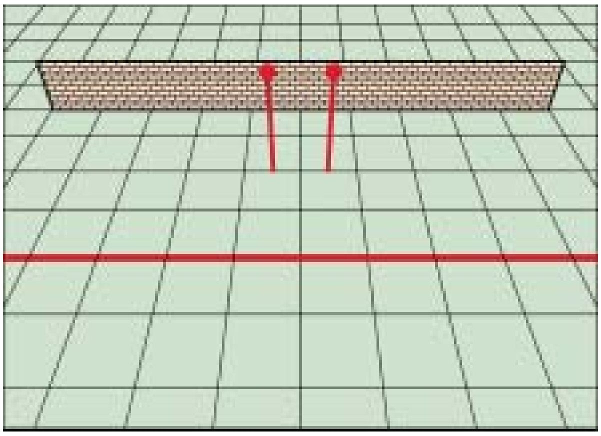


Figure 20 Stopping Area for Decel-to-Stop Manoeuvre

For these tests, the only degrees of freedom active in the simulation were pitch angle, controlled through conventional cyclic, and forward translation. All other motions were locked. The simulation model was the FLIGHTLAB generic articulated rotor helicopter, similar in configuration and dynamics (e.g. pitch rate response type) to the UH-60 Blackhawk. Six subjects, all non-pilots, were instructed to use the cyclic to decelerate the aircraft to a hover. Preliminary analysis of the data shows general consistency between subjects flying with various levels of aggressiveness, at different speeds and over different grid sizes. Figures 21 and 22 show a sample of results from 3 different subjects flying at three different initial speeds, 50, 75 and 100 ft/sec.

The left-hand plots in Figure 21 shows the range, velocity, deceleration and tau profiles. The right-hand plots in Figure 21 shows the τ profiles and a comparison of the motion tau (τ_m) with the constant acceleration guide (τ_g) according to equation 15. Also shown are the least squares fits of τ_m to τ_g. Note that the $\dot{\tau}$ values consistently increase to unity during the final 0.5 seconds of the manoeuvre, indicating that the subjects did not achieve a perfect stop. The coupling parameters are given by the slope of the fit function and are remarkably similar for the 3 cases. We can hypothesise that for such a simple, single axis, task the subjects pick up the same optical flow components from which the coupling strategy is activated. How to establish the value to prospective control of the various scene components is the subject of the continuing research, moving through to the second stage where 'scene-thinning' is carried out. Future simulation plans include examination of other simple manoeuvres, unlocking the secondary control axes for more complex manoeuvres (e.g. turn through gap, climb over rising ground) flown by helicopter test pilots, and different forms of scene content. Complementary to the piloted-simulation plans, a synthesis technique is currently under development whereby non-piloted 'constrained' simulations will be used to explore how pilot control strategies change when the available visual cues are changed. It is in the nature of such constrained simulation that the parameters of the pilot model reflect the changing task demands (Ref 16). In the current application we are developing a model that responds directly to errors in the tau-coupling; results will be reported on a future occasion.

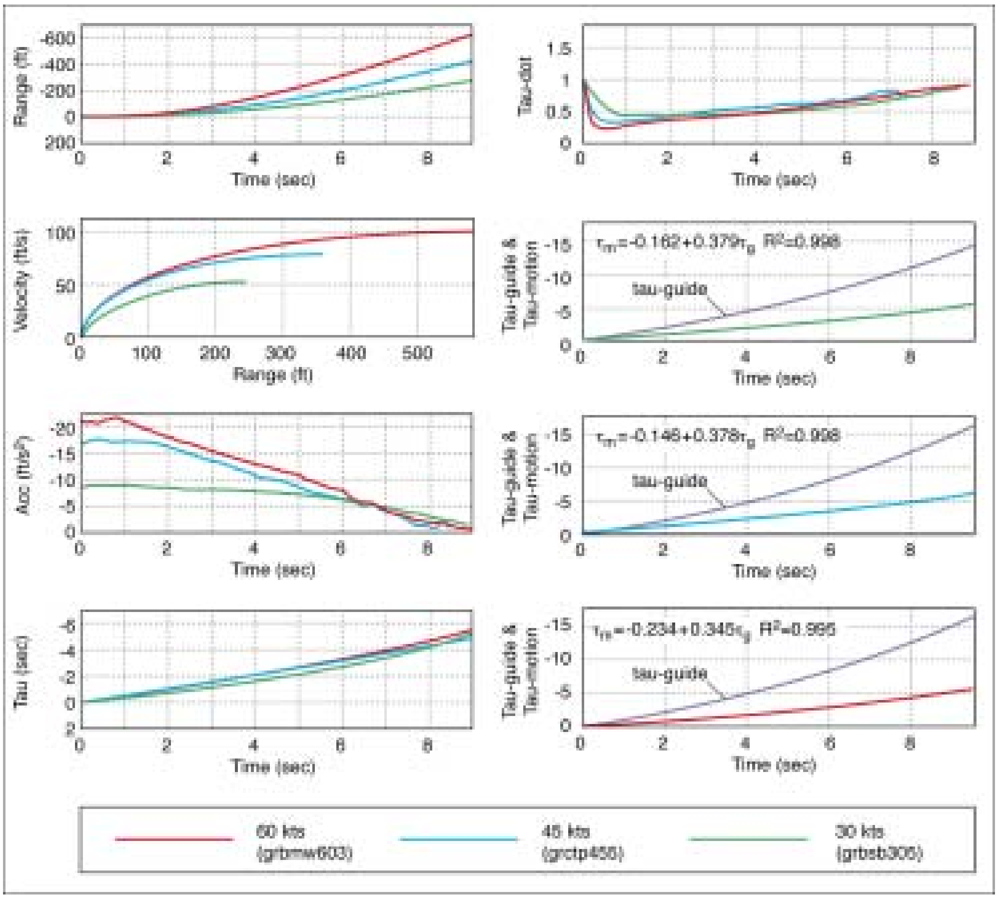


Figure 21 Decel-to-Stop Manoeuvre Results

Conclusions

This paper has presented the first application of tau-coupling to aircraft flight. The theory of tau-coupling has been considered within the context of helicopter flight close to the ground in a cluttered environment. Results derived from flight simulation tests conducted at DERA and The University of Liverpool have shown that when pilots fly stopping manoeuvres there is a close correlation between the motion-tau (i.e. instantaneous time to reach the stop point) and a pilot-generated tau-guide that can follow constant $\dot{\tau}$ or acceleration laws. The correlation is so tight that the inevitable hypothesis is that the tau-model of pilot visual perception and motion is eminently suitable for extension to other flight manoeuvres and forms a robust framework for the re-construction of visual information in pilot displays.

The answer to the question, 'how do pilots stop, turn or pull up?' is that they seek out the visual information from the optical flow on the surfaces, over and around which they fly, that provide for tau-coupling. When this information remains consistent and is sufficiently prospective, then the manoeuvres will proceed safely. When insufficient information is available to couple more than one motion tau, then the pilot creates a mental model of the prospective motion, from which a tau-guide is activated that leads the pilot along a safe flight path. Flight safety is only assured if the pilot has sufficient information for coupling motion tau's or following self-generated tau-guides. The tau-theory of visual perception provides a coherent framework for research into synthetic vision systems and, ultimately, the development of an integrated prospective flight control system.

Acknowledgements

The work reported in this paper was conducted by the authors for the Defence Evaluation and Research Agency as part of the UK MOD's Corporate Research Programme (Technology Group 5), under the technical authority of Malcolm Charlton at DERA Bedford. Special thanks are due to Julia Tims, Research Assistant in Aerospace Engineering at Liverpool, for the analysis of the data captured on the Liverpool Flight Simulator.

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Appendix E Review of Civil Regulations

1 Introduction

The review of the civil regulations was conducted taking account of the aims of the study and the type of operations under consideration, and includes the documents noted in Section 5 of the main report. The overall findings are discussed in the following sections. In each case a brief summary of the key points of interest is given, followed by comments concerning their relevance to the study.

2 JAR-27 and -29, Advisory Circulars AC 27-1B and AC 29-2C

The results from EMOCUES2 support the findings from the review of accident statistics that vehicle handling qualities play a significant part as contributory factors to helicopter accidents in degraded visual conditions. This was the case for VFR operations with both private, small rotorcraft and public transport rotorcraft.

The principal handling qualities and related requirements for civil helicopters are contained within the following JAR-27/-29[5] Sections:

- JAR-27/29.141 to 177 Flight Characteristics
- JAR-27/29.671 – 695 Control Systems
- Appendix B Airworthiness Criteria for Helicopter Instrument Flight

Referring to the accidents review again, other specific paragraphs of relevance and which can also influence handling qualities, include the following:

- JAR-27/29.773 Pilot Compartment View
- JAR-27/29.1303 Flight and Navigation Instruments

The Advisory Circulars AC 27-1B and AC 29-2C provide supporting explanatory material and evaluation procedures for the JAR requirements and so the two sets of documents were reviewed jointly. Note that these are referred to herein either individually, i.e. AC 27-1B and AC 29-2C, or collectively as the Advisory Circulars (ACs).

2.1 Subpart B - Flight Characteristics: JAR-27/29.141 to 177

JAR-27/29.141 General

Specifies general requirements for rotorcraft flight characteristics; the conditions under which they must be met (operating state and conditions, power-on, power-off flight etc.) are given in sub-paragraphs (a) and (b). The latter also specifies that the requirements must be met under *'…any operating condition probable for the type…'*, with mention of specific failure states (e.g. engine failures etc.). Paragraph (c) requires that the rotorcraft must have any *'…additional characteristic required for night or instrument operations*'. Instrument flight operations are covered in Appendix B, but further requirements for night operations are not specified and from CAA comments, aircraft that are cleared for day are usually cleared for night without any additional requirements.

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[5] As noted in the main report, JAR 27 and 29 have been renamed Certification Specification CS 27 and 29 following the formation of the European Aviation Safety Agency (EASA).

Advisory Circulars 27/29.141

Mentions that in testing against the requirements of (a), (b) and (c), the flight test crew '*…should be especially alert for conditions requiring great attentiveness, high skill levels…*'.

Comment:

The requirements reflect the general approach taken by the civil regulations to divide operations into either VFR or IFR categories, with no particular consideration given to the spread of degraded visual conditions encompassed by the former. In addition, although requirements for night operations are mentioned, they are not backed up by further detailed requirements as is the case for IFR and there is no explanatory material given in the ACs. The regulations have a clear 'catch-all' intention in the wording applied, as highlighted above, and it is considered that further explanatory/ advisory material concerning requirements for operations in degraded visual conditions (both by day and night) is warranted.

