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# Impact of Turbulence and Degraded Visual Environment on Pilot Workload

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## ABSTRACT

Offshore-Helicopter-Operations are frequently conducted in both turbulent and degraded visual environments (DVE). This investigation assesses the combined influence of turbulence and DVEs on pilot workload to identify first limits for safe operations. Flight tests using a simulation model of the research helicopter ACT/FHS (Active Control Technology/ Flying Helicopter Simulator) flight mechanics model were conducted in the Air Vehicle Simulator (AVES) at DLR Braunschweig. Tests were completed using four pilots, and results show the effects on pilot workload, task performance and control input activity. It was found that DVE and turbulence increase the workload and reduce task performance, but each in a different manner. Furthermore, the impact on control activity and pilot induced oscillation tendencies are shown to have dependency upon the environmental conditions.

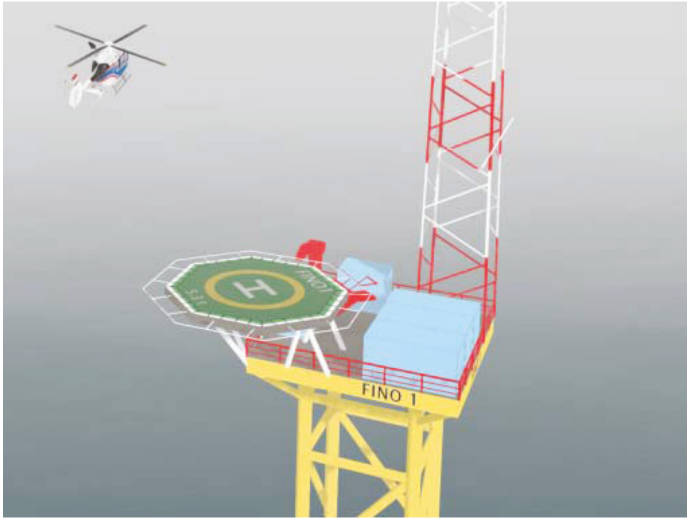


Figure 1: Typical offshore helicopter mission task

## 1. Introduction

This paper outlines the first steps in the project HELMA (Helicopter Flight Safety in Maritime Operations, 2016-2018), which aims to understand and improve the operational capabilities of helicopters during offshore operations, in particular when flying in degraded visual environments (DVE). HELMA is a collaborative project between the German Aerospace Center (DLR) and the German Federal Police Aviation Service, who is responsible for offshore police operations in the German Exclusive Economic Zone as well as on the high seas.

Due to the rapid development of the offshore energy sector, the expectations and demands for helicopters operating offshore are increasing. The continuing growth of offshore wind parks, and the resulting maintenance and search and rescue missions (SAR), is leading to an increased number of offshore helicopter operations. Furthermore, helicopters are being used over a wider range of the flight envelope than ever before, due to the increased requirements of the emerging field. During typical operations, external load operations and ship-deck-landings, pilot workload is known to be high. Platform maintenance in wind-farms, supply and personnel delivery, emergency and law enforcement operations all require the use of helicopters, which will hopefully be unhindered for 24/7 service capabilities in the near future. This means that the aircraft must be reliable and pilots must be able to complete missions unhindered in any condition expected offshore (DVE, night-flying, turbulence etc.). Currently, there are few objective requirements for both the quality of visual conditions and the allowable levels of turbulence for these types of operations. Figure 1 illustrates the lack of visual reference points in offshore scenarios, whereby the primary references are provided only by man-made objects. This is believed to increase the need for more detailed requirements for offshore operations than for their land-based equivalents. The goal of the current work is to show the influence of turbulence and DVE in combination on pilot workload and task performance, in order to obtain an initial understanding of the major contributing factors which need to be assessed within HELMA.

Current standards for offshore-operations are based on EASA Air Operations Regulations [1]. Offshore helicopter landing areas require certification before they can be used. German regulations [2] do not include limits for visual conditions or turbulence acting around helidecks. The British Civil Aviation Publication (CAP) 437 [3] defines standards for offshore helicopter landing areas, where the vertical airflow velocity should not exceed 1.75 m/s (3.4 kts) to ensure safe operations. There is no dependency upon pilot experience or changes in cueing conditions. Due to the lack of requirements for these operations, there is little understanding of the impact of such conditions on offshore operations.

Several investigations concerning the effects of DVE and turbulence offshore have previously been conducted as shown in the following literature. The primary focus of these investigations has been on the helicopter-ship interaction and simulations, through the use of different turbulence-models. Lee [4][5] evaluated pilot workload during shipdeck operations through offline calculation and the use of a pilot model, where the increase in workload caused by turbulent airflow above the ship-deck was assessed. The influence of time dependent and stochastic turbulence modelling was also investigated, whereby stochastic modelling appears to have the same overall behaviour compared to time dependent turbulence. Wang [6] investigated the effects of visual cues on pilot workload during helicopter-shipdeck-operations. Degradation of the Usable Cueing Environment (UCE) from Level 1 (best visual conditions) to the upper limits of Level 2 (medium level visual conditions) was found to increase pilot workload dramatically, and led to the requirement of control augmentation such as Attitude Command Attitude Hold (ACAH) or Translational Rate Command (TRC) for helicopter operations in DVE [7]. Cooper [8] investigated the same subject, where the use of pilot assistance systems was evaluated. To determine the effect of this system, he required pilots to fly maritime MTEs, derived from tasks specified in Aeronautical Design Standard -33 (ADS-33-E-PRF) [9]. The investigation was conducted in a flight simulator, and the workload for different settings was assessed. The majority of previous investigations relating to turbulence have stated that visual cues are also important but the evaluation has been beyond the scope of the work.

Further assessments have been conducted evaluating the sole effects of visual cues on pilot workload, including whiteout and brownout phenomena [10][11]. The development of assistance systems that provide the pilot with important information has been of particular interest. Nascimento [12] investigated offshore operations during night-time operations. Several pilots were interviewed about causes and danger areas that regard accidents during approach and landing on offshore platforms. Amongst other factors, good visual cues were mentioned as the major factor for safe operations and low workload.

This paper proceeds as follows. Firstly, the technical approach of this study is discussed, including the elements with regards to maritime Mission Task Elements (MTEs), turbulence modelling, and facilities used for the investigation. Secondly, results from the evaluation of the visual setting are presented, outlining the three UCE levels used for the investigation. Thirdly, the results from the study are presented, alongside key results which highlight changes in workload and task performance driven by changes to the conditions. Finally, the results are summarised, and conclusions are drawn from the initial study. These are accompanied by recommendations for future experiments.

## 2. Test Approach

The overall approach was to collect performance data and pilot opinion while flying a Hover mission in a number of different visual conditions and levels of turbulence. To achieve the proposed goal, flight tests were completed in DLR’s Air Vehicle Simulator (AVES). This provides insight into the influence of the combination of visual degradation and turbulence on the Handling Qualities (HQs) during hover and low speed manoeuvring. The Hover MTE from ADS -33 was selected and is described in Section 2.2 and Section 2.3, including explanations of all modifications made as part of the study. Assessments of offshore scenarios in onshore conditions have been completed by researchers in the past. Mitchell describes the proposed land based Superslide MTE as a useful extension for offshore assessment [13].

### 2.1 Test Procedure

It was decided to test in three visual conditions (see Section 3.2) in combination with three turbulence levels. This led to a 3x3 test matrix, with 9 test points completed in a random, pre-selected order. This was an attempt to minimise the influence of learning on the results obtained. Additional ‘repeat’ test points were completed throughout the study, whenever time allowed.

Three experimental test pilots and one operational pilot, who also had experience flying AVES, flew the hover task in different environmental conditions. All pilots had significant experience flying in both DVE conditions and in turbulent conditions when flying helicopters of a similar class to the one used within this study. For this reason, they were able to subjectively convey the sense of realism within the simulation.

