A TURBULENCE CRITERION FOR SAFE HELICOPTER OPERATIONS TO OFFSHORE INSTALLATIONS

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Abstract

This paper describes the development of a wind turbulence criterion for the safe operation of helicopters to offshore installations. The development of the criterion was recommended following a review of the environmental effects around offshore platform helidecks.

Currently, criteria exist for ambient temperature and for vertical wind component in the vicinity of helidecks, but a questionnaire survey of helicopter pilots revealed that the principal safety hazard and source of highest workload is turbulence around offshore installations. The new turbulence criterion will plug a long-standing gap in the guidance on offshore helideck design.

The paper describes how the criterion has been developed using piloted flight simulation in a research flight simulator together with data from wind tunnel tests on offshore platforms. Initial validation has been successfully performed, and will soon be extended to include correlation with the large database of helicopter operational flight data records being collected through the UK North Sea Helicopter Operations Monitoring Programme (HOMP).

The turbulence criterion will be used, together with existing criteria on vertical wind component and temperature, in the assessment of new offshore installation designs, or proposed modifications to existing designs, to determine wind conditions where turbulence is likely to be excessive for safe helicopter operations. These will be used to estimate helideck operability and thereby inform the installation topsides design process, and will provide input to the setting and maintenance of helicopter operational limitations for individual installations.

The work will lead to improved safety through better prediction of safe operating envelopes and helideck operability at the design stage. In addition, development of the work is expected to enable the wind environment around offshore installations to be mapped and monitored in-service using helicopter flight data records.

It is expected that the new turbulence criterion will be included in updated guidance on helideck design, and that offshore installation designers will be required to inform helicopter operators about wind conditions which result in violations of the turbulence criterion on their offshore installations (as is currently the case for the temperature and vertical wind component criteria).

1. The Need for a Turbulence Criterion

Since helidecks on offshore oil and gas platforms first became operational, the Industry has become increasingly aware of the potential hazards of structure-induced turbulence, downdraughting, and hot gas plumes generated by turbines and flares. Their effects at individual installations are assessed during the platform design process by means of wind tunnel testing and/or computational fluid dynamics (CFD) modelling. Modifications to the platform design will usually be made to improve the environment, but the scope for change is often limited by practical considerations and conflicting requirements relating to the primary functions of the installation. It is therefore not unusual for operating restrictions to be applied to offshore helidecks for certain ranges of wind speed and direction in order to prevent helicopters encountering environmental conditions that could present an unacceptable level of risk.

For environmental aspects, safe operating limits are defined in CAP 437- Offshore Helicopter Landing Areas - Guidance on Standards [1], published by the UK Civil Aviation Authority (CAA), and operating restrictions are applied via the Helicopter Limitations List (HLL) [2] when the criteria contained in this document cannot be fully met. Presently, there are two criteria relating to the environment on and around the helideck:

- The vertical component of airflows resulting from horizontal wind velocities of up to 25 metres per second should not exceed ±0.9 metres per second over the landing area.
- Where ambient temperature in the vicinity of the flight paths and over the landing area is increased by more than 2°C (measured as a 3 second average), the helicopter operator should be informed.

Both criteria apply to the airspace above the helideck required to accommodate the approach and take-off flight paths of the helicopter, defined as a height of 30 feet + wheels to rotor height + one rotor diameter.

However, a top-down review of helideck environmental issues, jointly commissioned by CAA and the Offshore Safety Division of the UK Health and Safety Executive (HSE) in response to a UK Air Accidents Investigation Branch (AAIB) recommendation following the heavy landing on the Claymore Accommodation Platform on 18 August 1995 [3] highlighted the absence of a specific turbulence criterion. The final report for this study, published as CAA Paper 99004 [4], recommended that a scientific basis be established for a limit on the permitted level of turbulence in the vicinity of offshore platforms.

The importance of considering turbulence as a specific hazard had also previously been illustrated in the results of a questionnaire survey of offshore helicopter pilots, reported in CAA Paper 97009 [5]. In this study, turbulence around platforms was ranked by pilots as being the greatest of the fifteen factors contributing to workload and safety hazards that were considered. Hence, although the existing vertical wind speed criterion in CAP 437 in combination with a system of operational feedback (turbulence report forms) appears to have served to contain the situation, the absence of a specific turbulence criterion in CAP 437 is regarded as anomalous and unsatisfactory.

In 2000, the CAA therefore commissioned a programme of work at BMT Fluid Mechanics (working with its subcontractors QinetiQ and Glasgow Caledonian University) with the primary objective of developing an easy-to-use maximum safe turbulence criterion for all helicopter operations to offshore helidecks. The basic assumption behind the approach taken to this work was that the margin of safety available at any point during the sections of flight of interest is inversely proportional to pilot workload, i.e. the higher the workload, the lower the margin of safety. Hence, in order to establish a maximum safe turbulence criterion, it was necessary to:

- quantify pilot workload and define a maximum safe limit; and
- establish a generic relationship between pilot workload and an appropriate measure of turbulence.

A well-established and widely accepted measure of pilot workload exists in the Cooper-Harper aircraft handling qualities rating (HQR) scale devised by NASA in the 1960’s [6]. This involves structured pilot debriefing to arrive at a rating on a scale of 1 to 10 where 1 is benign and 10 is unacceptable (see Figure 1). A safe upper limit of pilot workload can readily be identified by reference to the descriptions of task performance and pilot workload associated with each rating.