It is stressed in the ACs that in testing, attention should be given to identifying and addressing high pilot workload situations. IIMC and DVE cases clearly fall into this category and, regarding *'…any operation probable for the type…'*, the statistics show that such cases can and do occur - all aircraft operating at night are already in a potential DVE situation. Bringing these two issues together, it is considered that the AC should explain and develop the case for consideration and application of requirements to DVE operations, taking into account the associated pilot behavioural traits that lead to accident situations, as identified throughout this report.

JAR-27/29.143 – 177

These paragraphs specify controllability and manoeuvrability, flight controls mechanical and trim characteristics and stability requirements, where the latter address longitudinal and directional static stability, but not manoeuvre and dynamic stability.

Advisory Circulars 27/29.143 – 177

Explanatory material is given throughout for VFR and IFR operations and emphasis is placed on checking for '*…undue pilot workload, strain and fatigue…'* under those conditions. It is also explained that the stability requirements are intended to *'…require manageable pilot workload …under foreseeable operating conditions…'* (AC 27/29.171 sub-para (a)). Failure cases and the need for continued flight (AC 27/ 29.171 sub-para (b)) are also mentioned as special circumstances that could contribute to increased pilot workload etc.

Comments:

All of the JAR requirements are relevant to and intended to apply to all helicopter types and modes of operation, hence, the main issue concerns aspects that may be inadequately addressed, or missing altogether. In the accident cases considered, pilot workload was a key contributor driven by circumstantial factors such as vehicle stability, poor visual cues and division of attention. The JARs and the ACs rightly place emphasis on the first of these, but there are clearly gaps concerning the other factors where it is left to the discretion of the qualification test pilot to uncover potential problems. Moreover, the accident statistics seem to indicate that there is an equal (or higher) likelihood of encountering increased workload (and its consequences) due to poor visual cues and division of attention as for the occurrence of the failure cases that the JARs address.

Military requirements such as ADS-33 on the other hand have recognised the need for such requirements and, in addition to the general stability and flight control criteria such as provided in the JARs, as discussed above ADS-33 introduces comprehensive criteria for control augmentation requirements and vehicle stability and responses to control inputs specifically for DVE and divided attention operations. The latter are expressed in terms of numerical criteria for the short (attitude bandwidth), mid (attitude quickness) and long-term (control power – maximum attitude rate) attitude responses, which are backed up by extensive flight and simulation test data [15]. As discussed in Section 3.2 of the main report, the UCE concept and associated control augmentation requirements, i.e. response type criteria, are intended to ensure acceptable levels of pilot workload for DVE operations. While not necessarily a universal remedy for all accident scenarios, such criteria serve to alleviate pilot workload and can deliver attendant benefits to flight safety.

In addition, military requirements are usually much more prescriptive concerning flight controls mechanical characteristics (FCMCs) and provide objective criteria for control forces for spring centred control systems, trim characteristics, breakout forces etc. JAR 27.151 and 27.161 provide general qualitative requirements for FCMC while Appendix B provides further direction on FCMC requirements for IFR operations (see below). However, considering that FCMCs can have a direct impact on pilot work and the fly-ability of an aircraft, it would be appropriate to provide better guidance in the ACs on acceptable FCMCs for all civil operations. The FCMCs for the Basic configuration were particularly undesirable for the DVE conditions evaluated because they were poorly harmonised with the vehicle's stability characteristics and this should be reflected more explicitly in the civil regulations.

2.2 Subpart D - Control Systems: JAR 27/29.671 – 695

These paragraphs specify requirements for the flight control system in respect of its functionality, strength and failure characteristics. Points of interest include the following:

- JAR 27/29.671 – requires that '…control system must operate with ease, smoothness and positiveness…'.
- JAR 27/29.672 – for single failures for stability augmentation systems (SAS),

> *'…the controllability and manoeuvrability requirements…are met within a practical operational flight envelope…',*
>
> *'…The trim and stability characteristics are not impaired below a level needed to allow safe flight and landing…'.*

Comments:

The points noted above will have an impact on handling qualities and the criteria for SAS failures are particularly pertinent. It would improve clarity to define the required handling qualities envelope by specifying a desired level of handling qualities (e.g. low Level 2 – HQR 4-5) and appropriate criteria, as for example from ADS-33.

2.3 Appendix B Airworthiness criteria for instrument flight

Appendix B Paragraphs I – IX

These paragraphs define the additional requirements for IFR qualified helicopters. Those considered to be of most significance to this study include the following:

- Paragraph III Trim – must be possible to trim control forces to zero.
- Paragraph IV Static Longitudinal Stability – stick force must vary with speed so that substantial speed changes result in a clearly perceptible force, and for single pilot

operation, speed should return to within 10% of trim on release (under prescribed trim conditions) of the stick force.

- Paragraph VI Dynamic Stability – defines requirements for the mid to long period oscillatory modes for single and dual pilot operations.

Advisory Circulars

Mostly concerned with test procedures for demonstrating compliance with the requirements, but some additional points are emphasised as summarised below.

2) Trim

> *'…Essentially, the '…cyclic control should exhibit positive self-centring characteristics…'.*
>
> *'…Control system must '…permit small precise changes to flight path…'.*

3) Static Longitudinal Stability

> *'… positive static longitudinal stability is a key IFR requirement which assures a self-correcting airspeed response and allows the pilot to recognise any substantial change in speed…'.*

7) Controllability

> *'...Control harmony should be present. There should be no objectionable cyclic to collective or roll-yaw-pitch cross coupling…'.*
>
> *'…There should be no tendencies for pilot-induced oscillations…'.*

11) Cross-coupling

> *'…IFR handling qualities are enhanced by providing low levels of coupling between axes…'*

Comments:

The results achieved in EMOCUES2 for the two aircraft types emphasise the importance of the differences between the civil requirements for VFR versus those for IFR. If the Basic and ACAH types were to be assessed against the JAR requirements, it is likely that both would be cleared for VFR operation, but only ACAH for IFR operations. Basic would be eliminated because it has a cyclic stick with friction mechanical characteristics (ACAH has spring feel with a trim control) and poor stability characteristics and, hence, would not meet the IFR criteria for trim, static longitudinal stability or dynamic stability.

The accident statistics show that it is likely that both aircraft types can encounter severely degraded visual conditions when operating VFR, a situation where close attention to flight instruments is required and stable vehicle characteristics are highly desirable. That is, for operations in varying degrees of DVE, say from UCE 2 to 3 and beyond, the regulatory considerations for IFR and particularly those noted above, become increasingly relevant. Adoption of the JAR dynamic stability requirements (JAR 27/29 Appendix B VI Paragraph (a)) for both VFR and IFR types would be a helpful step towards eliminating such potentially accident-prone configurations as Basic.

2.4 Miscellaneous JAR-27/-29 Paragraphs

JAR 27/29.773 Pilot Compartment View

This paragraph specifies the general requirement for adequate and unobstructed pilot view from the cockpit and the ACs provide additional evaluation criteria and procedures. From the accident statistics, it appears that pilot situational awareness rather than cockpit view was the main problem. That is, pilot errors of judgement of proximity to objects or the ground during low-level flight. Obscuration of windscreens due to precipitation or sudden misting was another factor.

Comment:

The regulations appear to be adequate as a general requirement and, clearly, the impact of specific operational circumstances on cockpit view (e.g. operations to platforms, elevated landing sites) would be checked as part of normal clearance procedures. One aspect not addressed, though, which was noted by pilots in the EMOCUES2 trial, concerned the need for an adequate visual reference for attitude cueing. In a typical helicopter cockpit some part of the structure, e.g. the instrument coaming, would normally serve this purpose. In Trial 2, although the revised cockpit structure improved the view, it reduced its effectiveness as a visual reference. This had a notable impact on pilot workload, particularly for those visual conditions where the visual horizon was deliberately attenuated (i.e. Day and Night/DVE/Fog/Text cases).

JAR 27/29.1303 Flight and Navigation Instruments

This paragraph specifies the flight and navigation instruments that are required for IFR and VFR operations. For VFR operations with small rotorcraft (JAR-27), this includes an Airspeed Indicator (ASI), Altimeter and magnetic compass, but not an attitude indicator (AI). The latter is, however, mandatory for all other types and for IFR operations.

Comment:

It is perhaps surprising that JAR-27 does not specify an attitude indicator for VFR operations, although this is mitigated to some extent in JAR-OPS 3 Subpart K (Instruments and Equipment) under JAR-OPS 3-650, which requires that an attitude indicator is required for flight operations over water, out of sight of land or when visibility is less than 1500 m (see Section D4). It is considered that pilots would be poorly placed without an attitude indicator if faced with an inadvertent encounter with deteriorating visual conditions (as was the case in a number of the accident scenarios reviewed), particularly with an aircraft with poor attitude stability characteristics, e.g. Basic. From CAA comment though, it is unlikely that such aircraft would be qualified even for VFR operations without an attitude indicator. Notwithstanding, it would set a good example to better align the regulations with this basic safety standard.

3 ICAO ANNEX 14 Volume II

Annex 14 Volume II Chapter 5 Visual Aids

This document defines requirements for visual and approach aids for heliports, including:

- Designated approach, landing and take-off areas
- Obstacle-free approach paths
- Ground and air taxiway markings
- Air transit route markings
- Lights and lighting patterns
- Approach lighting systems
- Visual alignment guidance system
- Visual approach slope indicator

- Final approach, touchdown and lift-off area lighting systems

In general, given the cases under investigation these requirements do not fall within the scope of the current study, but there are some areas of relevance. For example, the requirements for 'Visual approach slope indicator' notes that such visual cues should be provided when the '…*Characteristics of the helicopter require a stabilised approach*…'. In addition, the requirements for 'Touchdown and lift-off area' (Chapter 5, Section 5.3.8) acknowledge that *'…surface texture cues…are essential for helicopter positioning during final approach and landing'*. Furthermore, it is recommended that *'…lighting should be provided at a surface level heliport intended for use at night when enhanced surface texture cues are required…'* (Chapter 5, Section 5.3.8.4), and that lights be arranged in a *'…pattern which will provide information to pilots on drift displacement…'* (Chapter 5, Section 5.3.8.5a).

Comment:

While acknowledging the importance of visual cueing for pilotage for the specified operations, it is not made clear exactly how and when the requirements should be applied in relation to visual operating conditions. Greater clarification would be desirable, particularly to take into account the possibility of operations in DVEs.

4 ICAO ANNEX 6 Part III

Annex 6 Part III Section 2, Chapter 3 Helicopter Performance Limitations

This document addresses operating conditions for helicopters operating in performance Class 2 or 3, including:

- Minimum required visibility for flight phases where a power-unit failure may cause a forced landing.
- Obstacle-free flight paths.
- Visibility conditions for performance Class 3 operations.

