HELICOPTER OPERATIONS TO MOVING OFFSHORE HELIDECKS
DEVELOPING NEW OPERATIONAL CRITERIA FOR LANDING AND ON-DECK SAFETY

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Abstract

The Oil and Gas industry relies heavily on helicopters for transporting personnel and cargo to and from offshore installations and support vessels. A growing number of offshore helicopter operations are to moving helidecks both on large vessels such as FPSOs, drillships, and semi-submersibles, as well as smaller service vessels. Landing a helicopter on a moving helideck presents additional challenges, not only at the point of touchdown and but also for the entire period the helicopter remains on the helideck. The UK Civil Aviation Authority (CAA), on behalf of the Helicopter Safety Research Management Committee (HSRMC), has commissioned Atkins to lead a comprehensive research programme aimed at improving the operational safety of helicopters landing on moving offshore helidecks. This paper summarises the main results from this long-term research effort. New deck motion and wind severity limiting parameters (MSI/WSI) are defined. Limiting values for these parameters ('MSI/WSI limits curves') are calculated using a bespoke probabilistic modelling methodology, which incorporates an analytical helicopter stability model (discussed in more detail in a separate paper [1]). This probabilistic approach has been developed based on discussions with stakeholders (helicopter operators, vessel operators, aviation and offshore safety regulators) and aims to find the right balance between enhancing safety and maintaining operability. The challenge of predicting helideck motion and wind conditions for 20 minutes after landing is also discussed. Finally, the specification for a new Helideck Monitoring System (HMS) is described. This system is currently being evaluated during in-service trials in the North Sea, with the aim of incorporating it in the CAA's Standards for Offshore Helicopter Landing Areas (CAP 437) in the near future.

1. INTRODUCTION

The Oil and Gas industry relies heavily on helicopters for transporting personnel and cargo to and from offshore installations and support vessels. A growing number of offshore helicopter operations are to moving helidecks on large vessels such as FPSOs, drillships, and semi-submersibles, as well as smaller service vessels. Landing a helicopter on a moving helideck presents additional challenges, not only at the point of touchdown, but also for the entire period the helicopter remains on the helideck.

The UK Civil Aviation Authority (CAA), on behalf of the Helicopter Safety Research Management Committee (HSRMC), has commissioned Atkins to lead a comprehensive research programme aimed at improving the operational safety of helicopters landing on moving offshore helidecks. This long-term research effort is now reaching completion and has produced a large body of results, with the technical detail as yet not published in the public domain.

New operational criteria have been developed, as well as a proposed new specification for Helideck Monitoring Systems (HMS). The helicopter stability model developed to support this work is described in more detail in a separate paper, [1].

The existing status in terms of operational criteria is defined in CAA's Standards for Offshore Helicopter Landing Areas (CAP 437) [2]. It recommends that moving helidecks are fitted with electronic motion-sensing systems to measure maximum pitch/roll angles and heave amplitude (PRH limits). More recently, heave rate (HR) has replaced heave amplitude, and harmonised criteria now apply across the UK and Norwegian sectors of the North Sea. The limiting PRH/HR values are jointly set by the helicopter operators via the Helideck Certification Agency (HCA). They are dependent on vessel type as well as helicopter type and a number of other factors, and are published in the Helicopter Limitations List (HLL) [3]. The limiting values are based on service experience and pilot judgement, and have generally proven to be satisfactory in terms of the touchdown itself.

Landing limits should protect a helicopter during both the touchdown and on-deck stage. It can be argued that pilots are best equipped to judge if it is safe to land on a helideck at the time of touchdown. However, it is very difficult for pilots to gauge whether a helicopter will be stable enough or remain stable once landed on a helideck. Thus, even though limits for touchdown may best be set empirically by pilots, the only rational way of deriving on-deck limits is by reference to a quantifiable measure of on-deck helicopter stability.

Military helicopters operating to helidecks on naval vessel face similar challenges, but there are significant differences between military and civil aviation operations. Consequently, many of the modelling approaches and methods of setting limits for military operations are of little practical relevance in a civil aviation context.

In particular, military helicopters are securely tethered while on-deck, whereas their civil counter-parts are not secured to the deck in any way, and their rotors are normally kept turning, generating an appreciable amount of lift. As a result, civil helicopters are at a much greater risk of tipping over or sliding on a deck for any given deck motion and wind conditions.

Very limited research had been carried out prior to the present project for calculating safe on-deck criteria specifically for civil operations, as reviewed in [4]. It was therefore necessary to develop a completely new framework and a range of bespoke modelling techniques to address the CAA's requirements. These requirements can be summarised as follows:

- Identify which parameters are required to define the severity of helideck motion, independently of vessel type and helideck location on the vessel, and relate this to the reserve of on-deck helicopter stability.
- Establish how the deck motion parameters identified above may be consolidated to form a single "measure" of helideck motion severity and indicate how appropriate limits would be established for a given helicopter type in terms of this measure.
- Establish a method of predicting this measure of helideck motion based on measurements taken prior to landing. Determine an appropriate length of observation period and appropriate level of statistical confidence.
- Develop an operational limits system that can be implemented in practice, leading to improved safety and, where possible, operability.

This paper explains how the above objectives have been addressed. New definitions of deck motion and wind severity limiting parameters (MSI and WSI) have been developed. Limiting values for these parameters ('MSI/WSI limits curves') are calculated using a bespoke probabilistic modelling methodology, which is informed by the input of all stakeholders (helicopter operators, vessel operators, aviation and offshore safety regulators). The challenge of predicting deck motion and wind conditions for 20 minutes after landing, and of finding the right balance between enhancing safety and not unduly compromising operability, is also discussed. Finally, the specification for a new Helideck Monitoring System (HMS) is described. This system is currently being evaluated during in-service trials in the North Sea, with the aim of incorporating it in CAP 437 [2] in the near future.

2. FACTORS AFFECTING ON-DECK HELICOPTER STABILITY

2.1 Forces Acting on a Helicopter while On-Deck

A number of forces act on a helicopter on a moving helideck:

- Helicopter weight.
- Inertial forces acting on the helicopter due to the helideck accelerations.
- Fuselage wind drag forces.
- Main rotor lift - when the helicopter is on-deck, the collective pitch is set at its minimum value (MPOG); even at this "idle" setting, a significant lift force can be generated.
- Lateral main rotor forces - resulting when the cyclic control is not set at its neutral (i.e nominally central) setting, or due to the interaction of the wind with the main rotor.
- Main rotor torque – acting on the helicopter fuselage in a direction opposite to the direction of rotation of the main rotor.
- Tail rotor force – the control force used in flight to oppose the main rotor torque and to manoeuvre the helicopter. When on deck, the pedal control setting is set to its central setting so as to not generate an additional sideways force on the helicopter.