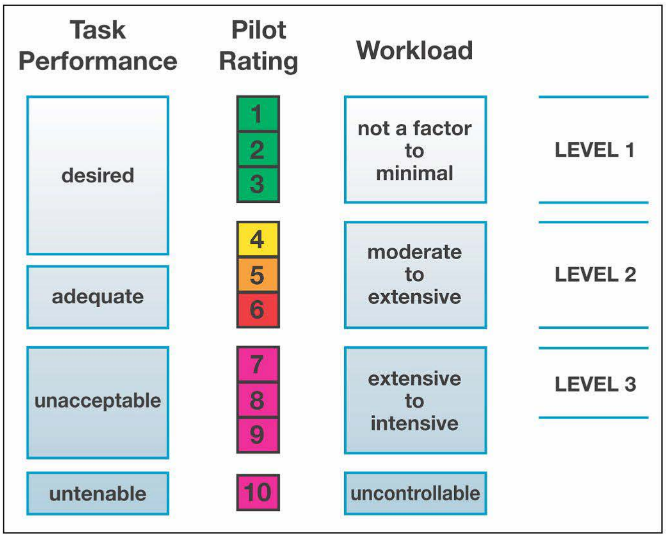

Figure 1 - Workload rating scale.

No precedents for establishing a relationship between pilot workload and turbulence were found to exist, however, and so addressing this issue effectively formed the main focus of the research. Although challenging in its own right, this task was exacerbated by the requirement that the resulting relationship be generic, i.e. not dependent on pilot, aircraft or offshore platform.

2. Development of a Turbulence Criterion

2.1 Overview

A number of tools and models were assembled in the course of the programme to satisfy the aim of establishing a generic relationship between pilot workload and measures of turbulence. The key components are illustrated in Figure 2 and are briefly described below.

At the top of Figure 2 is the wind tunnel data that provides measurements of the disturbed airwake around the offshore platform of interest. Such data are normally generated for new or modified platforms before entering service during the development of an appropriate safety case. However, due to the unsuitability of this data it was necessary to collect new data specifically for this project. The role that wind tunnel testing has played both in terms of this programme and its wider application in the clearance of offshore platforms is discussed in section 2.2.

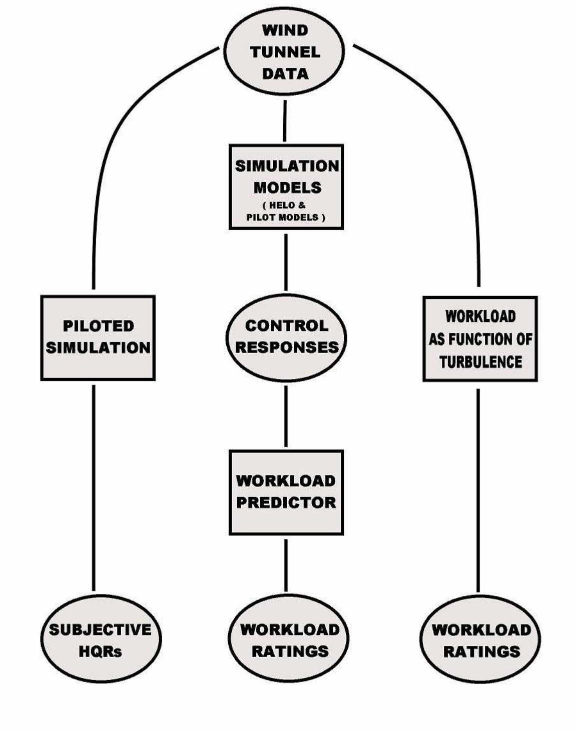

Figure 2 - Overview of tools and models for prediction of pilot workload.

As shown in Figure 2, there are three streams of work that use the wind tunnel data as a starting point. On the left is the piloted simulation that employs a helicopter model and visual database to allow a pilot to assess the severity of the platform airwake, and award a Cooper-Harper handling qualities rating to flying tasks in various wind conditions. The simulation has been targeted at a single helicopter / platform combination using a computer model of the Sikorsky S-76 and a visual database of the Brae-A platform. A description of the piloted simulation conducted during the programme is given in section 2.3.

In the centre of the figure there is the desktop simulation that uses the same helicopter model as the piloted simulation, but a pilot model and workload predictor replaces the human in the loop. The pilot model synthesises the control activity required to perform manoeuvres in the presence of the measured flow, and the workload predictor estimates the level of workload indicated by the control activity. The result is a workload rating expressed on a scale that parallels the Cooper-Harper HQR scale. Some of the data from the piloted simulation was required as 'training data' to configure the workload predictor, but the bulk of the information has been used to validate both the workload predictor in isolation and the entire desktop simulation process. A description of the components of the desktop simulation and their role in supporting the definition of a turbulence criterion is given in section 2.4.

Lastly, on the right of the figure is the relationship between turbulence and workload, developed to define the turbulence criterion that is applied to wind tunnel test results to establish a safe operating envelope for the corresponding offshore platform. The criterion is required to be easily applied and appropriate for use across any helicopter / platform combination. The results of the piloted simulation have been used to identify this relationship, which is described in section 2.5.