Task performance and pilot ratings were used to assess the effects of turbulence and DVE. For the assessment of HQs, the following items were required within the simulation environment.

- Suitable test course with a standardised task
- Assessment methodology for workload and task performance
- Real time helicopter simulation
- Variable visual cue environment
- Variable turbulence environment

Each of the four pilots gave ratings based upon their experienced during the Hover task. This resulted in assessments of all turbulence and DVE conditions.

### 2.2 Helicopter Handling Qualities

Good stability and controllability of an aircraft are of as much importance for a successful design as the designated performance. Flying and controlling the aircraft must be possible with a tolerable amount of workload, leaving enough mental and physical capacity for the pilot to accomplish the mission. With the design of modern flight control systems (FCS) and the introduction of fly-by-wire, the aircraft’s behaviour can be modified in a broad range. Beginning in the 1980s, a new approach to the specification and evaluation of military helicopter handling qualities was undertaken in the USA. The outcome was the Aeronautical Design Standard (ADS)-33, which is continuously updated and currently available as version E [9]. Several organisations supported the requirement development with analytical analyses, piloted simulations and flight tests. Today, ADS33E-PRF is accepted worldwide as a valuable contribution to the definition of requirements for helicopter HQs (e.g. [14][15][16]). The introduction of ADS-33 provided both new criteria and flight testing techniques. Improvements over former specifications are the broad introduction of frequency domain criteria derived from feedback and manual control theory, and the mission oriented approach. The classical HQ evaluation using the open-loop response to inputs, are supplemented with a set of demonstration manoeuvres, called Mission Task Elements (MTEs). Each of these MTEs represents one part of a typical helicopter mission and is used to assess the whole helicopter configuration in this part of the task.

Another important concept introduced by ADS-33 is the dependence of the required response-type on the level of degradation of the visual environment, respectively the presence or lack of visual cues the pilot needs to stabilise and control the rotorcraft. A method called Usable Cue Environment (UCE) is described to relate the quality of the visual environment to the required level of artificial stabilisation provided by a flight control system to achieve Level 1 HQs.

According to ADS-33 flight testing of the rotorcraft using the MTEs shall exercise its HQs over the full range expected in operation. At least three pilots shall assess the MTEs and assign a Handling Quality Rating (HQR) using the Cooper-Harper rating scale [17]. To obtain consistent ratings, performance standards are defined for each MTE, e.g. the allowed deviation from ground track or hovering position, the maximum allowed manoeuvre height over ground, or the maximum allowed manoeuvre time. Generally two sets of standards are defined, representing the more stringent “desired”, and the less demanding “adequate” performance. For the full list of MTEs, the general manoeuvre descriptions and the performance parameters the reader is referred to Ref. [9].

The Cooper Harper HQR scale includes a decision tree to aid the pilot in his/her assessment. The resultant HQR is one of ten possible ratings. HQR 1 to 3 imply that desired performance is achieved with low pilot workload, and the aircraft’s HQs are acceptable without improvement. This equals Level 1 HQs. Level 2 (HQRs from 4 to 6) indicates that the tasks can still be performed with desired or adequate performance, but pilot workload will be high, and thus improvements are deemed necessary. HQR 7 to 10 designates unacceptable HQs.

It must be ensured that the test pilot is fully familiar with the manoeuvre objectives and has developed a repeatable strategy to fly the manoeuvre. For example, if trying to achieve a desired performance is associated with an intolerable high workload, the pilot should back out and try to stay within the adequate boundaries, reducing his workload to a tolerable level. A de-briefing with the pilot is important to gather more, precise information about the reasons for the rating and the control strategy. This additional information is the basis for identifying potential handling qualities improvements. Depending on the debriefing, it might also be necessary to repeat certain test points if it is found that the measured and rated performances are different, or the visual cues were not satisfactory and had an influence on the HQR.

## 2.3 Modified ADS-33 Hover MTE

The objectives of the Hover MTE are to check the ability to transition from translating flight to a stabilised hover with precision and reasonable amount of aggressiveness, and to maintain precise positioning, heading, and altitude while hovering over a point. The task is to accomplish a transition to hover in one smooth manoeuvre. The target hover position shall be approached with a ground speed between 6 and 10 kts along a 45 deg ground track, relative to the aircraft’s heading. It is followed by a deceleration phase into a stable hover, which has to be maintained for at least 30 seconds. The target hover point is a ground-referenced point from which the rotorcraft deviations are measured. The performance parameters used for the current study are as defined for the Utility mission in ADS-33. These are shown in Table 1, with performance requirements dependent upon visual conditions. In addition to information displayed, for desired performance, there shall be no objectionable oscillations in any axis either during the transition to hover or the stabilised hover.

| **Performance Hover for Cargo/ Utility** | **Desired** | | **Adequate** | |
|---|---|---|---|---|
| | **GVE** | **DVE** | **GVE** | **DVE** |
| Attain a stabilised hover within X seconds of initiation to deceleration | 5 | 10 | 8 | 15 |
| Maintain a stabilised hover for at least X seconds | 30 | 30 | 30 | 30 |
| Maintain the longitudinal and lateral position within +- X ft of a point on the ground | 3 | 3 | 6 | 6 |
| Maintain altitude within +- X ft | 2 | 2 | 4 | 4 |
| Maintain heading within +- X deg | 5 | 5 | 10 | 10 |

Table 1: Performance parameters for the Hover MTE from [9]

During test preparation using the standard ADS-33 Hover MTE used in AVES for rotorcraft investigations, it was noted that the height was not sufficient for the testing. When flying at the standard height of approximately 4 m, the peripheral cues from the ground scenery provided the pilot with a method to stabilise the position. Instead of looking forwards and performing cross checks through the side windows, pilots using the ground as the primary visual reference. For this reason, in DVE, they were able to track their position precisely, with limited degradation from the case in GVE, by observing the ground drift. This situation was not representative of a ‘maritime’ scenario, where the pilots are often not able to see the platform (e.g. during a hoist operation). Due to this reason, the standard height for the manoeuvre was not considered appropriate for the investigation. Results obtained would not be comparable to offshore flying tasks, as this strategy would not be possible. Because of this, the height of the MTE was increased by 10 m. To achieve this, the height of the hover boards was increased. The desired effect was achieved and confirmed by pilot's comments. The complete test course used is shown in Figure 2.

Figure 2: Hover course layout

## 2.4 DLR Simulation Environment

DLR's Air Vehicle Simulator (AVES) features two cockpits, a replica of an Airbus A320 cockpit and of the ACT/FHS cockpit. The simulator is designed to be a modular, flexible platform, using the latest technologies for a comprehensive exploration of flight projects. The modern test facility closes the gap between numeric simulations and experimental flight operations at Braunschweig Research Airport. AVES is developed and operated by DLR's Institute of Flight Systems.

Figure 3: Air Vehicle Simulator (AVES)

All tests described here were conducted using the helicopter cockpit with motion. This was considered important in the investigation to obtain a realistic feeling of the influence and severity of the turbulence. The hexapod motion platform reaches 'Level D' requirements, and is described in detail in Ref. [19]. It is capable of reproducing motion at frequencies greater than 10 Hz, and has a maximum leg extension of 1.5 m. Tuning of the motion platform has been conducted by researchers at DLR, using the combination of pilot subjective evaluations and platform optimisation techniques. The motion configuration used in this investigation has been shown to provide representative cueing throughout the operational envelope of the simulated vehicle model.