2.2 Loss of On-Deck Stability (Tipping/Sliding)

Loss of equilibrium occurs when the total moment of the 'external' forces listed above can no longer be balanced by the moments of the deck reaction forces acting normal to the deck, and of the frictional forces acting in the plane of the deck to resist motion. There are two main modes of failure: tipping and sliding.

It should be noted that only helicopters with a three-wheeled undercarriage employing a nose wheel are considered in the analysis that follows, since this the type most used in the North Sea.

For tipping failure, a rotation about the axis connecting the nose wheel (N) and either of the rear wheels (Starboard-side (S) or Port-side (P)) has to occur (tipping axes NP or NS).

Sliding can occur in translation or in rotation. A rotational slide is more likely since only two of the wheels have to move instead of all three. Which two wheels will slide first will depend on the balance of moments, and thus each sliding scenario has to be considered in turn.

2.3 Defining the Reserve of On-Deck Stability

Having identified each mode of failure, the reserve of on-deck stability (ROS) for each mode can be defined by considering the balance of moments about the axis of rotation for each failure mode. For tipping failure this is the NS or NP axis, and for rotational slide modes, it is a rotation relative to the axis normal to the helideck.

Considering the ratio of destabilising versus restoring moments, the ROS has been defined as follows:

$$\text{(1)} \quad \text{Reserve of Stability} = 1 - \left| \frac{\text{destabilising moments}}{\text{restoring moments}} \right|$$

This is equal to zero at the point of failure and equal to 1 (100%) when no destabilising forces act on the helicopter.

For tipping failure, the destabilising moments are assumed equal to the total moment of the gravitational and inertial forces acting sideways on the helicopter (i.e. in the plane of the deck), plus that of all other external forces. The gravitational and inertial forces acting normal to the deck always act to restore equilibrium and thus the denominator is assumed equal to the moment of these forces. This restoring moment is effectively constant and does not depend on any of the other external forces.

For sliding failure, the only forces consistently acting to restore equilibrium are the frictional forces, and thus the restoring moment is due to these forces only. All other external forces make up the total destabilising moment. The frictional restoring moment will adapt to always balance the destabilising moment of the external forces. In order to have a meaningful definition for the reserve of stability, the maximum frictional restoring moment is used in the denominator. This is simply the moment due to each of the frictional forces assuming the maximum value of $\mu \cdot F_{R,}$ where μ is the deck coefficient of friction and F_R is the reaction force on each wheel. However, the reaction force on each wheel does depend on all other forces acting on the helicopter.

2.4 Modelling the Reserve of Stability (ROS)

To model the reserve of stability, it is necessary to model the moments of all the forces considered above. This can be accomplished using a computer simulation, and this was the approach initially taken for this work. The disadvantage with this approach, however, is that it does not offer much insight into the relative contribution of each of the forces acting on the helicopter.

In the case of tipping failure, because the restoring moment in the denominator of the ROS is effectively constant, it became apparent that it is easy to calculate the contribution of each of the external forces, by breaking up the ROS ratio into a number of separate ratios representing the destabilising contribution of each individual force.

However, because the restoring moment of the frictional forces is implicitly related to the destabilising moments, extricating the contribution of each force to the sliding ROS is not straightforward.

2.5 Analytical expressions for the Reserve of Stability

As discussed above, although it is possible to model the reserve of stability by adding all the forces/moments using a helicopter numerical model (e.g. Flight Lab), this approach has the disadvantage of not being very transparent. Furthermore, it requires several input parameters to describe the deck motion fully: roll, pitch, and deck accelerations in three directions.

To address this issue, an alternative, analytical derivation of the ROS was attempted, for each of the modes of failure. Firstly, a simple parametric representation of each of the forces was used. Then, the moments of each force and the ROS for each mode of failure were derived algebraically in a general form. This is discussed in more detail in [1].

These analytical expressions of the ROS have proved invaluable in understanding on-deck stability. Most notably, they have allowed a multitude of deck motion parameters (roll, pitch, and accelerations in three dimensions) to be consolidated into one main representative measure of motion severity. This is discussed in more detail in the sections that follow.

With this analytical approach it has also been possible to express the tipping reserve of stability as a function of the deck vertical reactions N, P and S, without the need for any information about the external forces. Thus, if the vertical reactions at each of the wheels could be measured in-service, then the tipping ROS could be calculated simply and relayed to the pilot. These expressions are derived and presented in [1].

3. DEFINING ON-DECK STABILITY MEASURES

3.1 Defining the Measure of Motion Severity (MMS)

Analytical expressions for the reserve of stability (as derived in [1]) are of the form shown below:

(2) $$ROS_{TIP} = 1 - \frac{a_h}{a_z} \cdot O_f(\theta) \cdot f_{grav} - \sum \frac{F_i}{m \cdot a_z} \cdot f_j$$

where:

- m is the mass of the helicopter.
- a_h is the total deck acceleration (gravitational and inertial) component in the plane of the deck.
- a_Z is the inertial acceleration component normal to the deck.
- O_f ("orientation factor") depends on the angle of a_h relative to the helicopter tipping axis, θ. This becomes a maximum when the accelerations act normal to the tipping axis, and zero, when they are parallel to it.
- f_{grav} is a term relating to the destabilising effect of the gravitational and inertial forces only. It contains only helicopter geometrical parameters such as the width and length of the undercarriage and the position of the centre of gravity.
- F_i is each of the forces (other than gravity) acting on the helicopter.
- f_i is a term depending on the point of action of the force relative to the CoG and the three points where the wheels contact the deck. It contains only geometrical parameters. Since the point of action of each force and its orientation relative to the helicopter will vary, a different f_i will apply to each force.

As expected, the ROS is equal to 1 (or 100% margin of stability) when the negative terms are equal to zero (i.e. the deck is level and there are no inertial accelerations and no external forces acting on the helicopter).

The first negative term represents the destabilising effect of the motion of the deck only, i.e. when no other forces act on the helicopter. Since the deck can accelerate in three dimensions, it is not surprising that three deck motion parameters are involved in this term: a_h, a_z and $O_f(\theta)$. As the deck moves, $O_f(\theta)$ will vary continuously, bounded by its maximum and minimum possible values. The (worst case) maximum value of O_f is a constant, which only depends on the width and length of the undercarriage.

The ratio of a_h / a_z has the physical significance of a "total dynamic slope", or the angle of a pendulum on an inclined and/or accelerating deck. This ratio is therefore chosen as the best single descriptor of deck motion, and has been termed the "Measure of Motion Severity" (MMS):

(3) $$\text{MMS} = \text{"dynamic slope"} = \frac{\text{"accelerations in the plane of the deck"}}{\text{"accelerations normal to the deck"}}$$

The currently used measure of total static deck 'Inclination' (INC), introduced relatively recently in the UK sector in addition to roll and pitch, does capture the static portion of the MMS, but it does not include the effect of the helideck accelerations.