There are limitations to the overall methodology in its current form. Firstly, from a pilot's perspective, it is generally accepted that the workload increases for night approaches due to the difficulties in judging the approach angle and closure rate towards the structure. Any turbulence encountered during this more difficult approach would clearly increase workload. In addition, it may become more difficult to choose a flight path avoiding turbulence, thereby increasing the probability of turbulence encounters. Furthermore, there are other factors that can lead to similar levels of degradation to visual cues such as rain, sleet, snow or fog. The pilot model used in this programme currently has no mechanism through which to represent the decrease in visual cues, and so no way of predicting the increase in workload needed to achieve controlled flight in turbulence under such circumstances. However, this situation is no different from that relating to the existing guidance and criteria in [1] and [2]. There is a presumption that the criteria apply to good visual conditions, and that operating pilots will use their training and experience to make their own adjustments in the dark, or in conditions of poor visibility.

Secondly, no attempt has been made to predict where departure from the safe flight envelope would occur due to lack of torque and power margins. This would require a higher fidelity model of the helicopter than was available to the project together with a number of enhancements to the pilot model. However, as turbulence is primarily a problem in high winds when the helicopter has a high margin of lift, it is considered that torque and power limits are unlikely to influence workload due to turbulence. This assumption may not be valid in cases where there is either a large downdraft impinging on the helicopter, or the rotor is shielded from the free stream flow by superstructure and thus operating in a regime more akin to the hover. In either scenario, the amount of power in hand will be reduced and may become an issue depending on the power margins of the helicopter being considered. In terms of applying appropriate criteria to measurements of the expected airwake, the combination of the existing vertical airflow component criterion and the proposed new turbulence criterion should suffice for those cases involving downdraft.

2.2 Wind Tunnel Tests

Due to the lack of any existing suitable data, it was necessary to conduct a series of wind tunnel tests to generate the wind flow data required for the project. The data were required for both the piloted simulation, and the desktop simulation.

2.2.1 General Description

Wind tunnel tests have been used for some years [7] to help ensure that the helidecks on offshore installations do not pose an excessive level of aerodynamic hazard to the helicopter, and to help identify wind conditions in which flights should be restricted. The aerodynamic hazards are influenced by the bulk and shape of the installation topsides, the location of the helidecks in relation to these topsides, and by the direction of the wind [8].

Models of new offshore installation designs are routinely tested in the wind tunnel, and designs are sometimes modified (e.g. by raising the height of the helidecks to increase the air gap to the accommodation block) in order to reduce the limitations and improve operability.

It is important that such tests are performed in flow conditions with a realistic representation of the atmospheric boundary layer found at sea. Purpose-designed wind tunnels with long working sections incorporating special features to model the variation in mean wind speed with height, and the level of naturally occurring turbulence are normally used. Aeronautical-type wind tunnels are generally not suitable for this kind of work.

2.2.2 The Brae A Test Programme

For the project described here a special series of tests was performed on a 1:100 scale model of the North Sea Brae A platform in order to provide input for the piloted flight simulation trials and the desktop simulation exercises. The platform model was rotated on a turntable in the wind tunnel to represent a range of wind directions. These directions were chosen so that the flow was sampled when the helideck was upwind and unobstructed, and also when it was downwind of identifiable obstructions to the wind flow such as the drilling derricks, or gas turbine exhaust stacks.

The test programme was carried out in the BMT Boundary Layer Wind Tunnel. This wind tunnel is designed for atmospheric boundary layer simulation. It has a working section of 4.8 m wide by 2.4 m high by 15m long, and is large enough to accommodate 1:100 scale models without significant blockage.

A typical marine atmospheric boundary layer was generated in the working section. This was achieved by using a barrier to induce an initial turbulent shear into the flow and promote effective mixing. Final conditioning of the boundary layer was achieved by a roughness covering the floor of the working section and extending across the test section (see Figure 3). This roughness represents the effect of the roughness of the sea surface.

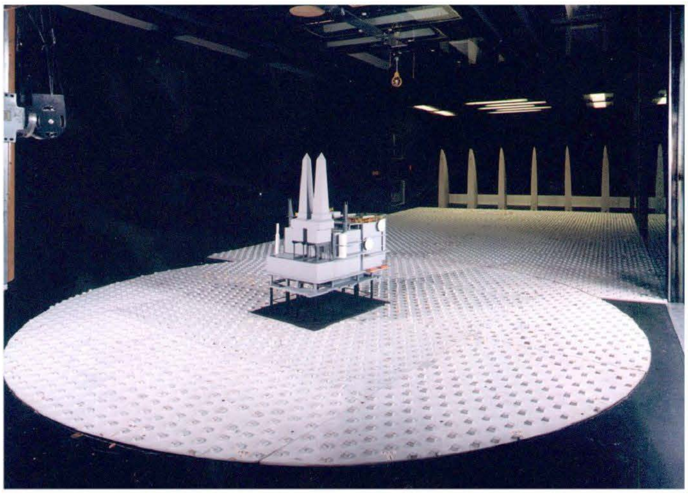

Figure 3 - Model of Brae A Platform in the BMT boundary layer wind tunnel.

Profiles of mean wind speed and turbulence were measured, and checked to be consistent with full-scale marine wind characteristics. The turbulence profiles were compared with a standard logarithmic profile for a roughness length of 0.001 m (typical of moderate sea conditions).