## 2.5 Vehicle Model Description

For this investigation, a vehicle 'representative' of typical offshore helicopters in current operation today was used. This is a model of the ACT/FHS research helicopter operated by DLR Braunschweig. The aircraft is a highly modified version of the EC135. For this reason, its performance and qualities do not reflect standard operational variants of the aircraft type. The simulation model features a basic SAS system, which provides a rate command response type. The Rate Command (RC) response type was selected as it was considered to reflect helicopters currently undertaking maritime missions. The command type and the availability of upper modes, including hold systems or autopilots, in current helicopters operating offshore is dependent upon the operator and helicopter type. ADS-33 recommends that at least an Attitude Command (AC) system is employed when operating in UCE > 1. Whilst this is based on a wealth of DVE testing, it is not a requirement. As a result, this level of control architecture is not currently used by the majority of operators. Therefore, to obtain an understanding of the current risk for maritime operations, the RC system was retained for all UCEs. Also, this allowed the performance to be directly compared following changes in visual complexity. Typically for offshore operations, the pilot may have access to a number of hold functions. For this investigation, these were not implemented in the simulation model, as it was not a requirement of the MTE. The nonlinear helicopter simulation model has been developed by DLR and is used in a real-time version in AVES [18]. The helicopter is configured with a mass of 2650 kg and rigid rotor blades.

The model was assessed against a number of ADS-33 objective requirements to determine its overall HQs. The results of the ADS-33 criteria analysed are listed below in Table 2.

| HQ Criteria | Level |
|---|---|
| Bandwidth - Pitch | Level 1/2 |
| Bandwidth - Roll | Level 1 |
| Cross Coupling | Level 1/2 |
| Quickness (all axes) | Level 1 |
| Low Frequency Pitch (Phugoid) | Level 2 (Full attention)<br>Level 2 (Divided attention) |
| Control Power (all axes) | Level 1 |

Table 2: Predicted handling qualities at low speed

As shown, the vehicle model exhibits HQ characteristics within Level 2 regions. These HQ assessments are dependent upon the vehicle role and intended task. For maritime operations, it is likely that pilots will be flying the helicopter with "divided attention" (i.e. crew communication, navigation, radio). Figure 4 displays the "Phugoid" mode of the aircraft at hover. The mode is predicted to have qualities within Level 2. The characteristics of this mode are shown in Figure 4. The Phugoid mode is unstable, and has a time to double amplitude of approximately 8 seconds. As shown, the mode is on the Level 1/2 boundary for Fully Attended Operations.

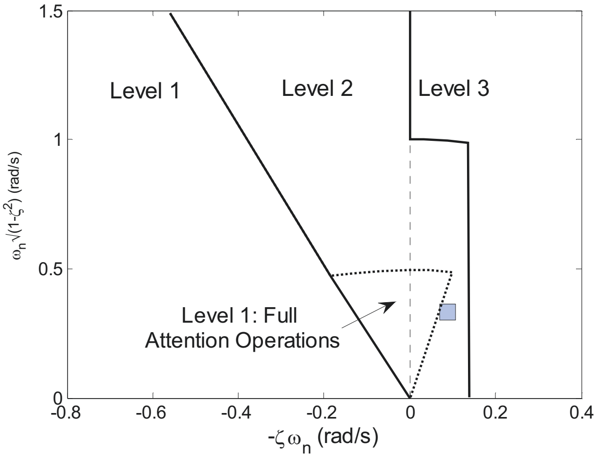


Figure 4: Phugoid response of the helicopter model

The bandwidth of the system defines the low amplitude, high frequency response. Figure 5 displays the pitch and roll bandwidth obtained with respect to ADS-33 divided attention/UCE > 1 boundaries. As shown, both are within the Level 1 region, with the pitch axes appearing on the boundary of Level 2. It is expected from this result that the HQs response to high gain pilot control will be superior in the roll axes, with the possibility to encounter PIOs or handling deficiencies for high gain flying tasks.

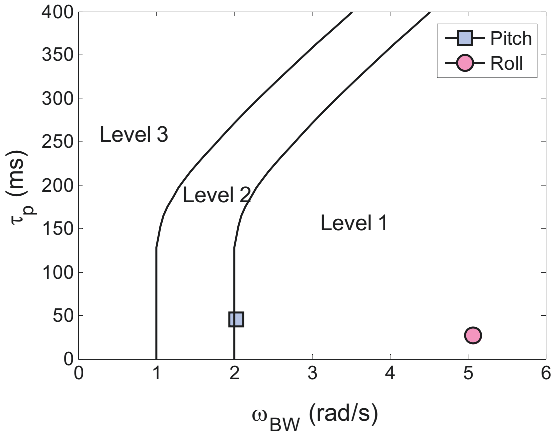


Figure 5: Bandwidth of the vehicle model

A further parameter that was found to be at the boundary of Level 1/2 HQs was the roll to pitch coupling. The resultant plot is shown in Figure 6 and shows that the aircraft has similar amounts of pitch-to-roll coupling as it does roll-to-pitch coupling. For hovering flight, the pilot must compensate for undesirable off-axis vehicle response. Therefore, the larger these couplings are, the higher is the pilot workload. This is particularly the case for tasks where the pilot must hold a precise position, such as precise hovering flight, or landing on offshore platforms.

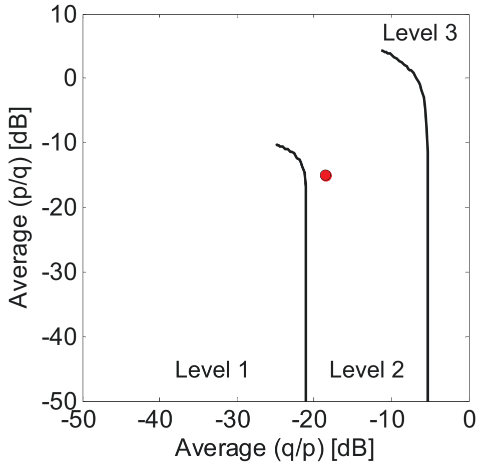


Figure 6: Roll to pitch oscillation requirements from ADS-33 [9]

Finally, Figure 7 displays points obtained for the collective to yaw cross coupling. Again, points appear at the Level 1/2 region. Results suggest that the long term response of the coupling is favourable, whilst the short term response could lead to some deficiencies

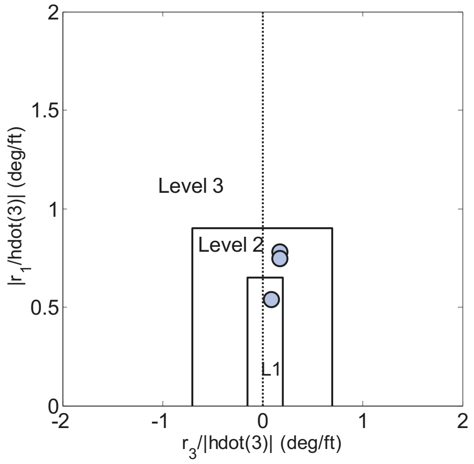


Figure 7: Collective to yaw coupling requirements against boundaries obtained from ADS-33 [9] where r1 and r2 represent the yaw after 1 and 3 seconds respectively and hdot(3) represents the change in height after 3 seconds

Overall, results suggest that the vehicle will have Level 1/2 awarded HQs, when performing MTEs contained within ADS-33. This suggests that deficiencies would warrant improvement, but that this is not deemed necessary. Despite HQ deficiencies, it should be possible to complete tasks to desired performance standards.

## 3. Visual Environment

### 3.1 Useable Cueing Environment (UCE)

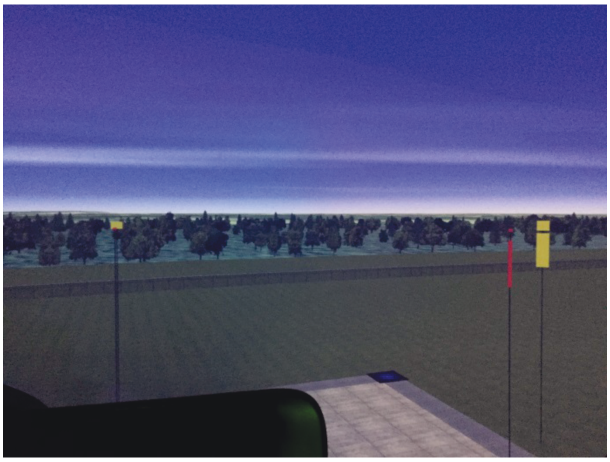
Prior to the HQ investigations in turbulent conditions, the Usable Cue Environment (UCE) of the scenario in AVES was assessed for different levels of DVE to obtain three different conditions for tests. The UCE is a metric quantifying how effectively the pilot can use available visual cues to perform his task and is described in ADS-33-E-PRF [9].