Of course, a_z is also important on its own, since it affects the effective weight of the helicopter $m \cdot a_z$. This appears in the denominator of all the force terms (other than gravitational/inertial). The physical meaning of this is obvious: when the helicopter accelerates vertically downwards, $m \cdot a_z < m \cdot g$, the helicopter rests "lighter on its wheels", reducing the ROS.

It is noted that the terms for each of the external forces only depend on the magnitude of the force divided by the effective weight $m \cdot a_z$ and a purely geometrical term depending on the position of the centre of gravity and the dimensions of the helicopter. The exception is the first term which describes the effect of deck motion only (gravitational/inertial force); this does not depend on helicopter weight, but only on MMS (a_h/a_z).

The expressions for sliding ROS are more complex, but the effect of deck motion can, again, be expressed in terms of MMS, $m \cdot a_z$ and O_f.

It is possible to avoid introducing a_z as an additional deck motion parameter. This is because a_z is directly related to heave rate (the vertical acceleration is the derivative of heave rate). Thus, a_z is already limited via the current heave rate landing restrictions. In terms of the Of, using its worst case (maximum) value is a reasonable assumption.

3.2 Introducing a Measure of Wind Severity

As explained in [1], both the fuselage drag and the main rotor lift are strongly dependent on wind speed. Currently there are no wind speed restrictions below 60kts; however this work has provided clear evidence that much lower wind speeds than this can cause a helicopter to tip over or slide. Wind speed is an important parameter for on-deck safety, arguably more so than deck motion. Even on a perfectly level and motionless deck, a mean wind speed much less than 60kts can compromise on-deck stability.

The wind speed should therefore be used in addition to the MMS as an on-deck landing parameter. Since the fuselage drag and main rotor lift are expected to correlate with the instantaneous wind speed, any wind severity measure should take account of this parameter.

The instantaneous wind speed can be expressed in terms of mean wind speed plus gust terms. The gust terms are, in turn, statistically correlated to the mean wind speed. So the mean wind speed can be used as a proxy for representing the effect of the instantaneous wind speed. This is covered in more detail in Section 5.2.

4. CALCULATING SAFE LIMITS OF OPERABILITY

Safe limits of operability for on-deck stability can be defined using the two limiting parameters identified above: one for the deck motion (MMS), and one for the wind speed, U. A "limiting curve", as shown schematically in Figure 1, would be used to define the safe operational envelope.

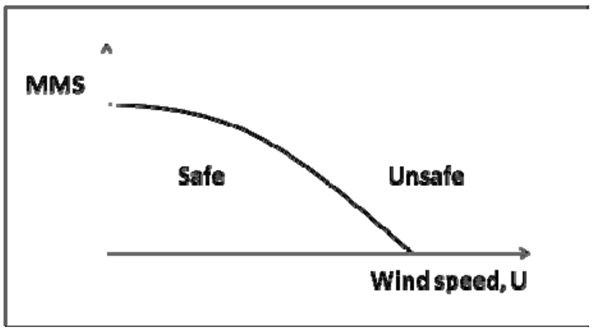

Figure 1: Schematic illustration of a limits curve

This curve can be calculated for each mode of failure using a numerical model (e.g. Flight Lab) and iteratively calculating the minimum MMS at which failure would occur (MMS_{crit}), for a number of wind speeds and over all possible deck motion combinations of roll, pitch and accelerations.

Alternatively, the analytical expressions derived for the ROS for tipping and sliding can be used to obtain simple analytical expressions for the limits of operability, directly linking MMS_{crit} and the wind speed U.

Assuming that failure occurs when the ROS falls to zero, using the expression for tipping as an example. the analytical expressions can be recast in the simple form:

$$(4)\quad MMS_{critTIP} = \left(1 - \sum \frac{F_i}{m \cdot a_z} \cdot f_i\right) \cdot \frac{1}{O_f \cdot f_{grav}}$$

This holds for any given combination of forces F_i acting on the helicopter, where f_{grav}, f_i and O_f are as previously defined.

The above equation effectively defines the shape of the limiting curve, MMS_{crit} as a function of U, since the forces that are dependent on the wind (i.e. fuselage drag and main rotor lift) can be expressed as a function of wind speed. The shape of the curve reflects the quadratic wind drag force dependence on the wind speed, and the quasi-linear main rotor lift dependence.

After some algebraic manipulation, MMS_{crit} expressions for the sliding failure modes have also been obtained. These can be cast in exactly the same simple form as that for the tipping modes, but with different geometric factors f_i and O_f, which also include the coefficient of deck friction μ.

The full analytical expressions are detailed in [1], and can also be generalised to calculate the limiting curve for any required threshold of stability (using an added safety margin of 10%, for example). The failure mode that will occur first will be that with the lowest MMS_{crit} for any given wind speed. Which mode will occur first will depend on the helicopter geometry, as well as the balance of all the forces acting on the helicopter.

In conclusion, the analytical limiting curve equations of MMS_{crit} versus wind speed provide a simple and transparent way of calculating the limits, for all modes of failure. They also provide a common platform for parameterising and comparing different approaches for calculating each of the external forces acting on the helicopter.

5. FORWARD PREDICTION OF ON-DECK CONDITIONS (DEFINITION OF MSI AND WSI)

5.1 Deck Motion Forward Prediction

Touchdown happens soon after the decision to land is taken, and the pilot can pick the best moment to land by observing the motion of the deck and timing his landing to avoid motion maxima. However, the helicopter will be exposed to helideck motions and the wind environment for the entire duration the helicopter remains on the deck. It is therefore necessary to predict prior to landing what the maximum (worst case) values of the on-deck parameters will be for this period to a given acceptable level of certainty.

For the MMS, this predictive measure is termed the Motion Severity Index (MSI), simply defined as the maximum MMS likely to occur during the next 20mins, for a given probability. The challenge lies in defining how the MSI should be calculated, based on measurements prior to landing. It is well known that such forward predictions are very difficult to perform accurately, especially for long periods such as 20mins. What is required, therefore, is to identify predictive methods that can be used in practice to assess their reliability/range of error, and then take their predictive uncertainties into account in the calculation of the limits.

Currently, the 20min maxima of roll, pitch, inclination and heave rate are measured prior to landing, and it is assumed that the maximum that will occur in the next 20mins, covering the on-deck duration, will be effectively the same. However, it is very clear that

20min maxima occurring during any given duration, even if ambient conditions remain exactly the same, will vary randomly and could vary substantially from one record to the next.