Simultaneous time histories of the three components of wind velocity were measured using 3 triple hot wire anemometers arranged in a horizontal triangular array. The radius of the out-scribed circle was set to 5.8m full scale, commensurate with the main rotor radius of the subject helicopter (S-76).

The probe triplet was mounted on the computer-controlled traverse system and was moved to prescribed locations at which longitudinal, transverse and vertical components of wind velocity were simultaneously recorded at each probe position. Figure 4 shows the probes in position. Time histories of velocity were recorded at a sample rate of 512 Hz for a sampling time of 64 seconds.

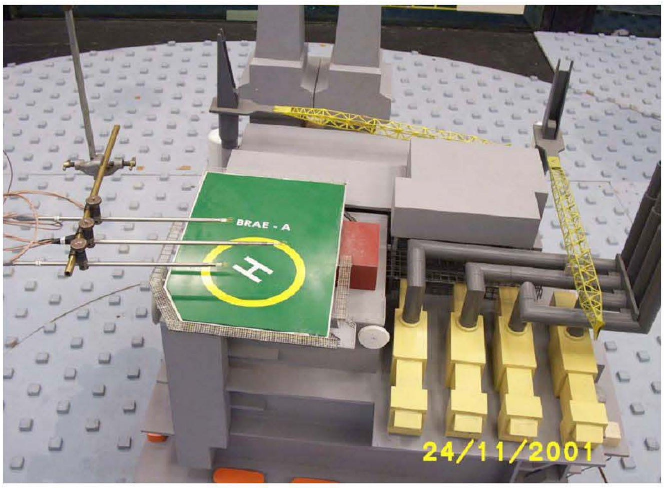

Figure 4 - 3-axis hot wire probes located above the helideck for exhaust obstruction configuration (wind blowing from right to left).

The test matrix captured flow time histories over a grid of points covering the region occupied by the helicopter rotor during the final approach and positioning to land. The exact grid used was modified according to the wind direction being considered in order to match the approach likely to flown by the helicopter in adapting to the layout of platform structure and the visual cueing environment in each case.

The results from the tests provided a 3-axis turbulent environment with realistic spatial variation in mean velocity and turbulence. Using this data, complete approaches could be flown in the simulator in a realistic turbulence field. Figure 5 shows an example time series of one component of wind speed measured by the hot wire anemometers in the wind tunnel.

The wind tunnel data were processed to provide time histories of both velocity and velocity gradients at the rotor hub. The distribution of vertical flows over the rotor disc was allowed to vary linearly in both longitudinal and lateral directions, thereby enabling the interaction of the helicopter with the airflow to be more accurately modelled. The pilots all commented that the result was the most realistic simulation of flight in turbulence in close proximity to an offshore platform that they had experienced. It did not exhibit the usual ‘plank-like’ characteristics evident in simulations where the entire rotor disc is subjected to the same wind flow.

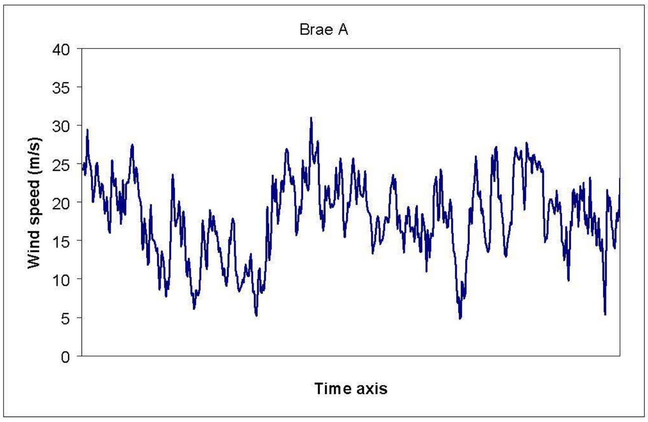

Figure 5 - Typical time series of a wind velocity component measured on the Brae A model.

2.3 Piloted Simulation

The piloted simulation exercise formed the core of the project and produced the relationship between turbulence and pilot workload used to establish the turbulence criterion. The results were also used to validate the desktop simulation described in section 2.4.

2.3.1 General Description

The facility used to generate the data was the Advanced Flight Simulator (AFS) at the QinetiQ site in Bedford, UK. The helicopter model used for the real-time work was identical to that employed for the desktop analysis described in section 2.4.1. For the purposes of the work a visual database representing the Brae A platform was produced with sufficient photo texturing to allow the pilot, as closely as possible, to use the same control strategies as for real world. Figure 6 shows a typical view from the visual database.

The simulator trials were conducted in two parts, designated trials BRAE01 and BRAE02. BRAE01 was used for initial collection of data and demonstration of the suitability of the simulator for delivering the required validation data. The BRAE02 trial involved assessments by three pilots to establish the variability in workload ratings due to individual pilot strategies. The pilots were all experienced and qualified test pilots who had flown recently to offshore platforms, although not necessarily the Brae A platform modelled for this study.