The visual environment has a significant influence on the pilot's ability to precisely control and stabilise the vehicle. In a visually rich environment, where the pilot can clearly see the horizon and has enough references that give clear and immediate feedback of angular and translational motion, aggressive and precise manoeuvring is possible with a helicopter that features a classical rate response type. In DVE, the visual references are reduced (e.g. at night, in fog, when flying over plain monotonous surfaces like calm sea or desert), it would not be possible to manoeuvre as aggressively and precisely as before. With an unaugmented rotorcraft, even if it has Level 1 HQs in a good visual environment (GVE), pilot workload will increase and the performance will eventually be much less achievable in DVE, resulting in degradation of the perceived HQs to Level 2 or even Level 3. Level 1 HQs in DVE can be achieved by augmenting the rotorcraft to provide Attitude Command Attitude Hold (ACAH) or even Translational Rate Command (TRC) response-type in combination with heading, height, and position hold functions [20].

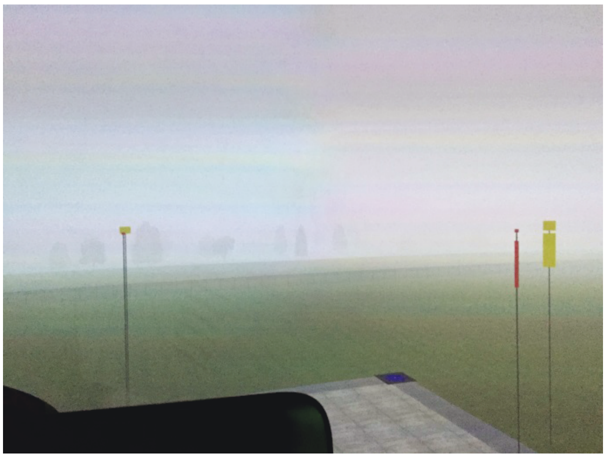
To quantify the influence of the visual environment on the possible aggressiveness and precision, the UCE method was developed by Hoh [21]. The level of UCE is determined from Visual Cue Ratings (VCR) returned by pilots after performing selected MTEs in the specific visual environment (day, night, fog, etc.). These VCR ratings have to be given separately from the pilot for the visual cues available to assess the helicopter attitude and translational rate for horizontal and vertical direction. Therefore a VCR rating scale is used (see Appendix Table 5). Hoh states that test rotorcraft shall have a rate response-type and Level 1 HQs. This shall assure that only the visual environment has an influence on the pilot ratings and not HQ deficiencies of the test rotorcraft.

## 3.2 Visual Setting

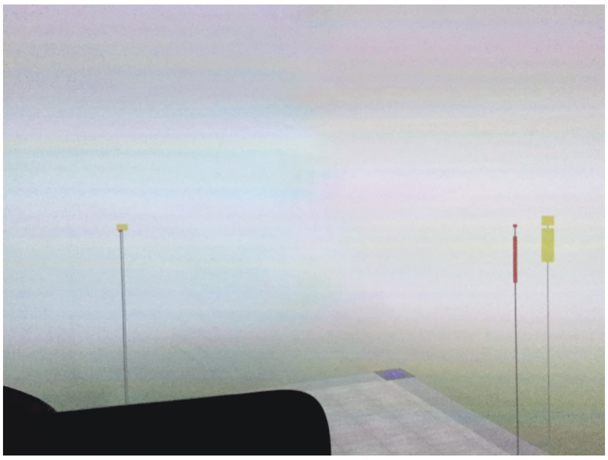
It was only required during these tests to assess the UCE for the Hover task, with the required modification discussed in the proceeding section. The introduction of fog within the simulation was used to degrade the UCE. Figure 8 gives an indication of the reduction of UCE within the simulation through the reduction in visual conditions. The figures show the same position within the environment. Figure 8a shows the best visual conditions used during the investigation. The outside view is unhindered by the visual conditions and, as a result, all markers and reference points can be seen. Figure 8b shows the situation where the visibility was reduced to 125 m. As shown, a drastic change in the visual complexity results, with the loss of the trees and a clear horizon. In this case, most of the distance ground references are also lost, with only the ground close to the aircraft visible. In the case shown in Figure 8c, the worst visual environment, the visibility was set to 75 m. In this case, all reference of the horizon is removed, and the view of the ground is further restricted. In both DVE cases, task markers are still visible, as so the pilot can judge their performance and determine whether it was completed successfully. In order to determine the UCE for each case, it was necessary to perform piloted assessment, using the method outlined above.



a. Good visual conditons (UCE 1)



b. Poor visual conditions (UCE 2)



c. Worst visual conditions (UCE 3)

Figure 8: Influence of Fog to Visual Cues

## 3.3 Assessment of Visual Conditions

Following the assessment of the UCE by all four pilots, the overall UCE was found for each visual condition using the procedure outlined in ADS-33 [9]. Figure 9 shows the UCE ratings obtained. The individual results obtained from all pilots for all visual conditions are shown in the Appendix.

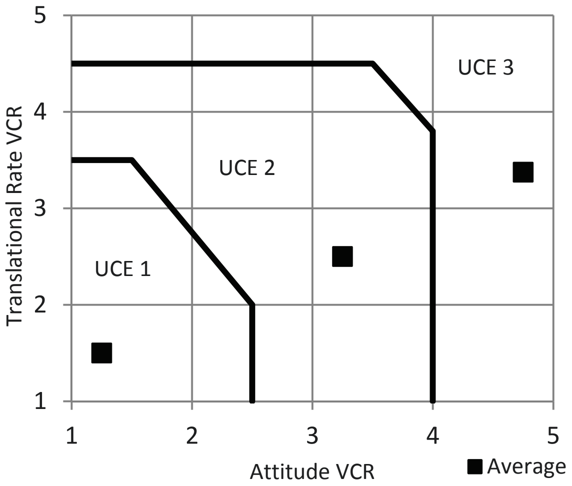


Figure 9: UCE ratings obtained

## 4. Turbulence Modelling

Turbulence was simulated using the Control Equivalent Turbulence Inputs (CETI) method. This is a stochastic turbulence method derived from flight tests. The model used in this study was obtained through hover and low speed flight testing and is only applicable to these conditions. The method was first proposed and tested by the Canadian National Research Council (NRC) [22] and further developed by the United States Army Aeroflightdynamics Directorate [23][24]. Von Gruenhagen and Seher-Weiß first derived CETI models for DLRs ACT/ FHS [25][26]. The advantage of this method over other turbulence models is its design for 'in-flight simulation'. As turbulence is calculated as a 'control input', it is possible to complete turbulence flight test campaigns in still conditions. This method also benefits from the fact that it inherently includes rotor-wake interaction effects.

To generate helicopter specific turbulence, hover and low speed flight tests in turbulent atmosphere were first conducted, with control inputs and helicopter response measured. With a helicopter flight mechanics model, the measured pilot inputs and vehicle response in a turbulence field are used to calculate control inputs which artificially recreate the turbulence. These control inputs subsequently replicate the response of the vehicle which was recorded in turbulence. From several flight tests, divided into different wind conditions measured (see turbulence level, mean wind and standard deviation in Table 3), disturbance inputs and corresponding Power Spectral Densities (PSD) were calculated. Filters for each control axis, developed from the PSD of each turbulence level, driven by white noise were used to generate additional control inputs, causing angular and vertical rates, similar to the flight in turbulent conditions. These additional control inputs are added to the pilot control inputs by the ACT/FHS experimental system during real flight test or simulator testing. The CETI turbulence models are available both in the ACT/FHS helicopter and within the AVES. The block diagram in Figure 10 shows the implementation. The complete process is described in Ref. [26].