It can be shown theoretically that for narrow-banded waves, and assuming a linear deck motion response to the waves, maxima will follow the statistical distribution described below, expressed as multiples of the Root Mean Square (RMS) of the signal:

(5) $\mathrm{Max} = \zeta \cdot \mathrm{RMS}$

with the multiplier ζ following the probability distribution:

(6) $P_N(\zeta) = (1 - e^{-\zeta^2/2})^N$

where P_N is the probability that the maximum over a number of cycles N will be less than or equal to ζ·RMS. The number of cycles can be calculated using $N = \Delta t \;/\; T_z$, where Δt is the observation window duration over which the maximum is taken (i.e. 20mins), and T_z is the mean up-crossing period of the vessel motion.

This is a standard, widely used theoretical result, as described, for example, in [5]. Measurements of linear helideck motions such as roll, pitch, heave, heave rate, and accelerations taken in-service from FPSOs as well as smaller support vessels fit the correlation above very well, provided that an appropriate value is used for T_z, and any average offset relative to zero (e.g. due to the vessel listing) is subtracted.

It is therefore possible to use this approach to predict the maximum in the next 20mins, based on the RMS value measured previously, for any required level of probability, P_N. The average measured previously is also needed to account for any constant offsets from zero.

The MMS however, is not a linear deck motion parameter; comparing MMS maxima against the RMS has shown clearly that the distribution of the ratio ζ is more extreme than that for all the other linear motions, i.e. the MMS maxima are larger multiples of the RMS at any given probability than all other motion parameters. There are also marked differences between vessels, as shown in Figure 2.

It is not clear, therefore, which probability distribution applies to the MMS for each vessel and therefore how, and if, it can be predicted based on the RMS or any other statistical measure of the signal; this is the subject of on-going work.

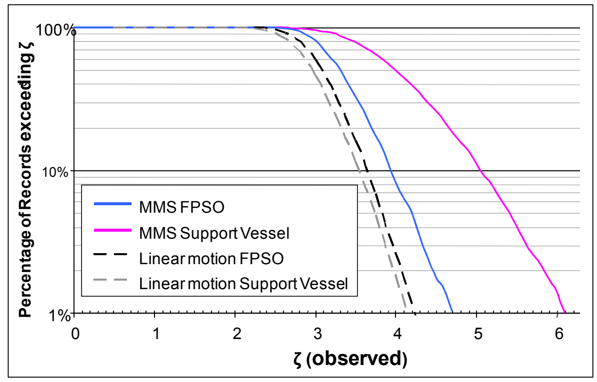

Figure 2: MMS distributions of ζ for two vessel types, compared to those for linear motions.

Whether using: (a) the previous 20min maximum to predict the next 20min maximum, or (b) using a theoretical method based on the RMS, or indeed any other method (c), there will be uncertainty, and this needs to be quantified. A way that has recently been proposed to assess the predictive ability of any given method (and its associated uncertainty) is to calculate the ratio R defined as:

(7) $R = \dfrac{\text{Predicted value}}{\text{Actual value}}$

and to plot its Probability Distribution Function (PDF) or Cumulative Distribution Function (CDF).

As illustrated in Figure 3, an unbiased measure should be equal to 1 on average (50%ile). The spread of values either side of 1 would be symmetrical if maxima and minima are evenly balanced. The narrower the spread, the smaller the uncertainty and the better the predictive measure; a perfect measure would have no spread at all. Plotting the CDF also allows the error in the prediction to be defined at any required probability/certainty level. As discussed later, a 'reasonable worst case' error value (e.g. at 2.5% or 2σ) could be incorporated as a safety margin in the prediction.

In the absence of a theoretical method for predicting the maximum MMS in the next 20mins (i.e. other than using the maximum in the previous 20mins) this R-value method has been applied as a first step to linear motion prediction (e.g. roll/pitch/heave rate). Comparing predictive methods (a) and (b) as defined above has shown that the two methods have a very similar spread of R, with method (a) being slightly better. This is not surprising with hindsight, since the maxima used in method (a) should follow the distribution on which method (b) is based.

However, measures can also be assessed in terms of their 'stability'. Using method (a) the variability between records can be large, even though the deck conditions remain the same. A multiple of the RMS is more representative of the deck conditions and varies a lot less, and a lot less abruptly, than method (a).

This is one of the reasons why it has already been proposed that the heave rate measure (currently calculated using the so-called Norwegian method) would be best replaced by using a multiple of the RMS of the heave rate signal [6]. This is to be adopted in the UK/Norwegian sector and included in CAP 437 [2] in the near future. By the same token, the existing measures of maximum roll, pitch and inclination could also be replaced by a multiple of the RMS.

Whatever the predictive method used to calculate the MSI, its uncertainty will have to be taken into account. This issue is revisited later in Section 6.

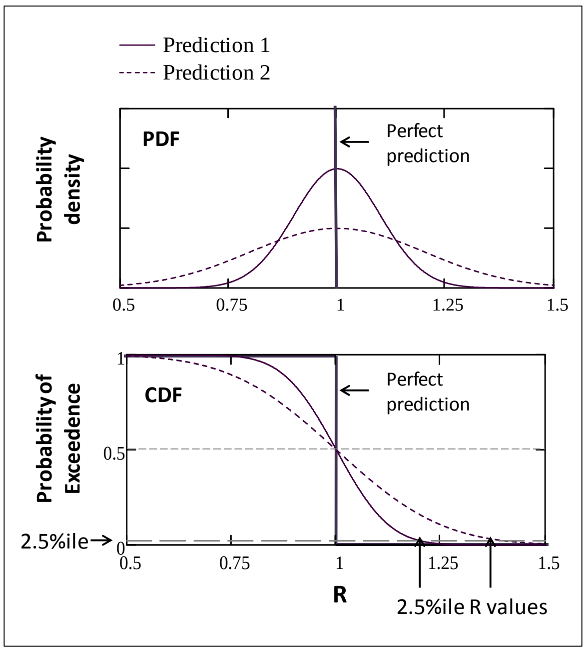

Figure 3: Using ratio R to evaluate forward prediction methods (Prediction 1 is better than 2).

5.2 Forward Prediction of the Wind

Wind speed and wind direction vary continuously during the time a helicopter is on-deck, and both have a strong effect on main rotor lift and wind drag forces. The detail of the variability of the wind during a landing event cannot be predicted in advance of a landing, but it is possible to represent probabilistically the expected changes in the mean wind from one 20min period to the next, and the associated gusts.