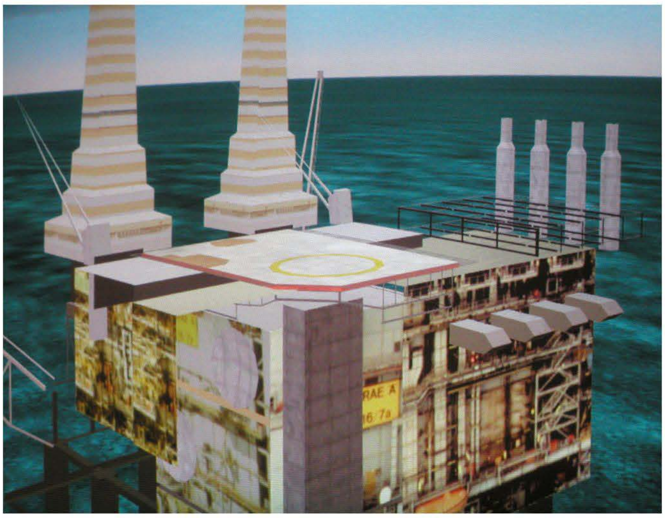

Figure 6 - Platform Brae-A visual database as used for Trials BRAE01 and BRAE02

2.3.2 Task definition

Two separate tasks were used during the BRAE01 and BRAE02 trials as follows:

- Hover task - establish a stable hover at a nominal height of l0ft above the helideck, and maintain for a period of 60 seconds (BRAE01 and BRAE02).
- Full approach - starting from a point lkm from the helideck on an into-wind heading, fly an approach to the helideck and land (BRAE02).

The hover tasks were flown by all three pilots and formed the bulk of the data generated during the trial, whereas only one pilot flew the full approach task. All runs were immediately followed by award of a Cooper-Harper Handling Qualities Rating (HQR). Task performance limits for the hover task were defined by desired and adequate limits of longitudinal, lateral and vertical drift from the initial hover position as well as deviation from the target heading.

Task performance for the full approach was more difficult to define as it was considered inappropriate to prescribe an exact flight path against which position accuracy could be judged. Not only would this have probably altered the pilot's normal planning and flying strategy for an approach to an offshore platform, but also would have required the addition of extra visual cues to allow the pilot to monitor his accuracy within the specified flight corridor, thus detracting from the realism of the task. However, during the approach a pilot will have a number of goals against which a general impression of desired or adequate performance may be awarded, e.g. setting an appropriate track and rate of descent in the early approach, and transitioning smoothly over the deck to establish a hover of the helideck during final approach. These were discussed with the pilot prior to the approach task tests to guide his assessment of task performance and the award of an appropriate rating.

A range of test points were flown whilst varying wind speed, wind direction and aircraft weight. Wind directions were chosen such that various parts of the platform superstructure were positioned directly upwind of the helideck as well as one direction where there were no such obstructions. Example plots of pilot HQRs as a function of wind speed for both the unobstructed wind direction, and that with the various obstructions upwind of the helideck are shown in Figure 7.

Figure 7 - Pilot HQRs plotted against wind speed.

A comparison of the trends in pilot HQR with wind condition showed an increase in ratings with wind speed for each wind direction with a similar trend being produced by each pilot. In general the spread of ratings for a particular test point was seen to span 2 HQR points with the exception of one case (in the lee of the crane at wind speed of 60kts) where a spread of 3 points was seen. It would normally be acceptable in such experiments for pilots to disagree by up to 1 HQR point only, and therefore the scatter obtained was larger than desired.

The reason for this is most likely the difficulty experienced by all the pilots in judging the task performance against the criteria supplied, due mainly to the lack of visual details on and around the helideck. Each pilot claimed to be able to rate the task performance with different levels of accuracy.

The occurrence of such issues was no great surprise, and a solution would have been to ensure an abundance of visual cues in the database to allow pilots to make more accurate judgements. However, much care would be needed in order to achieve this without compromising the realism of the simulation in terms of reproducing the true workload of the task. In the interests of realism, no artificial visual cues were introduced for either the BRAE01 or BRAE02 trials. For any future work, the addition of more detail to the helideck surface would offer the best way of increasing visual cueing without compromising realism.

2.3.3 Data Analysis

In support of the validation of the various components that have been developed a number of analyses were conducted as itemised below.

Figure 8 - Comparison of BRAE01 workload predictor and pilot HQRs.

1) The purpose of including the full approach task was to assess whether the strategy of using the hover task to estimate the severity of turbulence, in terms of workload, was a reasonable simplification of an entire approach and landing task. A comparison of the HQRs for the approach task compared to those from the hover task in equivalent wind conditions showed the ratings to be the same for all but one case where there was a difference of just 1 HQR point. These results, albeit limited in scope, suggest that the hover task was a valid simplification, and was appropriate for use in the desktop simulation exercise.

2) The bulk of the data collected on the trials was for the 60s hover in turbulence task. The control responses in BRAE01 were for a single pilot only and used an inferior implementation of the turbulence in the main rotor model. They did, however, provide a valuable set of control responses with associated HQRs that were used as training data from which the coefficients in the workload predictor were defined.

3) With the coefficients of the workload predictor fixed using BRAE01 data, this left the entire database of hover data (control responses and associated HQRs from three pilots) from BRAE02 as an independent set of data on which to validate the workload predictor. Overall, the predictions are higher than those awarded by the pilots by approximately 0.5 to 1 HQR points as shown in Figure 8. In the context of the work, however, this was considered to be an acceptable error.

4) Finally, the subjective pilot ratings were compared with the results from desktop simulation for the same wind conditions as a validation of the combination of the SyCoS pilot model and workload predictor (see section 2.4.2).