Of relevance to the study, requirement 2.3.1(a) stipulates that operators must define a minimum permissible operating visibility taking into account the characteristics of the helicopter, but not less than 800 m for performance Class 3 helicopters. In addition, operators must remain in sight of the surface. For Class 3 helicopters, requirement 2.3.2 states further that operations are not to be performed out of sight of the surface, at night or when the cloud ceiling is less than 600 ft.

Comment:

As with JAR-OPS 3 (see following section), there are a number of issues concerning visibility and minima that are not addressed by the ANNEX 6 requirements. For a given minima, the safety of operations will be dependent on factors such as the height and speed that the aircraft is flying at, and the available view over the nose of the aircraft. Hence, the comments given for the JAR-OPS 3 requirements are also applicable to this case.

5 JAR-OPS 3 (Commercial Air Transportation (Helicopters))

All Weather Operations

Parts 1 and 2 Sub-Part E

These two documents and their appendices address the rules for operating under reduced minima (i.e. Low Visibility Take-offs and Category II or III operations), and acceptable means of compliance. Topics covered include:

3.430 Heliport Operating Minima – General

3.440 Low visibility operations – General operating rules

3.445 Low visibility operations – Heliport considerations

3.450 Low visibility operations – Training and qualifications

3.455 Low visibility operations – Operating procedures

3.460 Low visibility operations – minimum equipment

3.465 VFR Operating minima

Minima are expressed in terms of meteorological visibility and Runway Visual Range (RVR). Of note, minimum visibilities are defined for VFR operations under controlled airspace rules, aerodrome/airfield rules and unrestricted airspace. The general requirement is set at a visibility of 5 km, but down to 800 m by day if permitted by the Authority. In addition, for operations where visibilities of less than 5 km are permitted, there is an additional requirement in Part 2 that *'…the forward visibility should not be less than the distance travelled by the helicopter in 30 s so as to allow adequate opportunity to see and avoid obstacles…'*. Hence, for example, the maximum speed associated with a visibility of 800 m would be about 52 kn.

In respect to this study, apart from the VFR requirements the emphasis of the rules is placed on operations to defined helicopter operating sites, e.g. heli-ports, heli-decks, for which they provide detailed requirements for the permitted operating conditions and operating procedures that are commensurate with flight safety. Of note, they also address flight crew responsibilities and actions to be taken in conditions of deteriorating visibility. That is, there is a general requirement that operators must address such procedures in the appropriate Operations Manuals, though no specific guidance is given as to what these should address. Operators must also ensure that aircrew are provided with adequate training for such eventualities.

Comment:

The statistics indicate that, on the whole, accidents tend to occur when the operating conditions have deteriorated beyond those permitted under the rules, i.e. as defined in the JAR-OPS. The statistics also indicate that such conditions are more likely to give rise to accidents under VFR operations en-route in unrestricted airspace as opposed to operations under controlled airspace and aerodrome/airfield rules. A factor in this is that the latter tend to involve better-equipped public transport helicopters with aircrews that are subjected to more rigorous training requirements.

For the former, factors that generally play a part in the probability of an accident include the aircraft's handling characteristics under the deteriorated conditions, the effectiveness of available visual aids (if any), pilot workload and situational awareness (including level of divided attention). Mitigating factors are the levels of aircrew training and experience. On the whole the regulations endeavour to address all of these factors and, clearly, it is their primary function to address the requirements for safe operations under all operational circumstance. While their emphasis on requirements for operations under controlled airspace and aerodrome/airfield rules would appear to be effective, the continuing occurrence of accidents in unrestricted airspace suggests that the related requirements need to be reviewed and strengthened in this context.

Regarding the requirements for visibility, there are a number of issues that need to be considered that are not mentioned in the documentation. For example, with a minima of 800m safety of operations will be dependent on factors such as the height and speed that the aircraft is flying at, and the available view over the nose of the aircraft. That is, at heights of 1000, 2000 or 3000 ft the look down angle for 800 m over the ground (i.e. assumed limit to forward visual range) will be roughly 20, 40 and 50 deg respectively. Even with an increased visual range of 1.5 km the look down angles would be 10, 20 and 30 deg respectively. With any degree of attenuation of the visual horizon, look down angles of more than 15-20 deg would mean that the pilot would be virtually flying on instruments due to lack of visual cues in the forward field of view. At the same time, with 800 m visibility the requirements allow a ground speed of about 52 kn (i.e. the speed at which the aircraft would travel 800 m in 30 s), which might pose problems in any significant (say 20 kn plus) tail wind.

Instruments and Equipment

Part 1 Sub-part K

Requirements for flight and navigational instruments, and other equipment such as anti-collision lights, landing lights, radio communications etc., for day/night operations under VFR and IFR, are covered by this sub-part. Points of interest include the following:

JAR-OPS 3.650: For Day VFR operations an attitude indicator and stabilised direction indicator are only required for helicopters '…with a maximum certificated take-off mass of over 3175kg or any helicopter operating over water, out of sight of land or when visibility is less than 1500m...'.

JAR-OPS 3.652: For IFR or night VFR operations an attitude indicator and stabilised direction indicator are both required. In addition, under paragraph (n)'…a chart holder in an easily readable position which can be illuminated for night operations…' is required for IFR operations.

Comment:

As discussed in Section D2.4 above, it is considered that small rotorcraft should also be required to be fitted with an attitude indicator to allow for inadvertent encounters with deteriorating visual conditions. It would also seem sensible that the IFR requirement for the chart holder be extended to all operations at night; the circumstances affecting accident Case 1 (Table 2) seem to be particularly relevant to this requirement.

Communication and Navigation Equipment

Part 1 Sub-Part L

This sub-part covers requirements for communication and navigation equipment for day/night operations under VFR and IFR. Points of interest include the following:

JAR-OPS 3.860: For operations under VFR over routes navigated by visual references, radio equipment is required to enable communications with ground stations and air traffic control facilities, and receive meteorological information.

Comment: It is noteworthy that even when communications are available to provide appropriate navigation and meteorological information, pilots can still become lost when navigating by visual references at night over sparsely populated terrain, as was the case with accident Case 1. This emphasises the need for improved guidance and training for aircrew for such eventualities in order to help prevent similar accident scenarios from developing.

6 CAA Flight Operations Department Communications (FODCOMS)

A number of FODCOMS issued by the CAA were included in this review because they address issues and concerns that arose from the accident covered by accident Case 1 (Table 2). Following this accident, the CAA in consultation with the Air Accidents Investigation Branch (AAIB), revised the requirements for aircrew training and the weather minima for night VMC operations. These culminated in legislative changes, which were introduced into Air Navigation Order (ANO) 2000. Subsequent FODCOMS have been issued to supplement and clarify the ANO requirements; these are discussed below.

6.1 CAA FODCOM 11/2001 VMC Public Transport Helicopter Flights at Night

This note sets out to clarify and update the minimum weather requirements for night Public Transport flights under VMC in accordance with the legislative changes introduced in ANO 2000, and also to align the UK requirements with JAR-OPS 3.465 criteria. The approach adopted by the CAA was to specify criteria for night VMC flights that are capable of entering IMC and those that cannot enter IMC (i.e. the pilot/ helicopter combination is either equipped or not equipped for, and capable of IMC operations). For the former, the minima for night VMC operations include: a visibility of not less than 5km; a forecast cloud base of not less than 1200ft above the highest terrain within 5nm of the planned route. For non-IMC combinations, the cloud base requirement was increased to 1500ft.

6.2 CAA FODCOM 5/2002-1 Training and Checking Required for a Public Transport Helicopter Night Qualification, for Flight Crew whose Licence does not include an Instrument Rating

This note sets out the training and checking requirements for compliance with the ANO regarding the Operator Proficiency Check (OPC)/Skill & Proficiency Check (Night Qualification). The ANO specifies that the OPC is required for flight crew whose licence does not include an instrument rating as a prerequisite for carrying out Public Transport night operations. The objective of the check is to demonstrate that the candidate has the skill levels deemed necessary (by the ANO) for safe conduct of VMC night operations.

The OPC requires that the pilot should demonstrate the ability to:

- Operate the aircraft within its limitations;
- Complete all manoeuvres with smoothness & accuracy (generally within height ±150ft, heading ±10 degrees, speed ±10kn);
- Exercise good judgement and airmanship;
- Apply aeronautical knowledge;
- Maintain control at all times such that the successful outcome of the manoeuvre/ procedure is never in doubt.

To this end, the pilot has to demonstrate the ability to fly the aircraft solely using instruments in a general handling exercise (including recoveries from unusual attitudes) and emergency homing (navigation to a nominated point) and let down procedures (instrument let down to an airfield).

6.3 CAA FODCOM 5/2002-2 Helicopter Single Pilot Night VMC Public Transport, when an Autopilot has become Unserviceable

This note sets out to clarify issues regarding the ANO requirement for the fitment of an autopilot for night VMC operations. The ANO requires that a crew of two pilots is required unless the aircraft is fitted with a serviceable autopilot that has at least altitude and heading hold modes. The FODCOM addresses the requirements and duties for the second pilot and the operational requirements concerning the case of autopilot failures. The main point of note is that single pilot flights are not permitted unless the autopilot's roll, pitch and yaw attitude stabilisation modes are serviceable.

Comment:

All three FODCOMs address issues that are of general relevance to flight safety in the case of an unexpected encounter with degraded visual cueing conditions en-route. Weather minima are specified to provide an operating margin so as to reduce the likelihood of occurrence of such situations, and the associated aircraft equipment fit and aircrew training requirements serve to mitigate the probability of an accident in the event that such encounters happen. The question of whether such measures could be more widely applied to all civil aircraft operations, including private, small rotorcraft operations is raised in the discussion in Section 5 of the main body of the report.

Based on the evidence from the accident statistics and results from the EMOCUES2 trial, other critical training issues that might be addressed more rigorously through such measures include transition from visual to instrument visual flight and divided attention operations when navigating by external references. FODCOM 5/2002 covers transition to instrument flight only in the climb out and it is desirable that more extensive checks be incorporated to cover situations that might occur when enroute. Similarly, loss of situational awareness associated with visual navigation can become a major distraction for single pilot operations and again, it is desirable that some form of visual navigation check be incorporated to cover this situation.

Appendix F Helicopter Pilot View

QinetiQ Report reference DRA/AS/MSD/CR95005/1 authored by A. J. Smith and H. J. Foster, originally published in June 1995 and subsequently published by CAA as CAA Paper 95014.

Abstract

The results of a study into the field of view available to civilian helicopter pilots are presented. The influence of weather conditions is addressed.

Executive Summary

The maintenance of high levels of safety and regularity of operations in the civil helicopter environment requires that all aspects of the operation are constantly reviewed and research initiated where enhancements are considered necessary.