The variability of the wind occurs over several timescales as described in [7], for example. The main variations are due to the passage of weather systems (synoptic, of the order of 5 days), the daily variation between and day and night (diurnal variation) and the variability due to turbulence. There is little variability in the wind for timescales between about 2 hours and 10 mins; this is known as the 'spectral gap'. Wind speed averaged over 10min to 1 hour will therefore be relatively stable, and will provide a good basis for describing the wind conditions. In this work, correlations drawn from the analysis of long-term historical data gathered at the Norwegian coastal site of Frøya [8] are used to quantify the variation of the mean wind speed and wind direction.

In order to quantify the effect of gusts, the dependence of main rotor lift and fuselage drag on wind speed needs to be defined. As discussed in [1], the main rotor lift can be assumed to vary linearly with wind speed, the slope depending on α_s:

(8) $$\mathrm{LIFT}(U,\alpha_s) = (a + b\cdot\alpha_s)\cdot U + \mathrm{LIFT}_0$$

where a, b, and c are constants, and LIFT_0 is the lift in zero wind.

The fuselage wind drag should be of the form:

(9) $$k_w(\beta)\cdot U^2$$

where k_w is a constant of proportionality which depends on wind direction, β.

Using a linear decomposition of the mean and gust component: $U = U_{mean} + u'$, and taking into account small changes in α_s and β due to the turbulent fluctuations ($\Delta\alpha_s = w'/U$ and $\Delta\beta = v'/U$), separate expressions for the destabilising terms due to the mean wind and gusts have been derived.

Statistical methods exist to predict gust factors, i.e. the instantaneous maximum wind speed as a multiple of the mean. However, these do not allow the individual turbulence components u', v' and w' to be quantified. For this reason a more sophisticated methodology was developed that allowed the gust terms in the expressions of MMS_{crit} to be calculated, for any required probability, as a function of mean wind speed.

Therefore, the Wind Severity Index, is simply defined as the mean wind speed (using an appropriate averaging time, e.g. 10mins). An appropriate correction has to be used to refer wind speeds typically measured at the top of a tall mast to helideck height. The effect of the gusts is then modelled within the calculation of the limits curve, as a function of WSI.

6. PROBABILISTIC CALCULATION OF THE LIMITS OF OPERABILITY CURVES

Having derived analytical expressions for MMS_{crit} as a function of mean wind speed U, it is then straightforward, in theory, to derive limiting curves. The difficulty, however, lies in quantifying input parameters that vary in operation such as: mass, centre of gravity location (primarily vertical location), variations in mean wind speed and wind direction relative to the helicopter, variations in the rotor angle of attack relative to the wind (which affects main rotor lift), possible additional lateral forces due to non-neutral control settings.

In addition, modelling the forces acting on the helicopter depends on a large number of empirical input constants that are either uncertain, difficult to obtain (e.g. because they are proprietary to helicopter OEMs), or are simply unknown and have to be estimated.

It was initially suggested that a 'Realistic Worst Case' value could be assigned to all parameters, and that this should be used as the basis for calculating the limits. The resulting limits curves were, however, too restrictive to be workable, and it appeared over conservative to assume that all parameters would assume worst case values simultaneously.

Setting limits inevitably involves making decisions about an acceptable level of probability and risk. To lower the probability of failure and improve safety more restrictive limits have to be applied, but this leads to reductions in operability. Therefore, it became clear that a probabilistic approach to modelling the limits was essential. A new methodology had to be developed to allow the limits curve to be calculated in a way that would be rational, well-defined, and transparent to offshore stakeholders, and would find the right balance between improving safety and maintaining operability.

6.1 Defining the variability of each parameter

The first step in this approach has been to quantify the variability or uncertainty in each parameter by defining a probability distribution for each of the main parameters.

For example, the minimum weight of the helicopter on-deck depends on the weight of the fuel at the time of landing before refuelling takes place. A distribution was derived based on data gathered by helicopter operators. An example of such data for the S76 helicopter from a UK operations database is shown in Figure 4.

In situations where less information was available (e.g. in quantifying the variation of the helicopter heading relative to the wind at the point of landing), expert estimates of a 'realistic worst case' were used as 2σ values, corresponding to a one-sided 2.5% probability (as described in [9]).

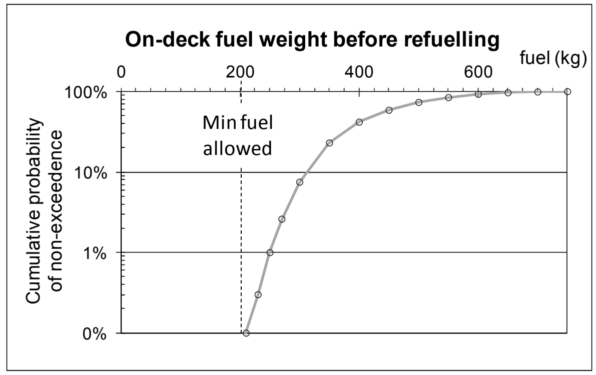

Figure 4: Example of a probability distribution used to represent an operationally variable input.

6.2 Monte Carlo Simulation

Having defined the probability distributions for all the input parameters, a Monte Carlo simulation was then used to calculate limits curves to any required level of probability.

An ensemble of a large number of on-deck scenarios is created, with each input variable following its assigned probability distribution. Interactions between variables (whether statistically independent or co-dependent) are also included as appropriate. All wind-related variables (i.e. variations in the 20min mean and the effect of gusts) were generated by reference to a given mean wind speed, or WSI.

For each of the landing scenarios in the input ensemble, a corresponding ensemble of MMS_{crit} values is calculated deterministically using the analytical limits equations of MMS_{crit} versus U. From the ensemble values of MMS_{crit} the centile corresponding to the required level of probability is calculated; this gives the limiting value of MMS_{crit} for each given WSI. This is repeated for a range of wind speeds, and for each failure mode, to build up one overall limiting curve. This process is shown schematically in Figure 5.

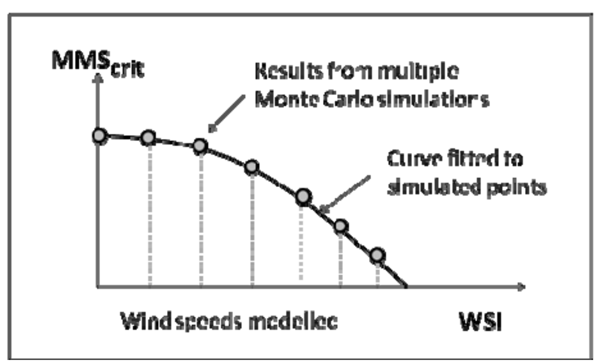

Figure 5: Building the limits curve using Monte Carlo simulations.

Indicative calculated limits curves are shown in Figure 6. Three curves are compared:

a) 'worst case' curve, assuming all parameters take their 'realistic worst case' values simultaneously;
b) Monte Carlo result calculated for a 2.5% probability of failure (2σ level of probability, corresponding to an overall "realistic worst case");
c) a 'mean' curve or 50%ile curve, with all parameters set at their mean values.