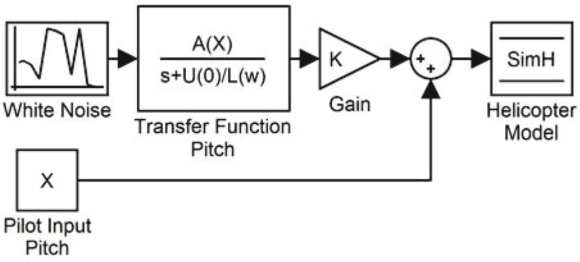


Figure 10: CETI block diagram for AVES implementation (pitch axis)

The derived transfer functions for each control axes are described in the following formulas.

$$\frac{\delta_{lon,gust}}{W_{noise}} = \frac{A_{lon}}{s + \frac{U_0}{L_W}} \tag{1}$$

$$\frac{\delta_{lat,gust}}{W_{noise}} = \frac{A_{lat}}{s + \frac{U_0}{L_W}} \tag{2}$$

$$\frac{\delta_{ped,gust}}{W_{noise}} = \frac{A_{ped}}{s + \frac{U_0}{L_V}} \tag{3}$$

$$\frac{\delta_{col,gust}}{W_{noise}} = \frac{A_{col}(s + 20\frac{U_0}{L_W})}{(s + 0.63\frac{U_0}{L_W})(s + 5\frac{U_0}{L_W})} \tag{4}$$

where $A$ is the turbulence filter amplitude, $U_0$ the mean wind speed (from test day, see Table 3) and $L_W$ and $L_V$ are main rotor respective tail rotor scaling parameters. Table 3 shows the mean wind speed and standard deviation in knots (kts).

The CETI turbulence models used in this investigation were validated in both flight and simulation, with results and comments presented in Ref. [26]. Subjectively, the use of the turbulence models when performing the ADS-33 Hover task was found to degrade the HQs, with ratings degrading from HQR 4 to HQR 6, which was stated to be in agreement with findings shown in [27]. Subjectively, pilots commented that their workload was similar to that on days when flying with turbulence. Evaluation was performed in a fixed-base simulator, where tutor pilots from the Empire Test Pilots' School (ETPS) performed the same task. They commented that the turbulence was representative of a really gusty day [26]. However, it must be considered that the simulation was conducted without motion, which may have a significant influence upon the subjective feeling of turbulence severity.

Subjective assessment of the severity of the turbulence was repeated as part of the current investigation. This investigation was conducted within a different simulation facility (considerably higher fidelity), with a different vehicle model, and different pilots. Prior to the start of formal evaluations, the severity of the turbulence was assessed using DEF STAN 00-970 Part 7/2 [28]. This contains a subjective rating scale to assess the intensity of turbulence, on a scale of 1 to 10.

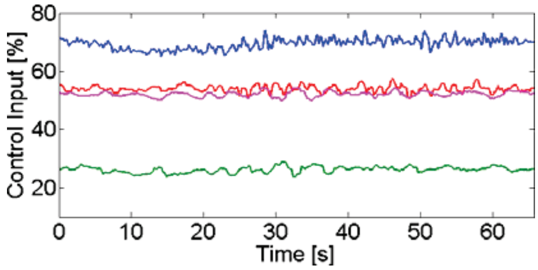
One evaluation pilot performed informal hover evaluations and determined the severity of the turbulence. This was done to tune the existing CETI levels to a standardised turbulence level in accordance with DEF STAN 00-970 Part 7/2 [28]. That also creates comparability of the used CETI turbulence with a known turbulence scale.

| **Turbulence level** | **Mean wind speed, kts** | **Wind standard deviation, kts** | **Gain K** | **DEF STAN 00-970 PART 7/2 14 [28]** |
|---|---|---|---|---|
| **No** | 0 | 0 | 0 | 1 - / |
| **Low** | 8.7 | 3.3 | 0.2 | 3 - Light |
| **Medium** | 11.1 | 3.9 | 0.5 | 5 - Moderate |

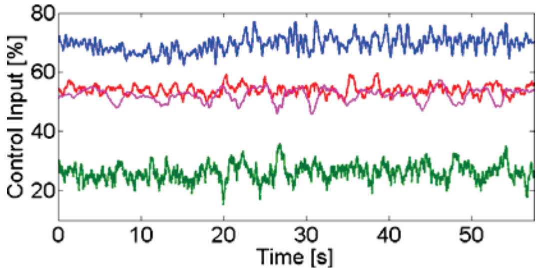
Table 3- CETI turbulence levels [26]

To set the CETI turbulence in the experimental system, the user has to select the level and the gain K. The gain K was tuned for each level of turbulence in order to generate a turbulence comparable to the DEF STAN 00-970 PART 7/2 [28] levels 1 (no turbulence), 3 (light turbulence) and 5 (moderate turbulence). The used settings are shown in Table 3. All tests were conducted without a mean wind, as the CETI turbulence is calculated using a predefined mean wind speed which is dependent on the turbulence level. During the tests, pilots described the feeling of the turbulence differently. Two of the pilots felt that the turbulence, including the reaction of the motion feedback, felt realistic. The other two pilots felt that the turbulence was perhaps not aggressive enough.

Figure 11 shows an example of the pilot control input during the Hover MTE for the four control axes roll (red), pitch (blue), pedal (green) and collective (purple). In Figure 11a, the direct pilot control input is shown and in Figure 11b, this input is overlaid with medium level CETI turbulence accordingly to equations (1) to (4).



a. Pilot control input



b. Pilot input with turbulence

Figure 11: Control Activity with and without turbulence (Roll - red, Pitch - blue, Pedal - green, Collective - purple)

## 5. Results from Piloted Evaluations

### 5.1 Handling Qualities

The individual ratings for all pilots are shown in Table 4, with green, yellow, and red denoting Level 1, 2 and 3 respectively. Ratings are shown with respect to both UCE and Turbulence level. As shown, predominantly HQRs awarded were found within Level 2 for UCE 1 and UCE 2 conditions. This is in agreement with objective criteria discussed in the preceding section.

| | | | |
|---|---|---|---|
| Pilot 1 | | | |
| Turbulence | UCE 1 | UCE 2 | UCE 3 |
| No | 4 | 5 | 7 |
| Low | 4 | 6 | 7 |
| Med | 5 | 6 | 7 |
| Pilot 2 | | | |
| Turbulence | UCE 1 | UCE 2 | UCE 3 |
| No | 3 | 4 | 5 |
| Low | 4 | 5 | 7 |
| Med | 4 | 7 | 7 |
| Pilot 3 | | | |
| Turbulence | UCE 1 | UCE 2 | UCE 3 |
| No | 4 | 5.5 | 7 |
| Low | 4 | 6 | / |
| Med | 5 | 6 | 8 |
| Pilot 4 | | | |
| Turbulence | UCE 1 | UCE 2 | UCE 3 |
| No | 4 | 5 | 5 |
| Low | - | 6 | - |
| Med | 5 | - | 6 |

Table 4: HQR ratings

Figure 12 shows the average HQRs awarded by the four pilots. A decrease in HQs as the visibility decreases (as the UCE degrades) is clearly recognisable. Ratings are found to change from HQ Level 2 to HQ Level 3 with the introduction of visual degradation. The degree of change is comparable for the majority of cases. In UCE 3, there was limited change found between ratings obtained in low and medium turbulence. Pilot comments indicate that for these cases, especially for UCE 3, the poor visual conditions are more prevalent than the turbulence and therefore the turbulence has less effect. Nevertheless, the turbulence was considered disturbing when attempting to conduct the hover task and the pilots believed that its introduction increased the workload. The effects of the degraded visual conditions on the pilot, related to the Hover MTE task, are described in Section 5.3.