The importance of adequate visual cueing for helicopter pilots was highlighted during a recent CAA research programme investigating helicopter handling qualities. There are two main elements to the visual scene; size (field of view) and content (visual cueing). This report investigates field of view issues. The visual scene is increasingly important as industry requirements for low visibility operations increase.

There are three areas of investigation within this study, these are:

- The extent of previous research in the area of visual cues for helicopter approach and landing.
- Collation of field of view data for a number of helicopters representative of the main types used in the U.K.
- Review and comparison of civil and military requirements.

The conclusions reached as a result of an extensive literature search and practical investigations include:

1. The basic field of view provided by the civil helicopters examined does not seriously affect operations in good visibility conditions.
2. In many instances, the available field of view is eroded by instruments/displays fitted in the cockpit (GPS, map displays etc.).
3. There are no minimum specifications for cockpit field of view in the civil industry, only advisory circulars showing acceptable methods for compliance with visual specifications (FAR, BCAR etc.). If these methods of compliance were to be developed into a minimum specification and enforced then some of the associated visual scene problems would be solved.
4. During precipitation or in the presence of other contaminants, the wiper swept area becomes the only useable segment of the windscreen thereby significantly reducing the available field of view.
5. During low visibility conditions, normal operating procedures for the aircraft can significantly reduce the effectiveness of the available field of view.

1 Introduction

The maintenance of high levels of safety and regularity of operations in the civil helicopter environment requires that all aspects of the operation are constantly reviewed and research initiated where enhancements are considered necessary.

The importance of adequate visual cueing for helicopter pilots was highlighted during a recent CAA research programme investigating helicopter handling qualities. There are two main elements to the visual scene; size (field of view) and content (visual cueing). This report investigates field of view issues. The visual scene is increasingly important as industry requirements for low visibility operations increase.

Before initiating a major project on this subject the CAA tasked the DRA (All Weather Operations) with the conduct of a study having the following objectives:

- A literature search to ascertain the extent of previous research into the subject of visual cues for helicopter approach and landing.
- The collation of field-of-view data for a number of helicopters representative of the main types used in the U.K.
- Review and comparison of civil and military requirements.

This paper presents the results of this study and identifies potential areas for further research.

2 Literature Search

A literature search was initiated at DRA Bedford using the key words: *helicopter, approach, landing, takeoff, take-off, take off, visual cues, visual approach, instrument approach*. 12 of the 25 papers thus identified, whose abstract suggested some degree of relevance to the topic, were obtained for detailed review. Also included for reference were specifications in FAR Chapter 27, BCAR Chapter 29 together with Advisory Circulars 27-1 Chapter 2 and 29-2a Chapter 2. The 12 papers are listed below:

1. *A Pilot Questionnaire Study Of Cockpit Visibility Requirements For Army Helicopters*, R.E. Ferrand : Civil Aeronautics Administration, Indianapolis. (1958)
2. *Comparison Of Visual Performance Of Monocular And Binocular Aviators During VFR Helicopter Flight*, Cptn. T.L. Frezell, M.A. Hoffman : US Army Aeromedical Research Laboratory, Alabama (1975)
3. *Decision Height Windows For Decelerating Approaches In Helicopters - Pilot/ Vehicle Factors And Limitations*, R.H. Hoh, S. Baillie, S. Kerelink, J.J. Traybar : DOT/ FAA/CT-90/14 (1991)
4. *Supplemental Visual Cues For Helicopters Hovering Above A Moving Ship Deck*, M. Negrin, A. Grunwald, A. Rosen : Israel Institute Of Technology (1989)
5. *Approach And Landing Guidance*, A.J. Smith, E.J. Guiver : RAE Bedford (1991)
6. *Development Of A Pilot Model For Helicopter Visual Flight Task Segments*, A.V. Phatak, M.S. Karmali : Analytical Mechanics Associates, California (1982)
7. Visual Cueing Aids For Rotorcraft Landing, W.W. Johnson, A.D. Andre : NASA Ames Research Centre, California
8. *Pilot Use Of Simulator Cues For Autorotation Landings*, W.A. Decker, C.F. Adam, R.M.Gerdes: NASA Ames Research Centre, California

9 *A Study To Determine The Characteristic Shapes Of Helicopter Visual Approach Profiles*, G.C. Moen : US Army Aeromedical Research And Development Centre

10 *Helicopter Fog Flying Trials*, N. Talbot, M.L. Webber : CAA, London

11 *Heliport Visual Approach Surface: High Temperature And High Altitude Tests*, S. Samph, R. Weiss, C.J. Wolf : FAA (1990)

12 *An Analysis Of Visual Tasks In Helicopter Shipboard Landing*, K.S. Berbaum, R.S. Kennedy : Essex Corporation, Florida (1985)

The research reported was heavily biased towards military operations, but since many of the landing problems are common to all helicopter operations, the data are of relevance to civil operations. The only material specifically targeted at civil helicopter operations was found in a CAA paper, which reported a fog flying experiment conducted with DRA Bedford.

The results from a questionnaire given to military rotorcraft pilots are detailed in Paper 1. The authors concluded that:

a) Field-of-view (FOV) requirements are not significantly influenced by pilot experience.

b) The downward FOV of the helicopter is assessed as adequate for all landing manoeuvres if it extends 29° below the horizon.

c) The forward and upward FOV is of significance only for take-off manoeuvres.

d) Visibility to the side is critical in confined areas; to be rated adequate the azimuth FOV must be at least 90°.

In Paper 2, the results of flight trials that used an eye mark recorder to determine the scan used by pilots in various manoeuvres are presented. With regard to the landing phase it was concluded that:

a) With the pilot in the right hand seat the visual cues to the left of the pilot were used infrequently.

b) The chin bubble windows were used infrequently.

The trials reported in Paper 3 were carried out to determine the size of the delivery envelope required for instrument approaches to a visual deceleration phase commencing at the decision height. The data is nearly all related to helicopter performance and handling limits at low speed. Only in the case of low approaches, when obstacles became a significant concern, was there any consideration of visual cueing. No quantitative data is presented. There is an indication that in a poor visual scene environment, increased demands may be put on helicopter performance capabilities.

The data in Paper 4 relates to an analysis of the problems associated with landing a helicopter on a moving ship. The authors noted that the main problem in the task arose from the lack of inertially stable visual references. This absence of useable cues is important because '*the pilot's main source of information originates from the visual field'.* The authors of the present paper are familiar with these problems and their potential solution but, due to the nature of civil operations (even those offshore), this particular area of research is not of prime importance.

Paper 5 presents data largely related to a review of non-visual guidance aids. The data presented describes the characteristics and performance of hardware under development for use on board ships. Some of the hardware is directed towards improving the visual task. Since this report is devoted to the ship landing problem it, again, contains little of particular relevance to the present study, although it does identify the need for research into hover and landing aids.

In Paper 6 work is described to develop a mathematical model of the pilot task in visual flight. This paper was published in 1982 and comments that '*the weakest link in applying a model based approach lies in not being able to define what a pilot actually does with the information provided by visual cues*'. However, there is some discussion of what are called '*plausible descriptive mechanisms'*. This paper concludes that flight simulation trials are required together with flight trials.

The results from a simulator trial using three approach lighting configurations are reported in Paper 7. The authors do not seem to be aware of some basic aspects of visual cueing during an approach to land and the paper therefore contains no useful new data.

Paper 8 is primarily targeted at simulator issues. Although not directly related to the present study the investigation did raise some issues of relevance. The simulation utilised military and civil pilots. The approach to land procedure is significantly different between the two sets such that the civil pilot has greater access to the visual scene compared to the military pilot because of the procedure adopted, particularly during the deceleration.

In Paper 9 the relevance of pitch attitude profiles during the final phase of approach is highlighted. In good visual conditions high pitch attitude control activity, maximum deceleration and pitch attitude changes all occurred within 120*m* range from the helideck with attitude changes of up to 11.5° recorded.

Paper 10 reports on a research project investigating the all weather operations capabilities of helicopters looking specifically at reduced visibility approach/landing tasks. The investigation was an attempt to quantify the special considerations given to helicopters for their unique operational capability. Standard fixed-wing visual aids were utilised. The trials were carried out by the CAA and the DRA at Bedford using simulation and flight test. These trials demonstrated that:

a) Helicopters can land from large lateral offsets in clear conditions.

b) This manoeuvrability cannot be utilised for low visibility operations due to the restricted visual cues.

c) Helicopters could operate in more restricted RVR conditions if helicopter specific cues and lighting patterns were provided.

d) Size of the visual segment (amount of approach lighting visible to pilot) is strongly dependant on cockpit cutoff angles, including side and chin windows.

e) In low visibility conditions the visual segment determines the minimum RVR allowable for each type of helicopter.

f) The landing decision is affected by the offset due to visual cue acquisition positions.

g) In low visibilities the nose can only be raised by a maximum of 5° in pitch before the visual cues are reduced significantly.

Paper 11 deals mainly with the handling qualities of helicopters at the high altitude/ high temperature end of operations. Very little new and useful information relevant to the study was available in this report.

Paper 12 is a report based on a military research programme to investigate the recovery to ship operation of helicopters and is not of direct relevance to the civil industry. However some of the conclusions reached are relevant and include:

a) '*All pilot's have a tendency to rely on eyesight above and beyond all else*'.

b) The more important visual cues during the approach to hover are artificial.

c) Chin windows play a significant part in the hover phase and cues on the deck are utilised to maintain the position relative to the deck.

In summary, in the papers studied in detail one thing is clear: cues in the visual scene are a key factor in the approach and land task of helicopter operations, particularly under low visibility conditions.

3 Helicopter Field of View

Evidence from the literature search suggests a strong link between available FOV and a pilot's ability to perform certain tasks such as take-off, approach and landing. While this connection has been recognised in military aircraft design, there is a lack of evidence that the importance of the relationship is acknowledged in the civil industry. Guidelines exist (AC 27 and 29) for defining an acceptable visual window, but these are only guidelines and not enforceable. Most military helicopters will, in future, have a known and diagrammatically represented visual envelope (see Figure 5). In order to develop a database of fields of view currently available in the civil industry an empirical method to derive helicopter cockpit FOV was developed for this project. The method relies on measurement techniques and trigonometric analysis of the data and comprises the following steps;

a) Derive the pilot's eye position in plan view and mark it. This is achieved by the viewer (pilot) lining up two markers (the further apart the markers the greater the accuracy) in the dead ahead direction, and two markers in a direction not less than 60° from dead ahead. The two lines thus defined should intersect at a point below the pilot and coincident with the eye position.

b) Measure the pilot's eye height relative to the ground.

c) The pilot then indicates points on the ground around the helicopter, coinciding with cut-offs caused by the helicopter structure. These points would ideally be corners at the intersection of elements of cockpit structure. A number of positions are marked in this way.

d) The marker position is then defined by an angle from dead ahead and a distance from the plan eye position.

e) This then gives the azimuth extent of the point and the elevation angle can be derived from trigonometry.