The 2.5%ile curve calculated with the Monte Carlo model is clearly much less restrictive than the worst case curve, demonstrating the conservatism in assuming that all parameters take their worst case value simultaneously. On the other extreme, the 50%ile curve is clearly too risky; the 2.5%ile curve lies in between the worst case and 50%ile assumptions.

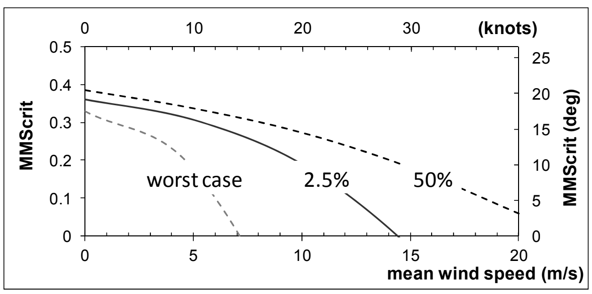

Figure 6: Limits curves calculated for various probabilities.

It is important to clarify what the level of probability used in the model, P_{limit}, refers to. It is not the overall probability of helicopter on-deck failure per landing. Instead, it represents the probability of failure per landing for a helicopter operating right on the limit curve. Such situations will occur more rarely than the bulk of operations. To estimate the overall probability of failure per landing, probabilities calculated by the model would have to be combined with the frequency with which limit values of MMS/WSI occur in actual operations, and integrate this across the entire operational envelope. This has not yet been attempted but it would be instructive to do so, comparing the results with historical operational risk levels.

P_{limit} probabilities of failure calculated with the model are likely to be overestimated since there are a number of conservative assumptions used in the model. For example, the weight of the helicopter is calculated assuming no passengers or cargo, and with fuel at its minimum value (i.e. that prior to refuelling). Also, it is assumed that 20min motion and gust maxima will coincide, and that even an instantaneous reduction of ROS to zero will necessarily lead to failure.

Despite the issues identified above, the Monte Carlo approach provides a rational way in which limits can be defined, and has been implemented successfully to calculate limits for two helicopter types, the Eurocopter AS332 Super Puma and the Sikorsky S-76.

The limits described above do take into account the variability of the wind, but not the variability in the MSI. It is possible to include this in the existing Monte Carlo modelling method, provided that a probability distribution for the MSI R-value can be defined. However, reaching the best balance between safety and operability remains subjective, since an acceptable level of probability needs to be chosen.

New probabilistic approaches are currently being considered to remove some of the model conservatisms and to find the best balance between safety and operability more objectively. One new approach currently under consideration is based on Receiver Operator Characteristics (ROC) methods. Such methods help to find the best balance between preventing genuinely dangerous situations ('true positives'), while minimising false alarms ('false positives ').

6.3 Sensitivity studies

In addition to the Monte Carlo simulations, sensitivity studies were carried out to assess and rank the effect of each of the input parameters. This was based on a 'Propagated Uncertainty' approach similar to that described in [9]. The sensitivity study results highlighted the importance of the relative wind direction and control positions, lateral cyclic and tail rotor pedal in particular.

This approach has also led to the development of a simple method for obtaining rough estimates of the probabilistic limits curve algebraically, to help explore sensitivities without having to carry out Monte Carlo simulations.

7. IMPLEMENTATION OF THE MSI/WSI LIMITS

The development of the MSI/WSI limits is supported by both UK and Norwegian regulatory bodies, and will be incorporated in CAA's CAP 437 once work has been completed. The intention is to initially introduce the scheme with a generic lower bound MSI/WSI limit covering all helicopter types. This will be applied as "advisory only", invoking consideration of revised on-deck handling procedures in order to mitigate the risk. It is intended that helicopter type-specific limits calculated and certified by the helicopter manufacturers will subsequently be introduced; these will be less conservative but will likely be mandatory.

The new MSI/WSI limits are to be used in combination with current HCA landing limits. The HMS specification developed by this project is to be incorporated in the HCA Standard Measuring Equipment for Helideck Monitoring System (HMS) and Weather data.

7.1 Effect on Operability

The introduction of the MSI/WSI limits will lead to a reduction of operability if current HCA landing limits are to be retained. Most of the operations lost will be at higher wind speeds. This is necessary in the interests of safety, however, and addresses an important weakness of the existing system which does not take the wind into account at all.

There is, however, scope for operability gains, especially at lower wind speeds, if the current landing limits could be relaxed. Existing HCA limits effectively cover both the touchdown and on-deck stability. Once introduced, the MSI/WSI limits will cover on-deck stability, leaving the existing landing limits to cover the touchdown only.

Figure 7 summarises the above issues. For illustrative purposes, current limits are presented as a line of constant MSI.

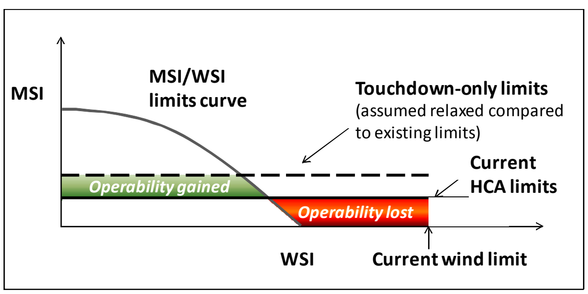

Figure 7: An illustration of the effect of new MSI/WSI limits on operability

However, it is stressed that the limiting parameters of R/P/INC/HR are only partially correlated with the MSI, and MSI values corresponding to existing limits will vary from vessel to vessel. Therefore the effect of the new MSI/WSI limits on operability will vary from vessel to vessel. For the same value of static roll and pitch, MSI values for a larger vessel will be lower than those for a smaller vessel, since accelerations on the latter will be larger due to its smaller motion period, T.

7.2 New HMS Requirements and Operational Procedures

For the MSI/WSI limits to be implemented in practice, current Helideck Monitoring Systems (HMS) would have to be upgraded to monitor the following additional parameters:

- MSI
- WSI
- Relative wind direction (RWD)

Most vessels are equipped with MRUs (Motion Reference Units) to measure current deck motion parameters, and these can easily be adapted to calculate accelerations and the MSI. Wind speed and direction is also routinely monitored on most vessels, however this is not necessarily linked into the HMS, and some modification to the software and data logging arrangements may be needed. Graphical User Interfaces (GUIs) used to display HMS data will also have to be updated accordingly. In addition, new deck motion status repeater lights will have to be installed, as described in Section 7.2.3.

A detailed new HMS specification [10] has been drafted in consultation with all the main monitoring equipment providers in the UK and Norway, and is currently being evaluated as part of the in-service trials on the Maersk GP III described in Section 7.3.