2.4 Desktop simulation

The purpose of the desktop simulation was to examine the effect of helicopter design parameters on workload, and to establish the applicability of the relationship between turbulence and workload developed from the piloted simulation exercise to platforms other than the Brae A.

2.4.1 General Description

In addition to the wind tunnel measurements of the platform being assessed, there are three essential components that make up the desktop simulation:

- The helicopter model which predicts the response of the aircraft in response to the disturbed airwake.
- The pilot model which synthesizes the control inputs needed to compensate for the motions induced by the airwake.
- The workload predictor which analyses the control responses and estimates the level of workload apparent in the signals.

2.4.1.1 Helicopter Model

The flight simulations utilised a commercial off-the-shelf package, FLIGHTLAB (from Advanced Rotorcraft Technology, Inc.), that provides a user-friendly modelling environment containing libraries of all the major model components required for a high fidelity helicopter simulation. The model components are generic and therefore need to be configured with suitable design data to represent the particular aircraft being simulated.

The helicopter type selected for the FLIGHTLAB simulations was the Sikorsky S-76. This was due, in part, to the volume of North Sea operations flown by this particular helicopter. As sufficient design data were not available in this instance, a model with S-76-like features was developed (and referred to as S-76X). The S-76X model was based on the FLIGHTLAB model of an existing hingeless helicopter model of a similar weight and size to the S-76. The rationale was, therefore, to use the existing model and replace the hingeless main rotor with an articulated main rotor of appropriate stiffness. The fuselage, control system and tail rotor remained unaltered apart from minor modifications to the weight of the vehicle.

It should be noted that no engine model was included in the helicopter model, with the result that some features relating to pilot workload (such as prevention of rotor under / over-speed, respecting torque limits etc.) were not represented.

2.4.1.2 Pilot Model - SyCoS

The pilot model is one of a family of models collectively referred to as SyCoS (Synthesis through Constrained Simulation), and referred to as the Fully Compensating Crossover Model (FCCM) [9]. The SyCoS pilot is a corrective pilot model developed to overcome some of the deficiencies of inverse simulation. Inverse simulation, in its exact implementation, generates the precise control actions required to fly a helicopter along a specified flight path. It therefore experiences difficulties with external inputs such as turbulence, or system constraints such as control limits, where the method attempts to calculate unrealistic or even unattainable control actions. A more practical approach is to systematically reduce the errors in following the flight path rather than eliminate them entirely, and that is what a corrective pilot model does, i.e. a pilot model is said to be corrective when it generates control actions that tend to correct an error between the observed output and a given reference value.

2.4.1.3 Workload Predictor

The pilot workload predictor is based on a linear combination of the standard deviation of control movements and the rates of the control movements. In order to obtain values for the coefficients, a set of training data is required that contains both an assessment of the workload and the associated control responses. For this work the subjective ratings used were Cooper-Harper handling qualities ratings. Although not a pure workload scale, the choice of Cooper-Harper allows the workload rating to be based on a well-known and established scale in which workload is a key factor.

The exact form of the workload predictor is as follows:

Workload Rating = $c1 + c2\,\sigma(\xi) + c3\,\sigma^*(\xi) + c4\,\sigma(\eta) + c5\,\sigma^*(\eta) + c6\,\sigma(\theta_0) + c7\,\sigma^*(\theta_0)$

where:
c1 – c7 = predictor coefficients
ξ = lateral cyclic position
η = longitudinal cyclic position
θ_0 = collective lever position
$\sigma(x)$ = function : standard deviation of x
$\sigma^*(x)$ = function : standard deviation of first derivative of x with time

The yaw pedal position was excluded from the workload predictor, as this was not seen to contribute significantly to the overall workload during development of the predictor.

2.4.2 Validation of the Desktop Simulation

The HQRs awarded by the pilots during the BRAE02 piloted simulation trial are plotted against the corresponding ratings generated by the desktop simulation in the same conditions (wind, turbulence and helicopter weight) in Figure 9.

Figure 9 - Comparison of desktop simulation and pilot HQRs.

Overall, the desktop method produced a reasonable set of predictions. The correct trend is clearly evident but the predictions are, on average, low by between 1-2 HQR points.

2.4.3 Role of Desktop Simulation in Defining a Turbulence Criterion

The aim of the research reported in this paper was to establish a simple metric to be applied to a suitable measure of the turbulence around offshore platforms for the purposes of predicting those conditions where it is unlikely that safe operation of helicopters can be guaranteed. The desktop simulation as described above is somewhat more complicated than required, and generally needs some expert knowledge in order to properly configure and run the models to produce results.

The overall role of the desktop simulation in the development of the turbulence criterion, however, was to provide a relatively detailed model with which to explore the generality of the relationship between turbulence and workload without recourse to a multitude of expensive and time consuming piloted simulation trials to consider different helicopter and platform combinations. The methodology has been to validate the desktop simulation against the available data for S-76 / Brae-A piloted simulation exercise, and then to investigate the influence of key helicopter design parameters on the predicted workload, and to apply the desktop simulation to other platforms and compare the results with predictions using the relationship established between turbulence and workload from the piloted simulation exercise.

2.4.3.1 Sensitivity of Workload Rating to Helicopter Type

The sensitivity of workload rating to helicopter type was investigated by varying the following four key helicopter design parameters:

- helicopter size (represented by weight class),
- helicopter weight (over the normal operating range for S-76),
- blade hinge offset, and
- blade loading.