These steps work well for the areas where the pilot can locate a ground based marker. When the overhead windows are also considered then a second technique is adopted which is based on angular measurements relative to data points defined above.

An assessment of S-61 and S-76 helicopters took place at Beccles using the above method. The data derived for the S-76 is detailed in Figure 4, data obtained for the S-61 was not useable in this instance but Appendix A does contain data derived from a Sea King which is a derivative of the S-61. Appendix A contains examples of FOV from other helicopters and demonstrates the different formats employed for presenting this data.

4 Discussion

This paper forms part of a research programme the purpose of which is to establish the means to specify and achieve an adequate visual scene for helicopter approach and landing operations. There are three basic areas to be addressed:

a) What is the pilot's task, i.e. what operations are to be carried out using external visual references?

b) How does the FOV as defined by the shape, size and disposition of the helicopter windows influence task achievement as the pilot manoeuvres the aircraft?

c) What visual cues does the pilot require to perform the specified operations safely and routinely, and how can these be provided?

The third area is the main focus of the research reported in this paper. The two remaining areas have a direct influence on the work due to the link between task difficulty and quantity/quality of information provided to the pilot to perform the task. The literature search provided a limited amount of information on the pilot task, the influence of the FOV and the role of the visual scene content. The most comprehensive and relevant data was identified in the fog flying trials work conducted by the CAA and the DRA reported in Paper 10.

In good visibility conditions, helicopters have an adequate FOV for most operations. There are strong similarities between rotorcraft and fixed wing initial approach phase requirements under all weather conditions. In both cases the pilot requires good cues in the sector immediately ahead of the aircraft. Cues in other directions are of limited value because, during the initial approach, the pilot is primarily trying to assess the degree of disparity between the velocity vector and the desired aiming/landing point in order to take necessary corrective action to make them coincide. Thus for the initial phase of the approach the FOV over the nose and the visual aid requirements are generally well understood and provided for. Practical difficulties arise when it is not possible to display conventional aerodrome lighting patterns due to facility size or when visibility conditions limit the forward view.

The helicopter/fixed wing requirements alter significantly when the helicopter enters the deceleration segment of the approach. During this manoeuvre, which is unique to helicopters, pitch attitude changes are much larger than those applied to control a steady speed fixed wing approach. In addition, as the helicopter decelerates it becomes increasingly susceptible to the effects of cross winds. The overall effect is to increase the visual area around the helicopter which can be detrimentally obscured either continuously or on an intermittent basis by these attitude changes.

As the helicopter enters the hover and landing phase, the FOV that the pilot needs to scan is further increased. At restricted sites such as helidecks on oil rigs, the aircraft may have to come very close to obstacles which may be difficult to see from the cockpit. Thus, FOV requirements are of greatest importance at the end of the landing sequence. The inter-relationship between task, FOV and visual cues is summarised in Table 1.

Task	FOV currently provided	Visual Cues Environment
Initial approach	Adequate	Adequate cues for line-up and glide slope can be provided by conventional lighting at large heliports. For smaller heliports, lack of space to deploy conventional lighting patterns can cause limitations, particularly for low visibility operations.
Deceleration	Adequate in good visibility, benign conditions. Inadequate in bad weather conditions	Adequate ground based cues become increasingly difficult to provide due to large areas of obscuration caused by helicopter pitch attitude changes. Requires cues over a large area ahead and around the helicopter to make best use of available fields-of-view.
Hover and landing	May be inadequate in all visibility conditions	Primary areas of interest are close to the helicopter and may include obstructions. Adequate cues, particularly at small heliports may only be available from visual aids mounted in the vertical plane.

Table 1 Task, Field of view and Visual Cue Relationships

Figures 1 to 3 show photographic views from two helicopter types commonly used for offshore operations. Figure 1 shows the windscreen area of an S-61. Figures 2 and 3 show the windscreen area of an S-76 which is a purely civil aircraft. It can be seen that the S-61 has a far greater windscreen area available to the pilot, indeed the wiper swept area of the windscreen is also comparatively large compared to the S-76. The S-61 is the airframe on which the Sea King military aircraft is based. Appendix A contains examples of FOV data gathered for seven other aircraft. All diagrams are representative of a clean aircraft with no retrofitted equipment such as GPS receivers, map displays or weather radar. Of these diagrams the Sea King is similar to the S-61 which was evaluated at Beccles (data not shown), the Super Puma is similar to the S-76 also evaluated at Beccles with derived data shown in Figure 4.

The problems associated with available FOV have already been addressed and solutions found. These solutions have been enforced, for operational reasons, in the military industry (MIL Stan 850B) but exist only as guidelines for civilian designers. The purpose of MIL Standard 850B is to establish criteria for providing adequate external vision for the aircrew stations of all military aircraft. Criteria are defined for minimum acceptable external vision based on the datum eye position for each crew member. The extent of the external vision is dependant on normal operations and typical mission scenarios, but basic criteria exist for all class of aircraft during the approach and landing phases of operation. Downward and forward vision enabling the pilot to use all available and relevant landing aids, is to be provided in all aircraft. The standard specifies:

a) The transparent area in azimuth and elevation for a range of aircraft types, missions and aircrew positions.

b) A maximum width for structural obstructions within the transparent area.

c) The clear vision area which is defined as the area of transparent material free of structure, edge bonding and any other material which causes obstruction to the external vision, and that area which is also kept free of ambient effects such as rusting, precipitation, ice and insects.

d) The quality of the external vision provided such that radii of curvature and angle of incidence of transparent components in the cockpit be consistent with aerodynamic, structural and fabrication conditions but reduce/minimise reflections and optical distortions which would interfere with pilot vision.

MIL Standard 850B as applied to two pilot, side-by-side arrangement rotorcraft includes:

a) Controls, consoles and instrument panels to be located such that visibility, particularly that over-the-nose, is not restricted.

b) Mounting or reinforcing frames or strips which divide transparent areas and cause obstruction be not greater than 2 inches wide when projected onto a plane perpendicular to a line between the structure and the pilot's eye at the datum eye position. Such obstructions should be distributed so as to avoid critical vision areas.

c) Minimum angles of unimpaired vision designated with respect to the main pilot. Figure 5 shows the minimum angles of unimpaired vision recommended for helicopters with two pilots seated side by side. The main pilot is assumed to be in the right hand seat. In addition the following is also stipulated:

  - There is to be no vertical obstruction between 20° right and 20° left of the longitudinal axis relative to the datum eye position
  - There is to be no horizontal obstructions in the area extending 15° above the horizon from 135° right to 40° left and decreasing to a point 10° above the horizon at 100° left. If necessary then the number of obstructions are restricted to one above and one below the horizon with a width of not greater than 4 inches.

Equivalent vision angles are provided for the co-pilot (left hand side).

The angular limitations are dependant on the mission, the aircrew arrangements and the aircraft type. MIL Standard 850B covers all aircraft procured by the military inclusive of fixed wing, VSTOL and rotorcraft. Also shown in Figure 5 (dotted line) is the only difference between MIL Standard 850B and the guidelines indicated in the Advisory Circulars 27 and 29. It can be seen that if the guidelines are followed, military and civil aircraft should have similar visual windows.

Figure 6 presents typical data indicating the track of a helideck superimposed in the FOV of a helicopter (S-76) during the approach to land phase of operation. The diagram illustrates the adverse effects of helicopter attitude changes during the deceleration phase. From this diagram, it can be seen that an offset approach makes better use of the available FOV, particularly during the latter stages.

In good visibility conditions the available FOV is generally not a major constraint on landing operations with current civil helicopter types. However there are two significant conditions where deficiencies exist. The first of these is illustrated in Figure 2 which shows the view available to a pilot when there is rain on the windscreen. It can be seen that the FOV is, in effect, substantially reduced since the only area that is useable, particularly at night in the presence of external lighting, is that which is swept by the screen wiper system. Since the wipers are only fitted to the forward windscreen, the FOV becomes inadequate as the deceleration phase commences, an effect that is exacerbated in the presence of cross winds.

The second area of deficiency was highlighted during the fog flying trials reported in Paper 10. In low visibility conditions current operational techniques require the pilot to perform the deceleration and landing phases using external visual references. In practice this results in the pilot deriving cues from the view ahead of the helicopter. For landings at aerodromes the cues may include approach and runway lighting. At other sites, particularly offshore, the cues will be those provided by the helideck and any adjacent structures. In all cases, the pilot needs to see cues ahead of the aircraft in order to acquire positional, attitude and rate cues and to estimate the instantaneous location of the helicopter velocity vector in relation to the desired aiming point. Since the deceleration requires a nose up attitude change the pilot is presented with the dilemma of either using normal attitude changes (at least 10º), and thereby losing sight of the aiming point, or using smaller attitude changes that result in deceleration distances which are in excess of the visual range available i.e. if the visibility is 300 m but the deceleration distance is 400 m the pilot cannot stop the helicopter in the distance known to be available and retain sight of the helideck. This problem is made more severe if the final glide path angle is large since, in this case, the datum position of the aiming point is closer to the cockpit coaming. From this point of view a level approach is preferred.

For future helicopter operations, avionics enhancements offer a practical solution to the problem of providing adequate visual cues ahead of the helicopter since it is feasible to conduct the deceleration to the hover by reference to cockpit instrumentation alone. However, unless means are devised for clearing the windscreen over a much wider area than is done at present the problem of FOV deficiencies in conditions of precipitation will remain for the hover and landing tasks.

The data presented in this study would suggest that, in the longer term, there is a need to develop and enforce a civil specification for helicopter FOV. Such a specification would need to include provision of adequate screen clearing and guidance on retrofitting cockpit equipment. In the short term operations will continue to be constrained by these design short comings, however the optimum use of available FOV could be the subject of further studies. For example, the development of new visual aids, including those that can be viewed through contaminated screen areas, is feasible. Alternative deceleration techniques could also have a beneficial impact on current operational limitations.

5 Conclusions

On the basis of the literature search and the practical measurements made within this study it is concluded that:

a) In good visibility conditions the basic FOV provided in helicopters does not seriously affect operational capability.

b) In many instances the actual FOV available to pilots is eroded by retrofitting additional equipment in the cockpit.

c) There are no minimum specifications for cockpit field of view in the civil industry, only advisory circulars showing acceptable methods for compliance with visual specifications (FAR, BCAR etc.). If these methods of compliance were to be developed into a minimum specification and enforced, then some of the associated visual scene problems would be solved.

d) When there is any form of precipitation or contamination on the windscreen the FOV is reduced substantially. This is particularly significant during the deceleration, hover and landing phases. At night the problem is exacerbated by excess lighting in and around the heliport producing disabling illumination of the water droplets on the large unswept screen areas, including the chin windows which would otherwise provide a useful source of cues in the hover and landing phase.

e) In low visibility situations, the view ahead of the helicopter becomes inadequate as pitch attitude changes are applied to perform the deceleration manoeuvre. Final approach patterns should be flown at shallow glidepath angles to optimise use of the available FOV.