7.2.1 Introducing the RWD

The relative wind direction (RWD) is a new parameter introduced to ensure that the lateral component of the wind drag is constrained, enhancing safety. By definition, RWD is equal to zero when the helicopter is facing into the wind, and 90deg for beam-on winds (+ve from starboardside).

The G-BKZE tipping failure accident onboard the West Navion drillship in 2001, was precipitated by an increase in RWD, due to a drift in vessel heading caused by the failure of the vessel's Dynamic Positioning (DP) system. This accident served to highlight the importance of orienting helicopters into the wind as much as possible, and monitoring for changes in ambient wind direction or vessel heading after touchdown. However the wind direction relative to the helicopter is not currently measured.

To enable the wind direction relative to the helicopter to be calculated, the new HMS operational procedures require the system operator on the vessel to input the heading of the helicopter at the point of landing into the system, allowing the HMS to calculate the RWD automatically over the entire on-deck period. Adding the RWD as a monitored parameter provides more control, and the more the relative wind direction can be controlled, the more scope there is to relax the MSI / WSI limits.

In deciding appropriate RWD limits, a balance needs to be found between tightening RWD limits and keeping nuisance warnings during normal operational conditions to a minimum. The unavoidable variability of the ambient wind and the accuracy with which a pilot can align the helicopter to the wind at touchdown both need to be allowed for. At lower wind speeds, the variability of the wind is larger and it is less easy for the pilot to align with the wind. At higher wind speeds the opposite is true, and it would therefore be expected that helicopters would tend to be better aligned with the wind. Hence, it is possible to justify a tighter relative wind direction limit at higher wind speeds.

Relative wind direction (RWD) limits have been modelled using a Monte Carlo approach, based on estimates of the variability of ambient wind direction and helicopter alignment with the wind (the former based on an analysis of data presented in [7], the latter on pilots' estimates), and assuming vessel heading variability is very small. Values corresponding to 2σ have been used to set the limits, and it is therefore expected that RWD alarms should only occur 5% of the time. The limits curves are shown in Figure 9, in Section 7.3.

7.2.2 Definition of deck motion status

Deck motion status is determined according to the following criteria:

A) Before landing:

- Blue status: safe to land based on P/R/HR and MSI/WSI limits.
- Red status: do not land (P/R/HR out of limits).
- Amber status: MSI/WSI limit exceedance only (consider using modified operating procedures).

It is noted that no operations are lost due to introduction of new MSI/WSI limits, only warnings that trigger consideration of the adoption of modified deck handling procedures.

B) After landing:

Motion status is 'frozen' to value prior to landing (i.e. steady blue or amber).

When the system switches to on-deck mode (upon entry of helicopter heading by the system operator) confirmation of the system mode change is provided with a distinctive light signal, e.g. three blue flashes.

Helideck motion status changes only if relative wind direction is out of limits:

- Flashing amber: relative wind direction exceeds amber limit - pilot and deck crew to consider appropriate mitigating action.
- Flashing red: relative wind direction exceeds red limit - pilot and deck crew to carry out mitigating action.

7.2.3. New deck motion status repeater lights

Following a request by helicopter operators, a helideck mounted repeater light system was added to the new HMS. This will indicate the helideck status as BLUE/AMBER/RED, providing direct information to the pilots and deck crew, instead of relying on the system operator to relay this information (NB: BLUE is used instead of GREEN, to avoid confusion with the green helideck perimeter lighting).

An analysis of near misses in the CAA MORS (Mandatory Occurrence Reporting Scheme) database has shown that about 30% of occurrences were caused by incorrect reporting of deck motion. It is therefore expected that the new deck motion status lights should help to eliminate such incidents, improving landing safety significantly by this simple measure alone.

7.2.4 New operational procedures

New operational procedures have been developed in consultation with helicopter operators and vessel OIMs (Offshore Installation Managers). A detailed Hazard Identification assessment (HAZID) was also carried out.

The new operational procedures cover pilot and deck crew actions prior to landing and during the on-deck period. It also sets out suggested modified operational procedures in the event of MSI/WSI exceedences or RWD warnings.

The modified deck handling procedures to be considered when operating to an offshore installation in steady amber conditions include:

- taking particular care to align the aircraft with the wind;
- both pilots remaining at the controls during re-fuelling, embarking or disembarking of passengers, bags and freight;
- swapping embarking or disembarking passengers one or two at a time;
- if necessary, refueling with passengers on board to maintain helicopter weight as high as possible;
- carrying out one operation at a time.

In the event of flashing amber or flashing red motion status lights immediately after touchdown, the pilot should take-off and re-align the helicopter with the wind. If a flashing amber warning occurs at any time after touchdown, the deck crew should investigate the cause and agree appropriate mitigating action with the pilot such as:

- if due to vessel heading change, deck crew to take action to correct vessel heading;
- if due to wind speed increase and/or direction change, pilot to consider taking off and re-aligning the helicopter with the wind.

If the RWD continues to increase and the deck motion lights flash red, the pilots should prepare to take-off and re-land on the deck oriented into wind. If the lights flash red towards the end of the on-deck period while passengers/cargo are embarking, the pilots should prepare for take-off as per normal but without delay.

Any number of the above may be selected by the pilot depending on the prevailing conditions, but the pilot should make clear to the deck crew in advance exactly what course of action is to be taken to prevent any confusion.

7.3 In-Service Trials on the GPIII

The new HMS and associated operational procedures are currently being evaluated in-service. A prototype HMS, including deck motion status repeater lights, has been installed by MIROS on board the Global Producer III FPSO (GPIII) owned by Maersk. The new system and operational procedures are being trialled by deck crews and by pilots during routine flights to the GPIII, currently operated by Bond Helicopters. Their feedback has been recorded on specially designed proformas.

The aim of the trials has been to test the operational aspects of implementing the new MSI/WSI limits in-service, rather than testing the limits curve per se. Nonetheless, measurements of MSI/WSI taken during the initial few months of the trials (including 44 landing events) have been recorded, and plotted in Figure 8.

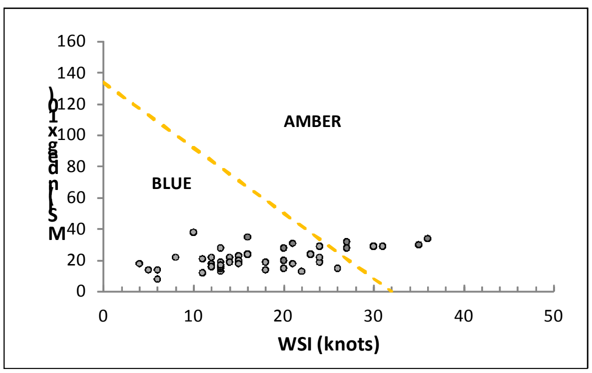

Figure 8: A comparison of GPIII trials data (MSI/WSI recorded just before touchdown) with a preliminary MSI/WSI limits curve.