The design properties for this parametric variation were selected on the basis of data available in the public domain for a wide population of helicopters.

The main conclusion from this part of the work was that changes to the selected parameters did not cause large variations in the pilot workload in turbulence. This was because there were balancing factors in most cases, e.g. increasing blade hinge offset increases the helicopter response to the turbulence, but it also increases the effectiveness of the control activity to stabilise the helicopter, and so the net effect is a small change in pilot workload. On the face of it, this suggests that the same limiting turbulence criterion could indeed be used for all helicopter types.

However, it is recognised that there is the potential for particular helicopter designs to exhibit a larger variation in pilot workload in turbulence if they happened to be designed with particular combinations of parameters not covered in the analysis. It was therefore not possible to conclude from the simulation study alone that the same limiting value of turbulence could be applied to all types. Following consultations with a number of experienced pilots however, it appears that there isn't any one helicopter type currently operating offshore on the European continental shelf that is commonly recognised as generating significantly higher workload in turbulence relative to the fleet in general, even though the feel and ride do vary significantly. This anecdotal evidence supports the notion that a single turbulence criterion is indeed appropriate for all aircraft types.

2.4.3.2 Applicability to Other Offshore Platforms

Wind tunnel data for a number of other offshore installations was available to the study. Data for Beatrice, Claymore and Schiehallion were used to generate predictions of workload rating using both the full desktop simulation, and the relationship between turbulence and workload developed from the piloted simulation exercise (see section 2.5). It was shown that, provided the expected underestimation of the desktop simulation method (see section 2.4.2) was factored in by making an adjustment of +1.5 HQR points across the board, the results from both methods agreed to within 1 HQR point for all cases considered. Data were considered for a total of 84 wind speed and direction combinations spread over the three installations using four locations over or near the helideck. In this way the predictions from desktop simulation were used to give confidence in the application of the relationship between turbulence and workload to platforms other than the Brae A used for the validation exercise.

2.5 Turbulence Criterion for Safe Helicopter Operations

All the samples of turbulence used for the BRAE02 piloted simulation trial were examined to establish a suitable metric for use in defining a relationship between turbulence level and pilot workload. The properties of the data were found to be such that only a single parameter was required, the optimum parameter being the standard deviation of the vertical component of the wind velocity. This parameter is shown plotted against the HQR ratings awarded by the three pilots in Figure 10. Also shown on the plot is the best fit line that is given by the following relationship:

HQR = 2.77 + 1.571*(std. devn. of vertical velocity)

Figure 10 - Pilot HQR plotted against standard deviation of vertical wind velocity component.

Applying this relationship to the wind tunnel data for the Brae A yields the workload predictions illustrated in Figure 11. The workload ratings are placed on a compass rose where the bearing represents the wind direction and the distance from the centre of the rose represents the wind speed. The arc of the coloured segment represents the angle projected by the width of the obstruction.

To define a turbulence criterion it is necessary to consider the workload rating that would constitute unsafe flight. By considering the descriptors associated with the HQR scale it is seen that the level 6/7 boundary is one where even extensive workload becomes insufficient to achieve adequate performance. This is therefore considered to be the boundary at which flight becomes unsafe in terms of achieving a landing on an offshore platform.

Although subjective HQRs will always have integer values, the workload ratings produced as predictions here can have non-integer values. If rounding is considered then 6.49 will give a rating of 6 and 6.50 a rating of 7. Therefore the rating considered to represent the limit of safe flight is 6.50.

Figure 11 - Workload predictions for Brae A using the turbulence /workload relationship established from piloted simulation trials.

Using this value and combining it with the identified relationship for workload rating as a function of the standard deviation of the vertical flow gives the turbulence criterion in its current form:

The standard deviation of the vertical flow must be less than 2.4 m/s for safe flight to be maintained.

Comparison of Figure 11 with the entry for the Brae A in the Helicopter Limitations List (HLL) has indicated that the results of applying the relationship between turbulence level and pilot workload derived from the BRAE02 to the wind tunnel data for the Brae A are broadly consistent with current operational experience.

3. Future Work

There are two distinct, but related, areas of future work. The first is connected with the validation of the turbulence criterion that has been established, and the second is the use of the pilot workload algorithms to provide in-service, data-driven operational feedback to supplement the use of turbulence report forms in continuously monitoring the environments around offshore platforms as experienced by helicopters.

3.1 Validation of the turbulence criterion.

Although considered highly successful, the research to develop the turbulence criterion necessarily embraced a number of assumptions and approximations and, as is normally the case with work of this nature, there is a need to validate both the modelling process used, and the limiting criterion established. Two potential approaches to this task were identified:

- Apply the turbulence criterion to archived wind tunnel data and compare the resulting operating envelopes with helicopter operational experience as documented in the Helideck Limitations List (HLL) [2].
- Implement the collective and cyclic control movement-based pilot workload algorithms in the Helicopter Operations Monitoring Programme (HOMP) [10] analysis software, and use archived HOMP data to map the environments around offshore helidecks and compare the results with helicopter operational experience as documented in the HLL.

The latter approach has initially been adopted partly due to the paucity of suitable data for the former, and partly because of the attractive 'spin-off' of providing a means of continuously monitoring the environments around all offshore platforms if the HOMP-based approach is successful.