6 Recommendations

It is recommended that:

a) Further investigation into the guidelines defined in Advisory Circulars 27 and 29 and development of these guidelines into an enforceable specification for civilian helicopters should be conducted.

b) Investigation into the effects of developing approach profiles which would minimise the adverse FOV effects especially during low/poor visibility operations should be conducted.

c) Visual aids that are useable with contaminated windscreens should be researched and developed.

d) The short/medium term benefits and feasibility of instrument deceleration techniques should be investigated.

Figure 1 View from S-61 right hand seat at Beccles

Figure 2 View from S-76 right hand seat at Beccles

Figure 3 Cross cockpit view from S-76 right hand seat at Beccles

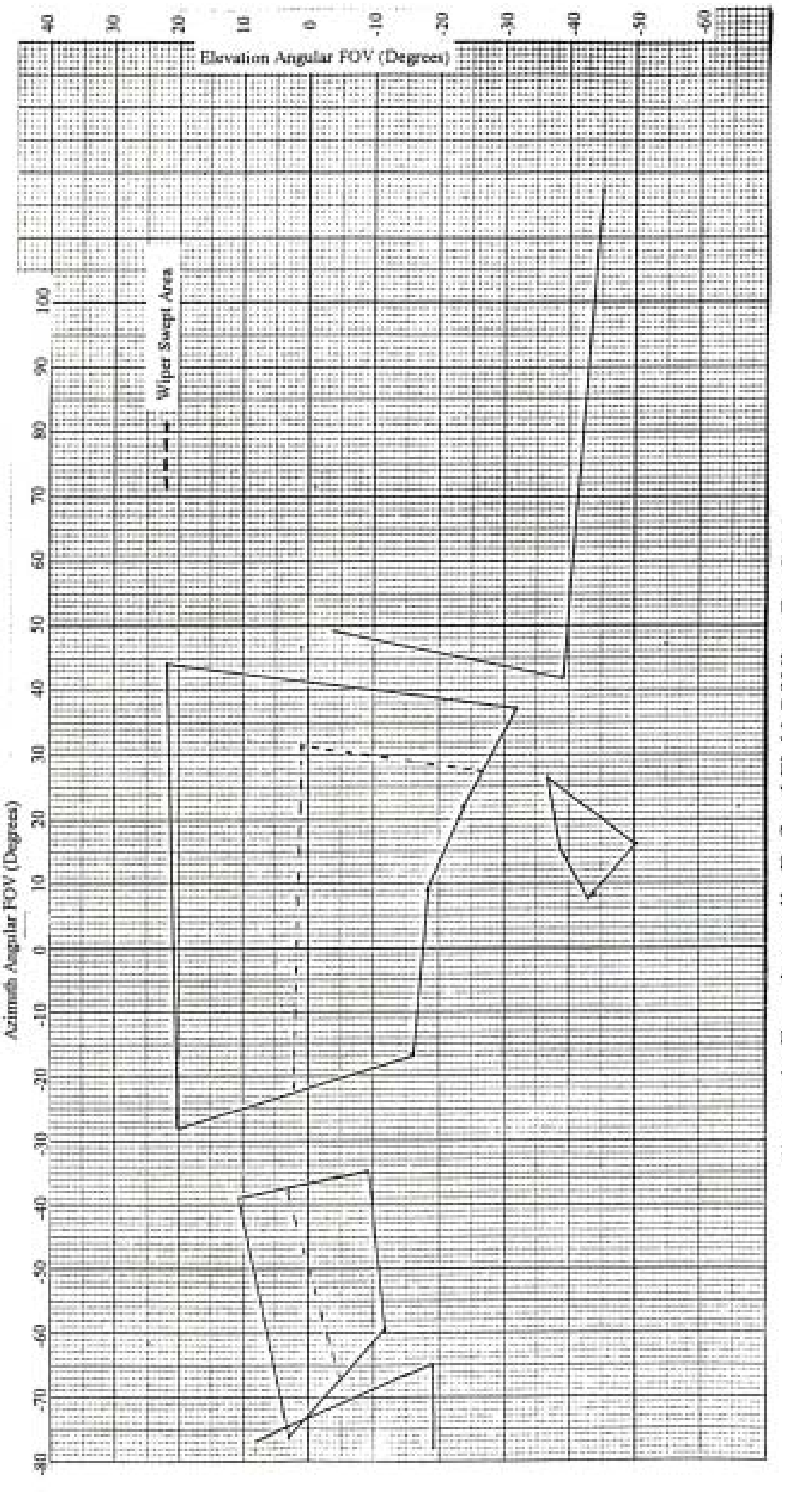

Figure 4 Experimentally defined field of view for S-76

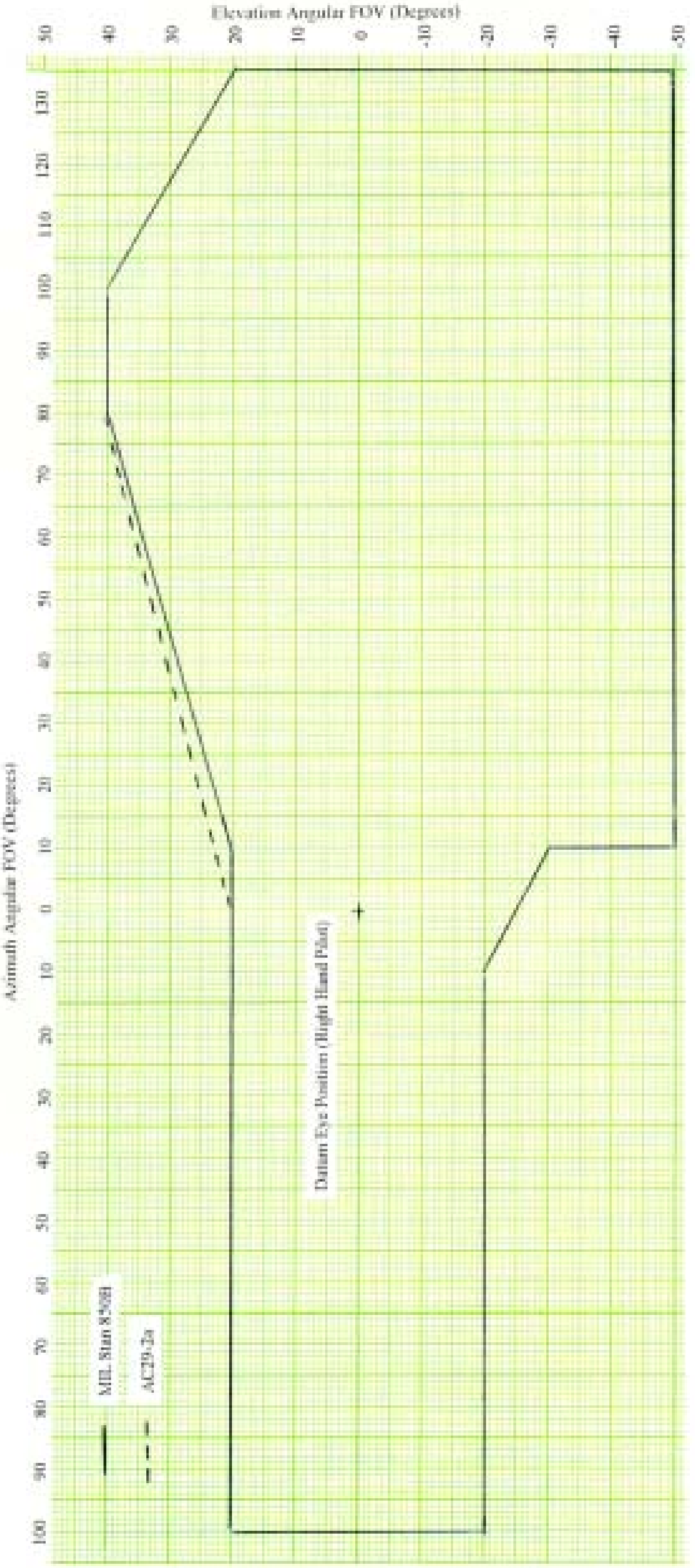

Figure 5 Diagramatic representation of MIL standard 850B for side by side helicopter