The MSI/WSI limits shown are preliminary, working versions of the limits for a Eurocopter AS332 Super Puma helicopter. For simplicity the limits were approximated to a straight line connecting the maximum MMS and WSI values which is conservative. It can be seen that some MSI/WSI excedences (steady amber events) occurred at higher wind speeds, which allowed the amber procedures to be exercised in-service.

Measurements of RWD at touchdown are also plotted in Figure 9. These are compared with the upper bound values that pilots had expected can be achieved at the point of touchdown, as well as preliminary flashing amber and flashing red limits (which allow for ambient wind direction and modest vessel heading changes after touchdown). Most landings were under that threshold, with the exception of two events at higher winds, which then triggered flashing amber warnings later in the on-deck period.

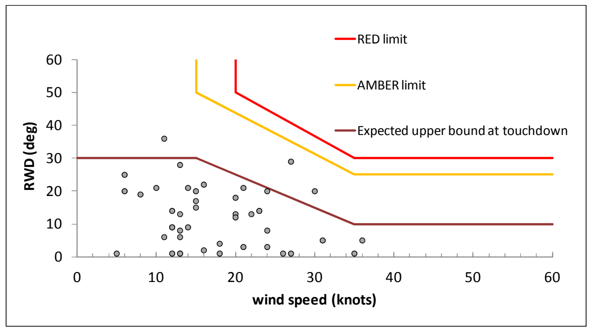

Figure 9: A comparison of GPIII trials data (RWD recorded at touchdown) with the expected upper bound at touchdown and the preliminary RWD limits.

8. CONCLUSIONS AND RECOMMENDATIONS

This paper has described the main results from a long-term research programme aimed at improving the operational safety of helicopters landing on moving offshore helidecks. This was commissioned by the UK Civil Aviation Authority, on behalf of the Helicopter Safety Research Management Committee (HSRMC), and was managed by Atkins.

The parameters affecting on-deck safety were carefully reviewed and a simple, yet effective theoretical model of on-deck stability was developed. This is discussed in more detail in [1]. Analytical expressions were derived for the Reserve of Stability (ROS) for all modes of on-deck failure (tipping over and sliding). These expressions allowed the relevant deck motion parameters to be consolidated into a single measure of deck motion severity (MMS). They also demonstrated how the wind (not included in current landing limitations) is an important parameter that affects on-deck stability and must be taken into account.

It was then demonstrated how a safe operational envelope can be defined as a function of MMS and wind speed ('limits curves'). Simple expressions were derived for the minimum value of MMS (MMS_{crit}) for which failure can occur at a given wind speed, which effectively define the limits curves mathematically.

Although a number of simplifications were used to derive the analytical expressions for the ROS and the limits, this approach has been very effective. Numerical helicopter models, and rotor models in particular, continually grow in sophistication; however these are not immune to significant uncertainties and errors. The simpler and more transparent analytical approach used in this work (and as described in more detail in [1]) has not only helped clarify the contribution of each destabilising factor but has also helped identify and address a number of modelling uncertainties.

The expressions for calculating the limits curves require a number of inputs, some of which are uncertain or proprietary (as for example vertical CoG or drag coefficients). In addition to information obtained from flight manuals or helicopter OEMs, many other inputs were measured for the first time during dedicated field trials. The limits curves also require inputs that are operationally variable. These include not only the helicopter-specific parameters (such as mass and CoG position), but also the deck environment parameters of MMS and wind speed/wind direction, which are used as limiting parameters.

The worst case deck motion maximum and wind gust during the on-deck duration (typically up to 20mins) need to be 'predicted' based on measurements taken prior to landing. However, it is not possible to predict these with great accuracy. In order to deal with this variability and uncertainty, a probabilistic approach was developed: a) to deal with the forward prediction requirements for the MMS and the wind, and b) to define workable limits curves based on a probabilistic description of all other operationally variable inputs.

The forward prediction of the deck motion and wind is embodied in the definitions of the Motion Severity Index (MSI) and the Wind Severity Index (WSI). Methods for modelling them based on measurements prior to landing have been discussed.

A Monte Carlo probabilistic modelling methodology has been developed to calculate MSI/WSI limits curves, in a transparent and rational way. The variability of all inputs has been described probabilistically using best available data and in consultation with stakeholders (helicopter operators, vessel operators, aviation and offshore safety regulators). The limits are calculated for a given probability level, however judgement is still required to establish an acceptable level of risk.

As a first step, a 'Realistic Worst Case' probability of 2.5% has been used as the basis for calculating limits. Preliminary limits curves have been calculated for two helicopter types used in the North Sea: the Eurocopter AS332 Super Puma, and the Sikorsky S-76.

Further work is planned to refine the method used to calculate limits to remove conservatisms as much as possible. For example, a new approach is currently considered, based on Receiver Operator Characteristics (ROC) methods to help find the optimal balance between preventing genuinely dangerous situations ('true positives'), while minimising false alarms ('false positives').

In addition to measuring MSI/WSI, a relative wind direction (RWD) limit is also introduced, as well as the requirement for a deck motion status repeater light system directly visible to pilots and helideck crews. The addition of a deck motion status light system was proposed by pilots and is expected to lead to a reduction in landing incidents of the order of 30%.

A specification for a new Helideck Monitoring System (HMS) has been produced which incorporates the results of all of the work performed. A HMS built to this specification has been installed on a vessel operating in the North Sea and is being evaluated in-service. Once fully validated, the specification will be incorporated in CAP 437, hopefully during 2013.

It is envisaged that the initial implementation of the MSI/WSI limiting criteria will be on an advisory-only basis (i.e. triggering amber warnings only, with no loss of operability), using a generic limits curve for all helicopter types operating in the UK/Norwegian sectors of the North Sea. It is expected that helicopter OEMs will be required to assume responsibility for deriving safe limiting curves specific to each of their own helicopter types for inclusion in the helicopter flight manuals. By definition, these limits should be less restrictive than the initial generic limits, but will correspond to red or 'do not land' warnings.

In terms of other recent activities in this field, a Joint Industry Project called HELIOS started in April 2011, with the aim of improving landing limits for helicopters landing on offshore helidecks. This is led by MARIN and NLR in The Netherlands, and is currently seeking the participation of a wide range of industrial stakeholders. CAA and Atkins are supporting the efforts of this JIP, offering access to the large body of knowledge described in this paper, as well as providing guidance and advice.

ACKNOWLEDGEMENTS

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