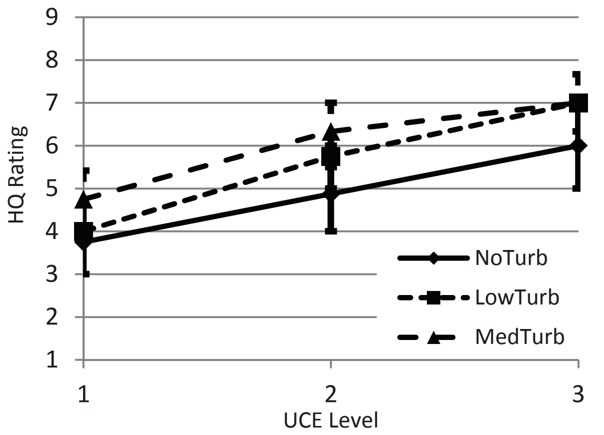


Figure 12: Average HQR rating with respect to UCE level

Figure 13 shows the average ratings of the four pilots with respect to the level of turbulence. Compared to Figure 12 it can be seen that the degradation through turbulence is less recognisable than through visual degradation and is approximately one rating point from no turbulence to medium turbulence. It should be mentioned that the severe turbulence (worst possible) was not used in the investigation. However, UCE 3 represents the worst possible visual conditions. Nevertheless for this test procedure the change in UCE level has a more visible influence on pilot HQ ratings than turbulence.

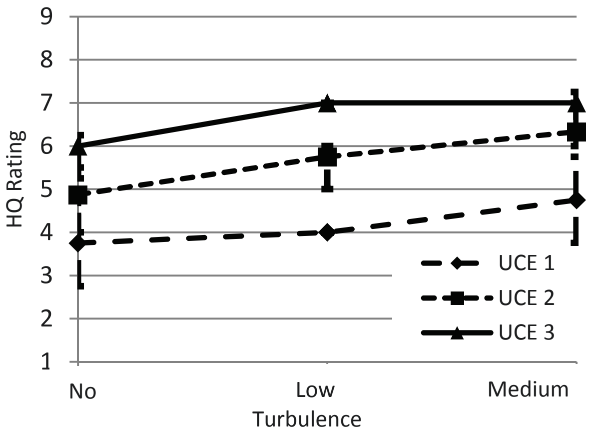


Figure 13: Average HQR rating with respect to turbulence level

In general, the turbulence levels used in this study provided more of a disturbance/annoyance, rather than a significant factor for the task performance. Pilot comments indicated that the pilot input frequency increases with the level of turbulence. This will be discussed in Section 5.3.

Pilots stated that the translational element of the task was often harder in DVE than the stabilised hover elements. This was due to the lack of cues during the approach phase, where even less visual cues were available to determine aspects such as speed, acceleration, and height. During the stabilisation phase, the cues used to estimate the translational speed were not sufficient for desired task performance, leading to larger and more unprecise inputs. When a stable hover was reached, the poles and hover boards were sufficient references to hold the position, reducing the workload in comparison to the translational phase.

### 5.2 Task Performance

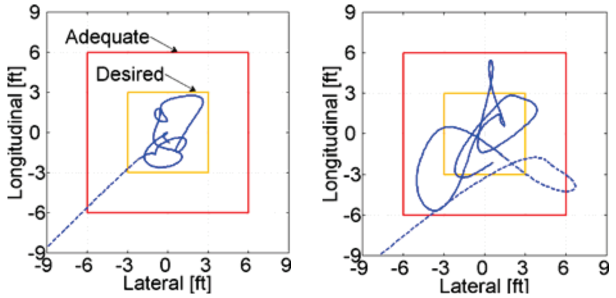
This section discusses the performance during completion of the task. Both desired and adequate performance task tolerances are defined within the task definition. The main boundaries to achieve desired or adequate performance are time to stabilise, lateral, longitudinal and vertical deviation from the reference point and the heading. The definitions for these values are given in Section 2.4. These boundaries taken from ADS-33 are dependent on helicopter type (Cargo/Utility) and the visual conditions. For the research described in this paper, all tests were assessed with the boundaries for good visual conditions to obtain comparisons between all tests. Normally, all tests under DVE would have been conducted with relaxed task performance tolerances. A direct comparison between GVE and DVE in this case would not be possible, and therefore it was not useful for this study.

Task performance is shown primarily with reference to the lateral and longitudinal position deviation. However, all other parameters relevant for assessing the task performance were also observed, to ensure they stayed in the desired or adequate boundaries during task completion.

As described in the previous Section, the HQs are a combination of pilot workload and the ability to complete a defined task.

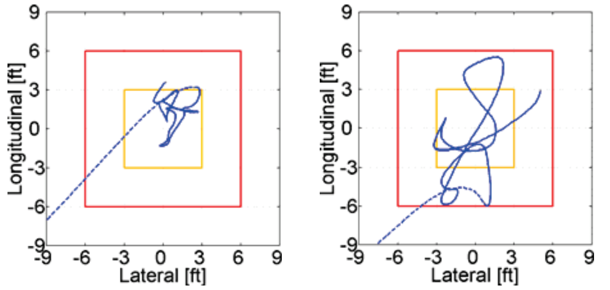
Figure 14 displays the task performance through lateral and longitudinal deviation to the hover point of Pilot 2 over four cases. These cases represent both the best (top, left) and worst (bottom, right) levels of turbulence and UCE. The plot contains the desired (yellow) and adequate (red) boundaries and the helicopter position referred to the reference point (blue line). The blue dotted line shows the helicopter position during the stabilisation phase. Comparison of Figure 14a and b (no turbulence) and Figure 14c and d (medium turbulence) shows no dramatic differences due to the presence of turbulence. Only the flight in UCE 1 and medium level turbulence appears to be less precise than without turbulence. In both cases, the addition of turbulence does not change the ability of the pilot to stay in desired (As shown in Figure 14c.) or adequate (As shown in Figure 14d.) performance.

In contrast, the degradation in the visual condition influences the task performance in a more significant way. In Figure 14b and d, where the pilot was flying in UCE 3, it is evident that the task performance is reduced from desired to adequate (due to larger position deviation). For this case, it means that the visual degradation appears to have significantly more influence than the increase in turbulence. It is possible that this would be different if the turbulence level was tested up to the worst case with a high level or strong turbulence because the vision was reduced to the worst case but not the turbulence. The lack of visual conditions caused the pilots to see delayed attitude errors which caused larger translational errors, resulting in larger control inputs. This effect is evaluated in a more detailed way in the following Section 5.3.



a. Performance plot position, UCE 1, No Turbulence

b. Performance plot position, UCE 3, No Turbulence



c. Performance plot position, UCE 1, Med Turbulence

d. Performance plot position, UCE 3, Med Turbulence

Figure 14: Task performance for Pilot 2

The plots shown in Figure 14 are giving a good indication of one MTE test flight. It can be seen if the pilot is able to hold the lateral and longitudinal position in desired or adequate, and how big the position deviations were. Furthermore, these plots can be used to compare the test runs. But in order to get an overview of the test runs under all environmental conditions from one or more pilot, these plots are not suitable. To evaluate the task performance, another method has to be investigated.

When evaluating the task performance and ensuring that all requirements are reached, the positional deviation is the main factor. To have a parameter which is meaningful and easy to compare, the time in which the pilot achieved remaining within desired performance was determined. To achieve Level 1 HQs, the pilot should maintain desired performance for the complete manoeuvre (Time in desired = 100%). The calculated times are the averages of test runs. For easy comparison, this parameter was divided by the hover time which was at least 30 s. That means that a desired performance referred to the boundaries stated in Section 2.4 requires a time in desired of 30 s respectively a time factor of 100 %. For the evaluation, the test runs of Pilot 2 were analysed and are plotted in Figure 15, dependent from the UCE level and in Figure 16, dependent on the turbulence level.