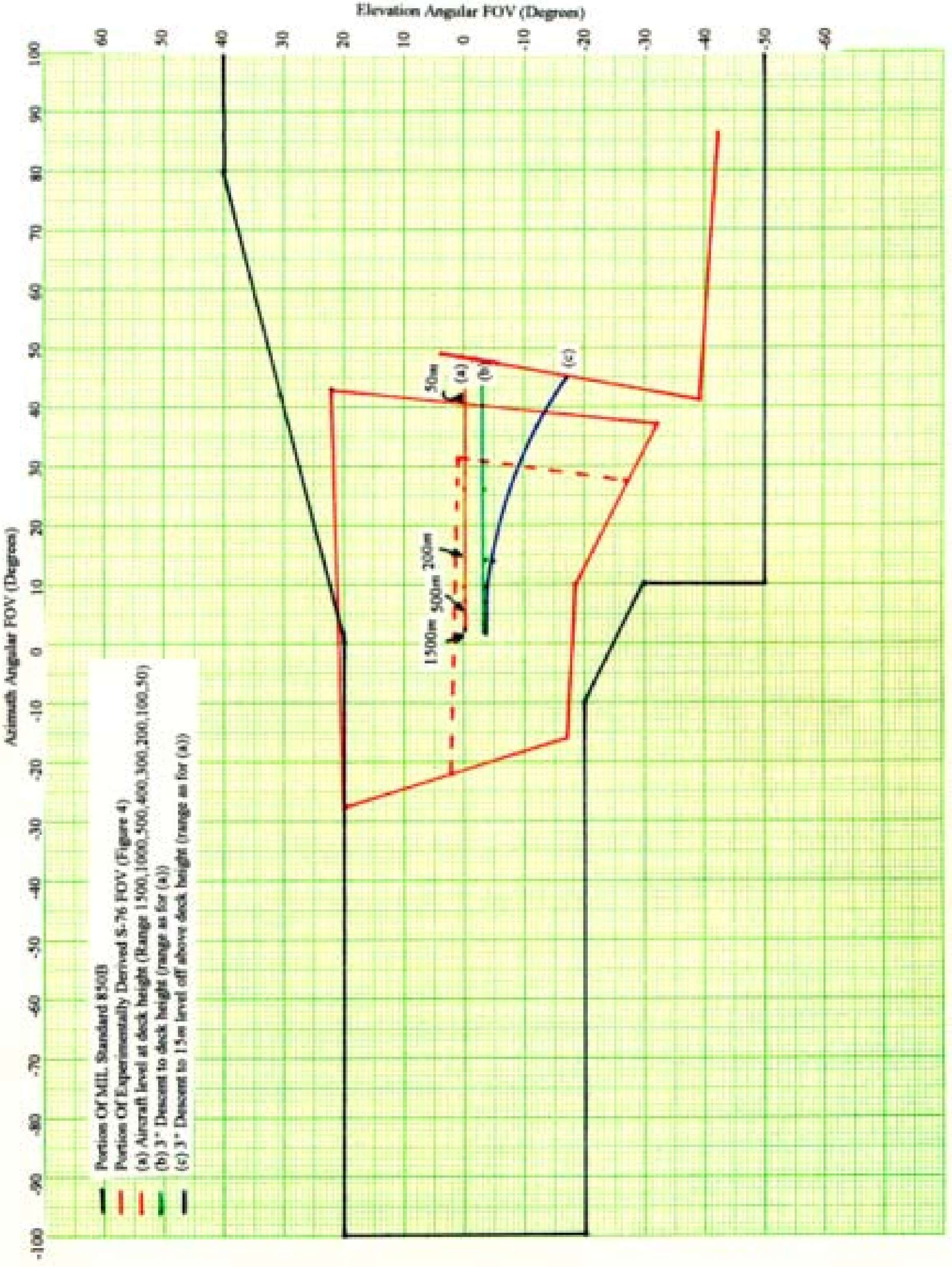

Figure 6 Movement of helideck through window of S-76

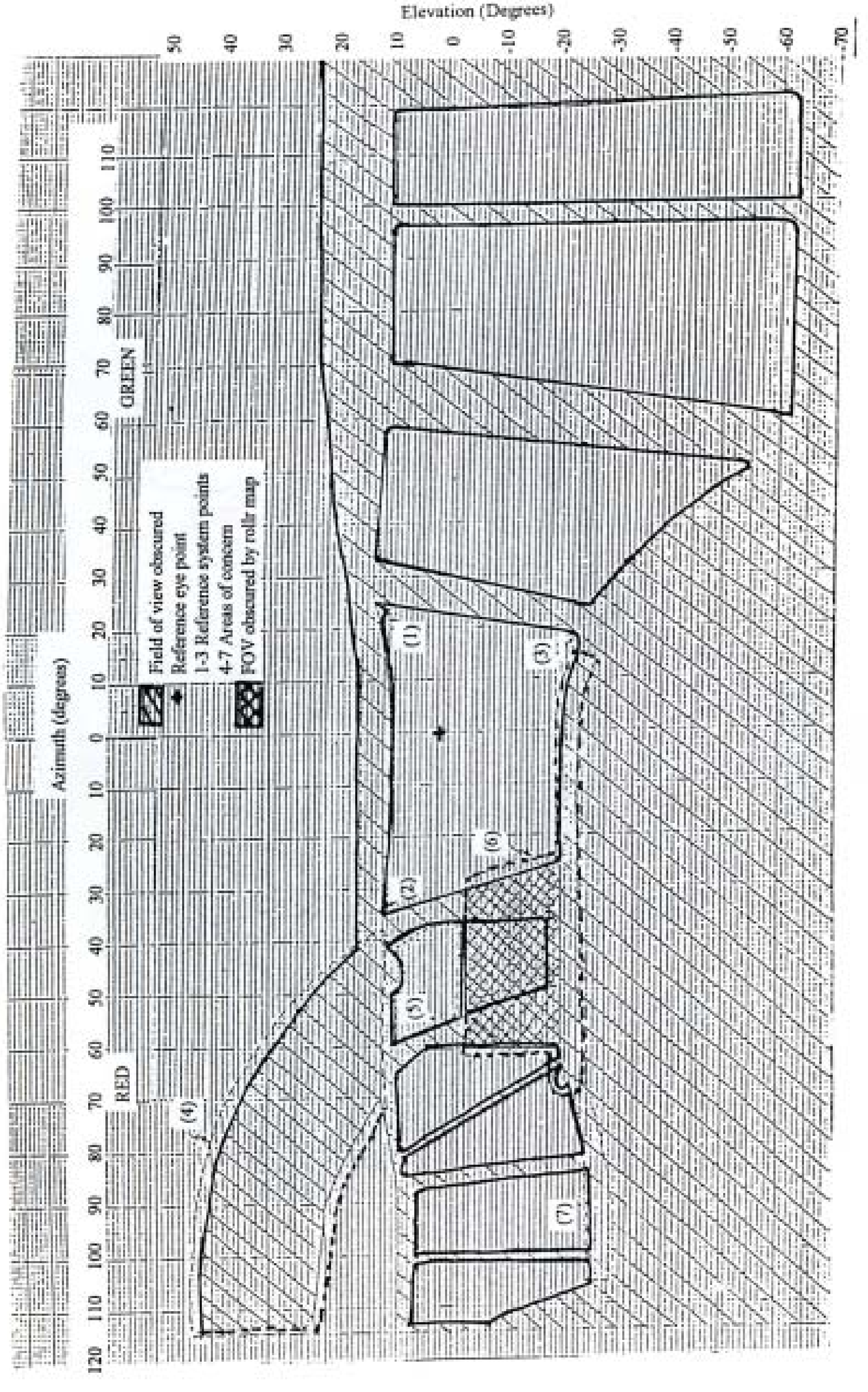

Figure 7 Sea King Mk 1/2 - Cockpit field of view

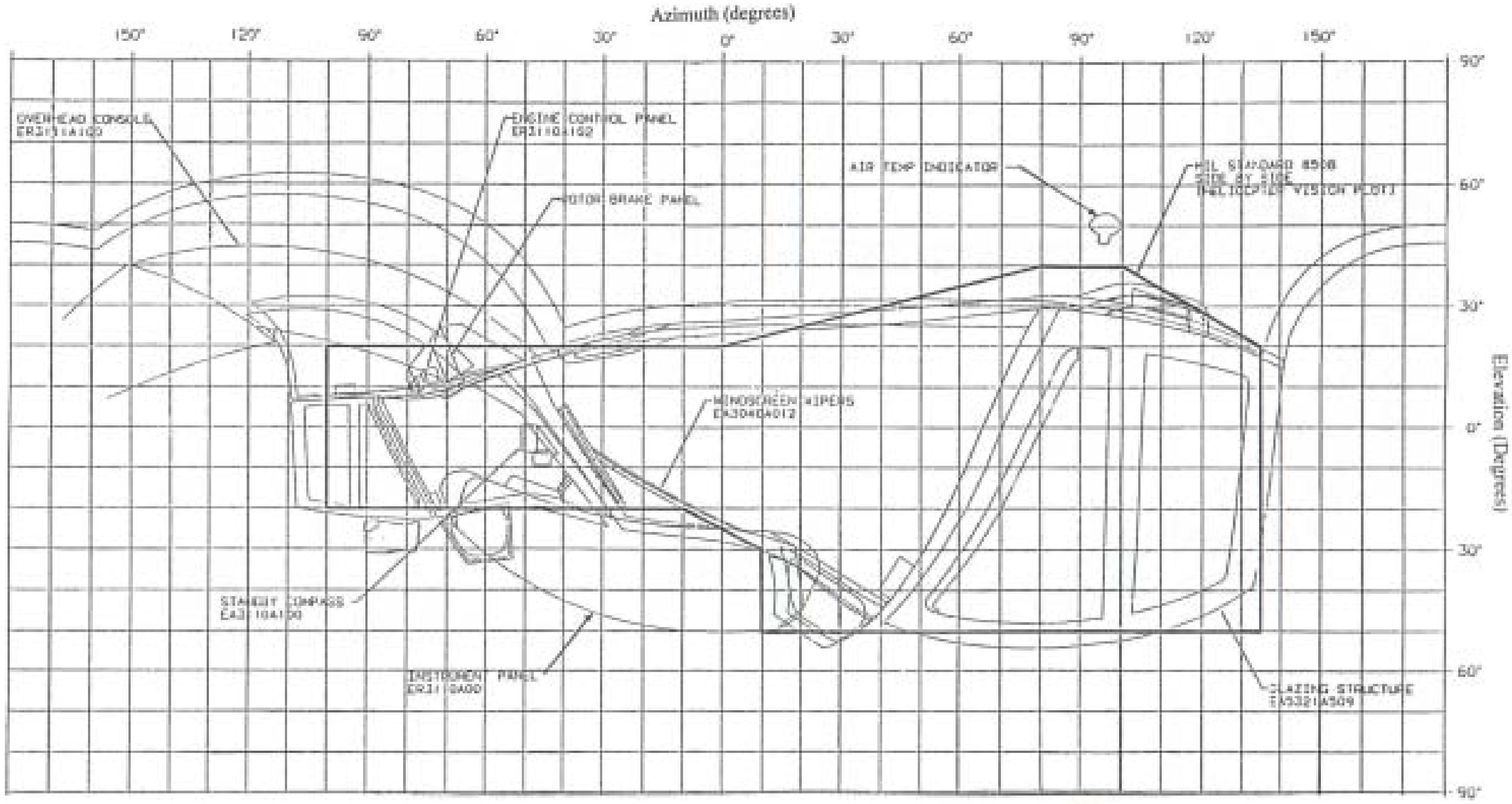

Figure 8 EH 101 Naval - Pilot vision diagram (eye centre: x 3495, y 600, z 2875)