3.2 Continuous monitoring of offshore platform environments.

Within HOMP there is a facility called Flight Data Measurements which allows the values of parameters available to HOMP to be routinely and automatically sampled, analysed and presented. The data samples taken during each flight may be used to establish their 'normal' distribution, and may also be grouped according to other parameters and then compared.

In the context of the present work, the parameters of interest are the identification of the offshore platform, the wind speed and direction, and the associated value of the pilot workload algorithm. Each approach to any given platform will thus generate a workload value which is then plotted on a wind rose. Workload values might helpfully be grouped and colour coded, e.g. values of 1 to 3 (minimal = green), values 4 to 6 (moderate = yellow), values 7 and over (excessive = red).

Over time, the wind rose will become increasingly populated and any wind speed/direction sectors consistently generating high workload values will be obvious. These can then be correlated with any turbulence report forms and compared with any HLL entries for the corresponding platform. Action to reinforce and/or modify any existing limitations or otherwise investigate the phenomenon (e.g. wind tunnel and/or CFD study) can then be taken as appropriate.

The strengths of this scheme are that: once set up, the data collection, analysis and presentation is entirely automatic; the information is objective and links directly to air flow properties (as opposed to turbulence report forms which are essentially qualitative); the process is continuous and will therefore identify any modifications to platforms, either temporary (e.g. use of the helideck air gap for storage) or permanent (e.g. cladding of a derrick), that affect the air flow.

It should be noted that any platform modification likely to affect helicopter operations should ideally be notified to the helicopter operator in advance, and wind flow studies performed as necessary to establish its impact (see [4]), but the HOMP-based monitoring scheme is viewed as a necessary and welcome 'safety net'.

3.2 Implementing the pilot workload algorithms in HOMP.

Crucial to the two preceding items of future work is the successful implementation of the pilot workload algorithms in the HOMP analysis software. This task is, however, not straightforward for the following main reasons:

- The workload algorithms were developed using flight data derived from stationary or steady state conditions, i.e. with the pilot hovering in a fixed position and at a fixed height over the helideck for an extended period of time (about one minute). In reality, however, the flight data records of interest are non-stationary, being the result of a continuous approach and landing task performed by the pilot.
- An important difference between the flight data used to develop the workload algorithms and that available from HOMP is the sampling rate. Control position data for the former were sampled at 20Hz; within HOMP, however, control positions are typically sampled at only 4Hz.
- Within HOMP, the cyclic control position is taken from the swash plate and therefore will include both the pilot's inputs and those from the series actuator driven by the helicopter's automatic stabilization system (AFCS). Although the resulting workload values will be more indicative of the turbulence encountered, they will ignore the ability of the AFCS to reduce pilot workload and maintain safe flight.

At the time of writing, work is ongoing to address these three issues. For the first, windowing techniques are being applied from which it is hoped a single maximum or characteristic workload value can be produced for each approach. An initial study of the second issue has established that a reduction in sampling rate from 20 to 4Hz affects only control rate terms, leading to a modest under estimation of workload, which increases with increasing workload value. The ability of the workload parameter to distinguish between cases of high and low workload is, however, unaffected. An investigation of the third issue has indicated the result to be an overestimation of workload by between 5 and 22%, the overestimation generally increasing with increasing workload value.

At present, it appears likely that some re-formulation of the workload algorithms may be necessary in order to adequately overcome these complications. Although there is still much work to be done, those involved with the project remain optimistic that the workload algorithms can be successfully implemented in HOMP.

4. Conclusions

This paper has described the development of a wind turbulence criterion for the safe operation of helicopters to offshore installations. The work is not quite complete, there being a need to fully validate both the modelling process used and the limiting criterion established. This validation is currently underway by an implementation of the control movement-based pilot workload algorithms in the Helicopter Operations Monitoring Programme analysis software. An analysis of archived HOMP data to map the environments around offshore helidecks will compare the results with helicopter operational experience as documented in the HLL.

In the mean-time the following main conclusions can be drawn:

- Piloted flight simulation has been used to provide a relationship between turbulence, measured in terms of the standard deviation of vertical wind component, and pilot workload. The results of applying this relationship to platform wind tunnel data appear broadly consistent with current operational experience.
- From consideration of the HQR descriptors, the relationship between turbulence and pilot workload has indicated that the standard deviation of the vertical flow should be less than 2.4 m/s for safe flight to be maintained.
- A desktop simulation technique has been developed to derive pilot workload ratings from wind tunnel test

data. The technique was found to under-predict workload by 1-2 HQR points.

- The sensitivity analysis of the effects of varying certain helicopter design parameters on pilot workload performed using the desktop simulation, supported by pilot opinion, suggests that the turbulence criterion may be applied equally to all helicopter types currently operating offshore on the European continental shelf.
- The favourable comparison of the results from desktop simulation and the application of the relationship between turbulence and pilot workload to wind tunnel data from three dissimilar platforms, is considered to give confidence in the application of turbulence criterion to platforms other than the Brae A used for the validation exercise.

The planned implementation of the pilot workload algorithm in HOMP will permit pilot workload estimates to be routinely and automatically sampled, analysed and presented. These can be correlated with pilots' turbulence reports, and the turbulence around offshore installations mapped on a wind rose. Periodic examination of these roses will help to reinforce or modify any existing operating limitations and identify any modifications to platforms, either temporary or permanent that are affecting the airflow.

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