In Figure 15, with the exception of one case, all results appear to display a trend of decreasing task performance (reduction in time in desired) with an increase in turbulence. The time in desired is significantly reduced which is consistent with the HQ ratings (see Section 5.1) which were, for best conditions, on the border between desired and adequate and for the worst conditions in adequate and sometimes beyond adequate.

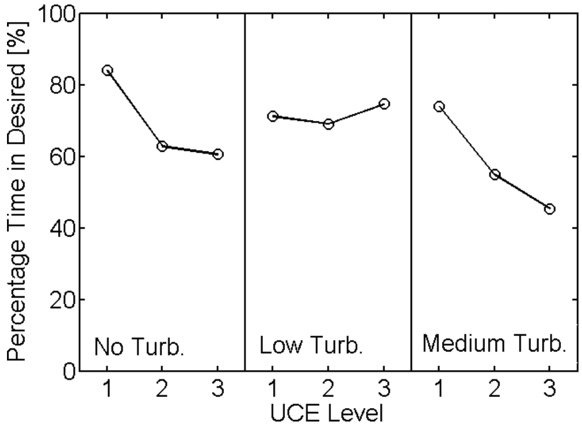


Figure 15: Time in desired dependent on UCE level for Pilot 2

When evaluating this time factor with respect to level of turbulence, the results show the same trend from no turbulence to medium turbulence. However, it is not as clear regarding the change in task performance with low turbulence. As noticed before, the level of turbulence had a smaller effect on the achievable task performance than the level of UCE.

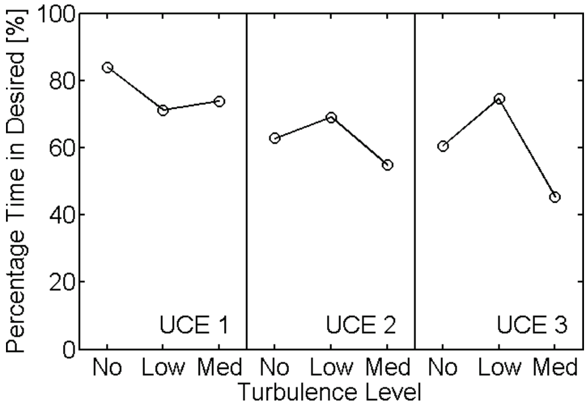


Figure 16: Time in desired dependent on turbulence level for Pilot 2

### 5.3 Input activity

Figure 17 shows the cut-off frequency for one pilot flying in UCE 1 for all control axes depended on the turbulence level. The cut-off frequency is a means to show the main frequency range which is used from the pilot for inputs. It shows up to which frequency 70 % of the control input power spectrum is reached. From the analysis of cases in UCE 1, an increase in cut-off frequency is apparent in longitudinal, lateral, and pedal axes. This suggests that the pilot has increased his workload in these axes, applying high magnitude of control at higher frequencies. The largest change is visible in the longitudinal axis, which could be a result of the bandwidth shown in Figure 5. These results reflect the comments of the pilot. It was stated that with an increase in turbulence, there is a corresponding increase in the input activity.

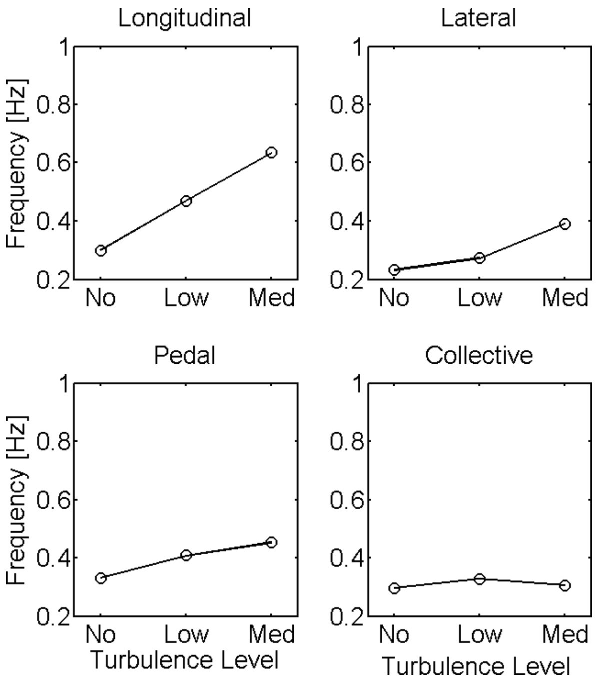
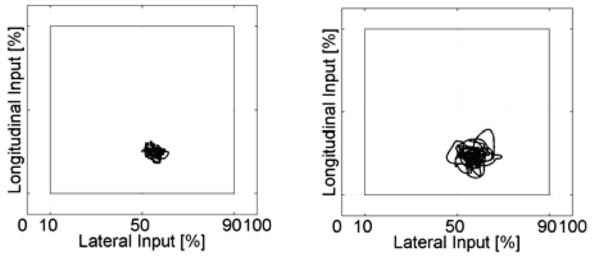


Figure 17: Input frequency for Pilot 2 (UCE 1)

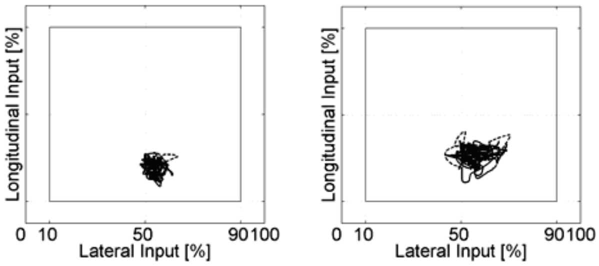
Derived from pilot comments, it can be assumed that the biggest effect to the pilot occurs through the loss of sight of the horizon in poor visual conditions (UCE 2 and 3). This causes reduced cues for the helicopter attitudes respectively its error. The poles and boards used for completion of MTE are the remaining references. This reduced attitude cueing causes greater attitude errors and hence larger position deviations. Under good visual conditions, the pilot is able to recognise an attitude error earlier which gives the time to make a quick and suitable reactive response. Overall this reduced ability to realise attitude errors causes bigger position deviations, delayed reaction and larger, less precise control inputs.

This effect is shown in Figure 18, where representative cyclic control inputs from one pilot (Pilot 1) for UCE 1 and UCE 3 are plotted. Especially under UCE 3 conditions, nearly all peripheral cues are gone, causing a further reduced awareness for the orientation in space. There is no reference to detect horizontal translational rates, except for the ground and the hover boards in UCE 3. This fact decreases the ability to attain a constant ground speed during approach and to decelerate to hover in a fast and precise manoeuvre. Figure 18 was derived from the test data from one pilot, but is still representative for the others, where this effect is visible in the cyclic input as well. The pilot input behaviour and strategy was different from pilot to pilot. Some were working with smaller inputs and some with greater under best environmental conditions but in the worst condition the stick deflections became greater for all pilots.



a. Cyclic at UCE 1, No Turbulence

b. Cyclic at UCE 3, No Turbulence



c. Cyclic at UCE 1, Turbulence Medium

d. Cyclic at UCE 3, Turbulence Medium

Figure 18: Cyclic input activity of Pilot 1

### 5.4 Potential PIO Susceptibility

One aspect that is not directly covered in HQ criteria is the potential for Pilot Induced Oscillations (PIOs) to occur. PIOs are dangerous interactions, which can materialise in a number of ways, to cause vehicle instability as a result of pilot interaction. The required presence of pilot-in-the-loop activity means that oscillations can be suppressed through freezing or removing control. However, lack of pilot recognition and training can lead to increase in pilot activity and further worsening of the situation.