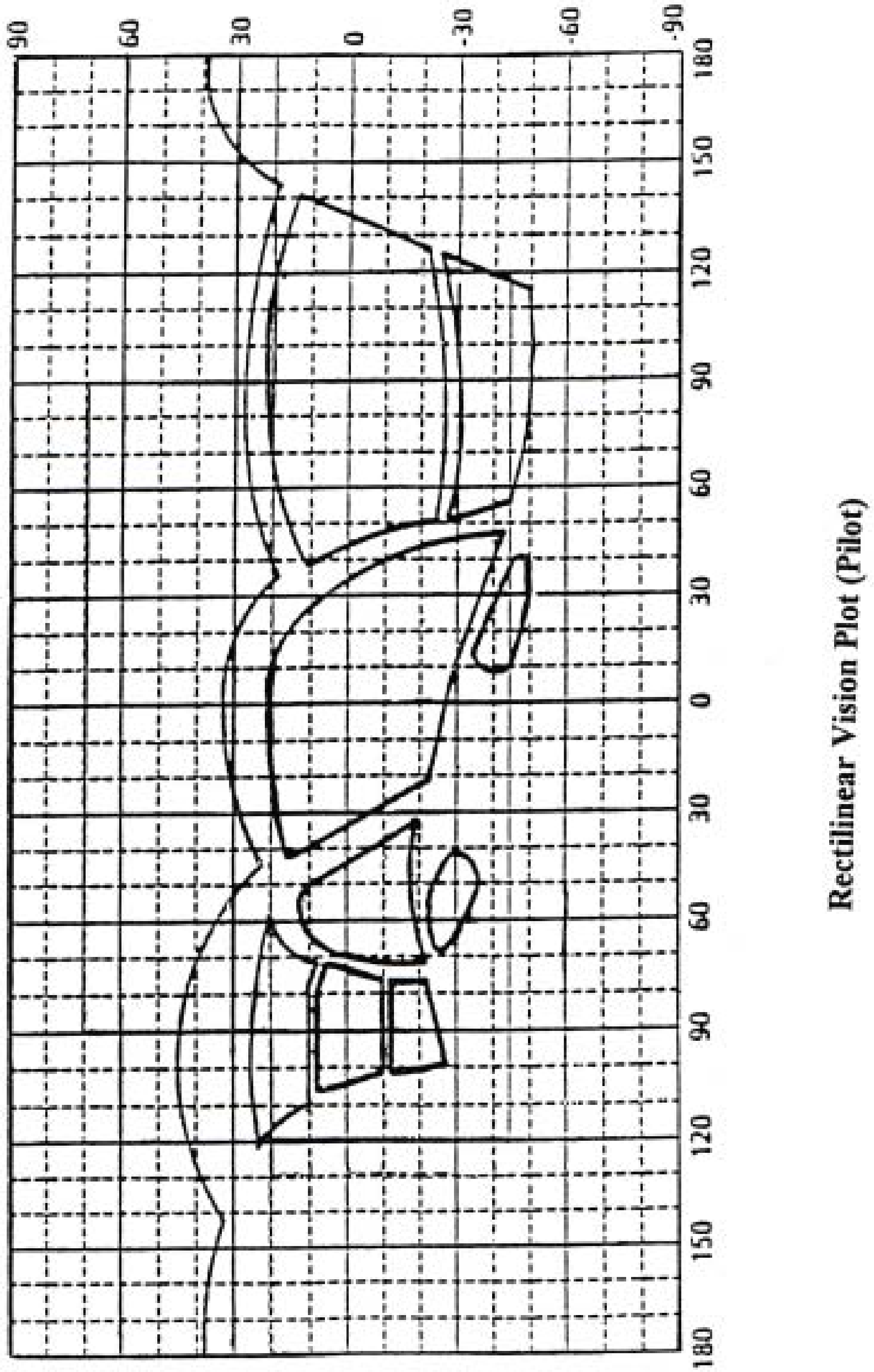

Figure 9 Bell-Boeing MV-22A - rectilinear vision plot (pilot)

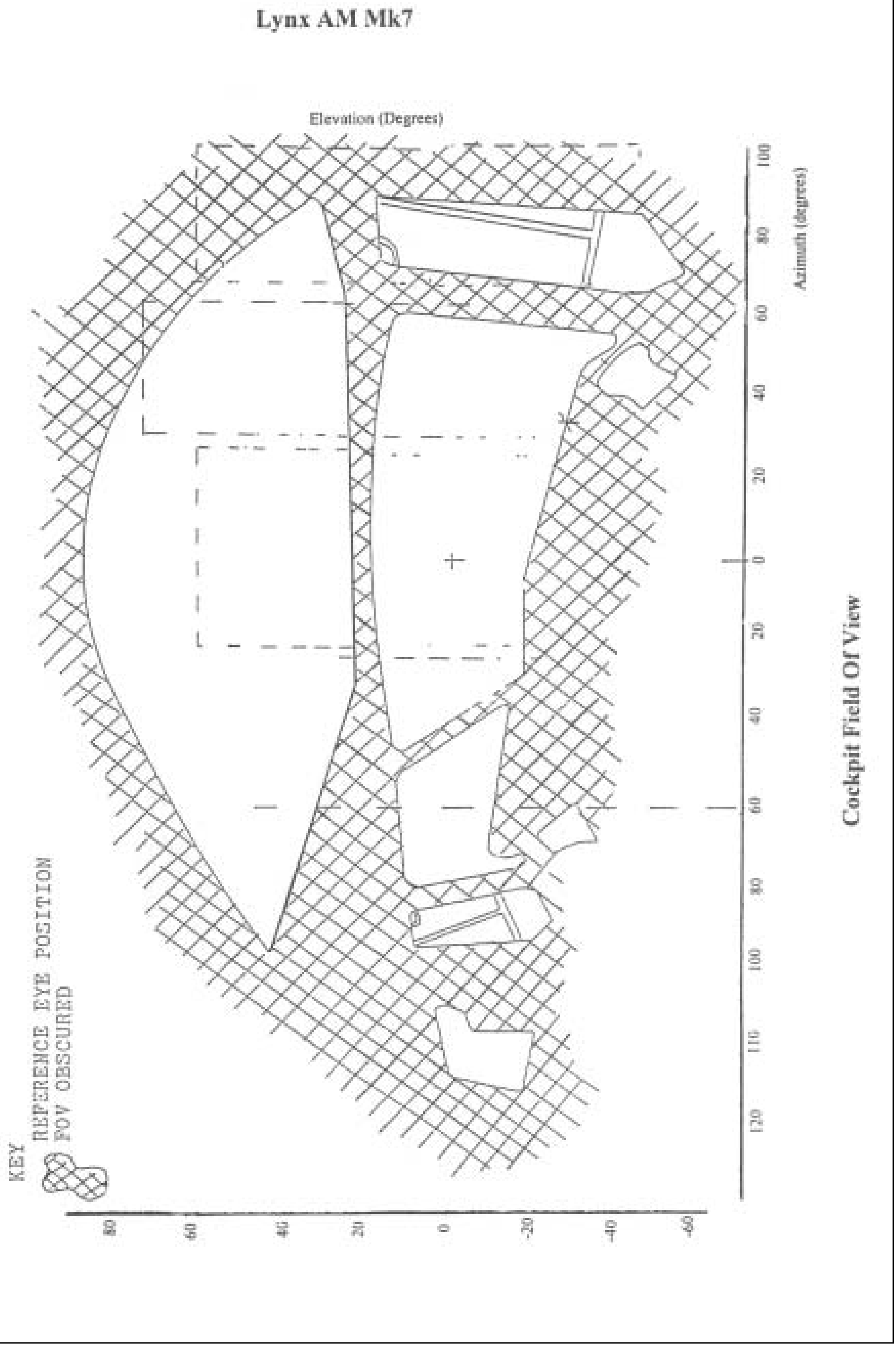

Figure F10 Lynx AM Mk 7 - Cockpit field of view

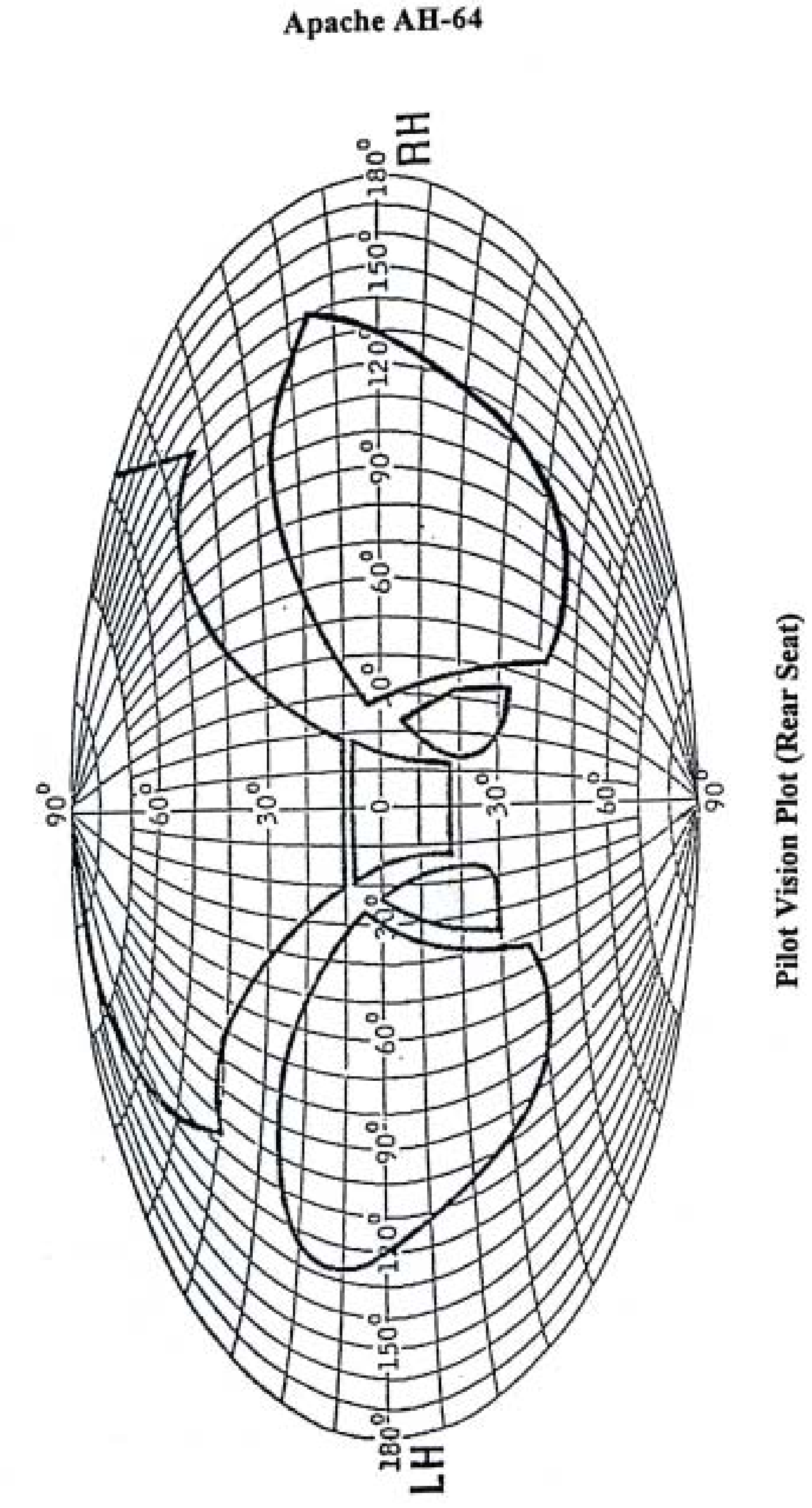

Figure 11 Apache AH-64 - ATOFF'S equal area projection of the sphere (radius of projected sphere equals one decimetre)