In order to assess the potential PIO susceptibility, both with respect to UCE and turbulence, the proposed Phase-Aggression Criteria (PAC) was employed. This criterion validated through detailed and extensive simulation investigations using vehicles with rate command type systems. In [29], boundaries were defined for the observation of PIO detection in both the pitch and roll axis. The criterion is a real-time monitoring approach to detect PIOs ‘in-flight’. Through this approach, pilots or on-board systems can be alerted to impending oscillations, and necessary mitigation action can be taken. Pilot control input and vehicle rotational rates are monitored in real-time, and the phase distortion between the two signals is measured. In order to observe only the active content of pilot control (and not higher frequency passive responses – which have the potential to lead to so-called Pilot-Assisted Oscillations (PAO), the input and output are low pass filtered with a cut-off frequency of 2 Hz. Every input is assumed to be oscillatory, and is used to calculate the frequency of control input. For each oscillation, phase distortion and pilot Aggression is calculated. Results are displayed on a 2-D Phase v. Aggression plot. For post processing, all points from a recorded test run can be observed, to display the scatter and spread. In this respect, post processing can also be used to determine if (and when) PIO have occurred.

In Figure 19 the comparison of flights recorded with no turbulence in UCE 1 (squares) and UCE 3 displays points obtained from flights in UCE 1 and UCE 3. Square points are from those obtained from flight in UCE 1, whereas round points are from a flight in UCE 3. As shown, there is a significant difference between the scatter of the cases, despite the fact that the same vehicle is used for both. For these cases, no PIO has been recorded. This was expected from the HQ analysis shown in Section 2.

Finally, Figure 20 displays a case with no turbulence and a case with moderate turbulence in UCE 3. The scatter in data recorded with UCE 3 is consistent with data shown in Figure 19. However, for the case with turbulence, an increase in pilot Aggression occurs. This has the effect that it pushes a small number of points into the “Moderate PIO region”. Scattered points in this way are said not to constitute full-PIO [29][30], but show the definite potential if the situation worsens. This could be displayed through an increase in pilot Aggression or through an increase in turbulence. The analysis shows that the turbulence is exposing further deficiencies in the vehicle as its performance envelope is increased.

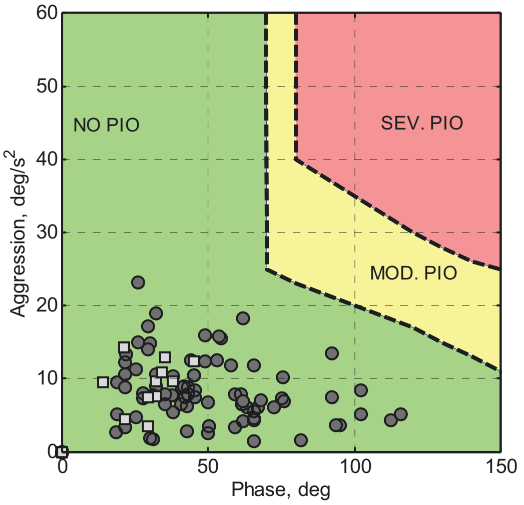


Figure 19: Comparison of flights recorded with no turbulence in UCE 1 (squares) and UCE 3 (circles)

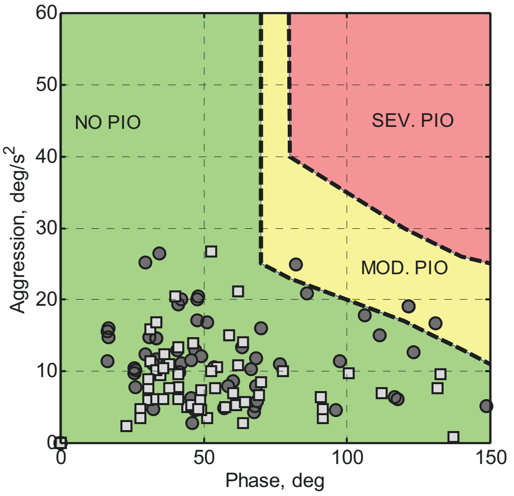


Figure 20: Comparison of flights recorded in UCE 3, with no (squares) and moderate turbulence (circles).

## 6. Conclusion

1. The method to set the UCE level using fog was successful during the tests. The UCE rating is dependent on all visual cues in the scenery. To obtain a good visual cueing environment (i.e. UCE 1), several visual references (static objects, performance markers) must be present. For the hover task employed in this investigation, cueing was always provided by poles with affixed hover boards. By reducing the visibility, the influence of all other cueing elements were either reduced or removed. This was particularly true during the stabilisation phase of the manoeuvre, where cues were not sufficient to achieve desired performance.
2. The UCE ratings, obtained using four pilots, displayed the impact of reduced visibility. When the pilot loses sight of elements such as the horizon, which allows estimation of attitude error for pitch and roll, it is no longer possible to react before a translational error occurs. So the pilot will delayed perceive a translational error compared to good visual conditions. This effect and a reduced awareness for the orientation in space are shown to lead to larger control inputs.
3. It was found that the degradation of the visual environment in combination with turbulence decreased task performance and increased pilot workload. The degradation of the visual environment was found to have a more significant effect on performance than the turbulence. One reason for this might be that turbulence was employed only to a subjective level of “Moderate” instead of “Severe”, whereas visual quality was degraded to UCE 3 (the theoretical ‘worst case’).
4. Change in HQRs was more prevalent with visual degradation. However, the impact of turbulence was also shown to have a dramatic impact on the test. With turbulence, the pilots reacted to the disturbance with inputs of higher frequency. This and the uncomfortable, ‘bumpy’ helicopter behaviour increased the workload of the pilots. Pilots commented in all tests with medium level turbulence that this task could not be conducted for a longer period of time.
5. The combination of turbulence and DVE force the pilot to use greater effort to successfully conduct the task resulting in higher workload and thus resulting in increased fatigue. This is a factor which is more relevant for real missions with a longer duration or more subtasks successive and is only marginally considered in the ADS-33 test procedure. The ability for pilots to perform other tasks whilst flying in the turbulent conditions was questionable.

This work represents the first steps in the HELMA project. The results show coherence between visual conditions, turbulence, workload, task performance and HQ ratings for four pilots. When considering only task performance, visual conditions caused the most significant degradation. It must be mentioned that the turbulence was not tested up to the worst case (high or severe). When considering all results of this paper, it is suggested that the whole mission should be the focus of further tests. This would require the definition of a number of tasks, which should be conducted in succession and maybe with secondary tasks in parallel, so that pilots are under a higher level of stress. Furthermore, real-time modifications to the flight conditions could help to observe the change in workload and performance more clearly. It would also help to determine if any transient effects result from the impact of turbulence and changes in the UCE.

## Acknowledgements

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## Appendix

| VCR Rating | Visual Quality | Description |
|---|---|---|
| 1 | Good | Can make aggressive and precise corrections with confidence and precision is good |
| 2 | | |
| 3 | Fair | Can make limited corrections with confidence and precision is only fair |
| 4 | | |
| 5 | Poor | Only small and gentle corrections possible and consistent precision is not attainable |

Table 5: VCR Rating Scale [9]

| VCR | Attitude | R. Trans. Horizontal | R. Trans. Vertical |
|---|---|---|---|
| Pilot 1 | | | |
| UCE 1 | 1 | 1 | 2 |
| UCE 2 | 2.5 | 1 | 2 |
| UCE 3 | 5 | 2 | 2.5 |
| Pilot 2 | | | |
| UCE 1 | 1 | 1 | 1 |
| UCE 2 | 3 | 2 | 2 |
| UCE 3 | 5 | 4 | 4 |
| Pilot 3 | | | |
| UCE 1 | 1 | 2 | 2 |
| UCE 2 | 4 | 4 | 4 |
| UCE 3 | 5 | 5 | 5 |
| Pilot 4 | | | |
| UCE 1 | 2 | 2 | 1 |
| UCE 2 | 3.5 | 3 | 2 |
| UCE 3 | 4 | 3 | 2 |

Table 6: Separate Pilot VCR Ratings