The Key Facts of Ship Helicopter Operational Limitation Development

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The helicopter-ship qualification test campaigns are based on a high number of independent variables causing the full operational potential usually impossible to achieve within the small window allowed for sea trials. For some reason, there are no regulations or standard procedures to conduct the required ship helicopter operational limitation development, and consequently it strongly differs between countries the kind of interpretation is given. In general, the helicopter industry delivers a helicopter that has already undergone elaborate test campaigns performed in order to demonstrate safe flight and to establish operational limitations. However, to determine the full operational potential and limitations for helicopter-ship operations are considered national responsibility. As it is assumed that each country aims for maximum operational flexibility of each helicopter-ship combination, with minimal expenses and without any concessions in flight safety, this paper attempts to summarize the key facts of ship helicopter operational limitation development. So far, tremendous savings in time and expenses of various helicopter-ship qualification test campaigns with different ship and helicopter types has been achieved in the Netherlands. The ship helicopter operational limitation development process is aided by a predictive software tool, named "*SHOL-X*", which eliminates subjective elements as much as possible in order to determine unambiguous operational envelopes used for in-service conditions in a world-wide theatre for many years to come.

Figure 1; NH90 NFH sea trials

NOMENCLATURE

AEO	All Engine Operative
AOB	Angle Of Bank
AOR	Auxiliary Oiler Replenishment
CFE	Candidate Flight Envelope
CG	Centre of Gravity
DIPES	Deck Interface Pilot Effort Scale
FADEC	Full Authority Digital Engine Control
LCF	Air Command Frigate
LPD	Landing Platform Dock
MCP	Maximum Continuous Power
MFRI	Multi-purpose Frigate
MPV	Maximum Power Vertical
NFH	NATO Frigate Helicopter
OGE	Out-of-Ground Effect
OPV	Ocean Patrol Vessel
ROC	Rate Of Climb
SHOL	Ship Helicopter Operational Limitation
TFCP	Trimmed Flight Control Position
VAR	Vibration Assessment Rating
WCA	Wind Correction Algorithm

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INTRODUCTION

Whilst the helicopter itself is always limited to operations within its service release envelope, and may be cleared for shipboard operations, each unique helicopter-ship combination needs to be explored in an appropriate manner. The goal of the present paper is to present the key facts of ship helicopter operational limitation development. The experience presented in this paper is gained during various test campaigns with the NH90 NATO Frigate Helicopter (NFH), but also with the AS 532 U2 Cougar and Alouette III operated from different ship types in the Netherlands. The ship helicopter operational limitation development consists initially of shore-based hover trials to document the low speed flight characteristics, as a function of referred weight and relative wind condition. These data are combined with airwake data for each ship type to develop the so-called "*candidate flight envelope*". This Candidate Flight Envelope (CFE) is partially validated during sea trials. The CFE is used to increase trial effectiveness as it functions as the starting point for sea trials, allowing quickly exploring the potential boundaries of the operational envelope.

A predictive engineering tool developed by the main author, named "*SHOL-X"*, is used in the qualification process to perform early evaluation of safety limits for operating helicopters from ships. In this way, the qualification process is less dependent on the results from the dedicated sea trials. Especially, as occasionally has happened during previous test campaigns that either due to prevailing weather conditions, ship availability and/or helicopter availability, the limits of the particular helicopter-ship combination could not be fully explored up to the potential boundaries of the envelope or at some masses. This resulted in restrictions of the operational capability [1]. The developed predictive tool not only reduces time and expenses of the test campaigns, but also improves the accuracy of the finally determined operational envelope to be used for in-service conditions for many years to come. Additionally, it allows assessing the impact of design changes to both helicopter and ship with regard to trimmed flight performance and control capability after the Ship Helicopter Operational Limitation (SHOL) has been released to service. The described methodology in this paper for SHOL development is considered a considerable improvement compared to other methodologies available worldwide [2,3].

TEST CAMPAIGNS

A three-step approach for establishing operational envelopes is applied as shown in Figure 2. First the ship-environment (green box in figure) in which the helicopter will operate is determined by conducting wind tunnel measurements of the airflow in the take-off and landing paths of the ship. This is still followed by a validation with full-scale measurements of the airflow above the flight deck with the associated ship motion. For the helicopter (yellow box in figure), shore-based hover trials are carried out to verify precisely the helicopter limitations, in terms of handling qualities in cross-wind conditions, engine performance and control margins. Thereafter, the CFE (blue box in figure) is obtained by combining the behaviour of the isolated helicopter, the specific conditions for a particular ship and other miscellaneous items. The miscellaneous items (red box in figure) could be added to optimize the CFE, for example experience from previous test campaigns with either the helicopter or the ship under test. Finally, based on the CFE, a (partial) flight test campaign on board the ship is conducted in a range of weather conditions by day and by night (black box in figure). This is to determine for the particular helicopter-ship combination the effects on the pilot workload for e.g. visual references, ship motion and turbulence.

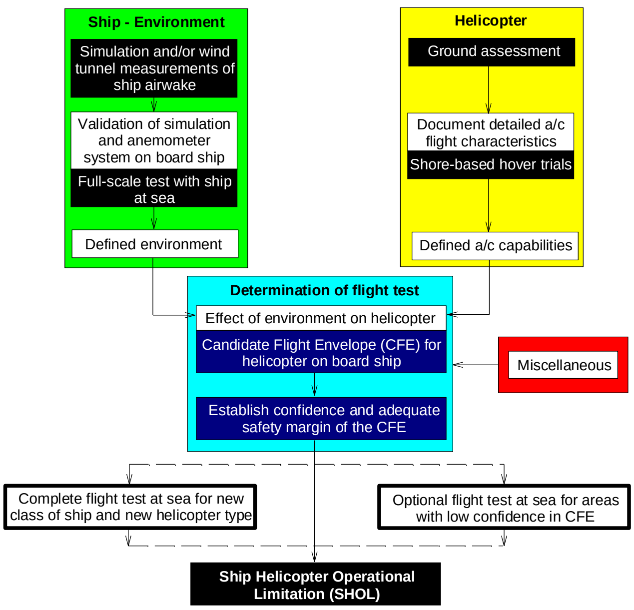

Figure 2; Flow chart SHOL development

The time required and expenses associated with each SHOL development are dependent on the confidence in the CFE and the experience with the helicopter and ship type under test. A predictive tool, "*SHOL-X*", developed by the main author of this paper is based on specific rejection criteria for each helicopter type and their dependencies in the ship environment [4]. This tool is used to determine the CFE and to analyze the onboard flight test results, and thus enables SHOL development with only a bare minimum amount of effort during expensive sea trials. The benefits of this tool are numerous, like rapid introduction of new helicopter types across the fleet and drastically increased cost effectiveness of SHOL development.

HELICOPTER ITEMS

The flow chart for SHOL development, as shown in Figure 2, distinguishes between environment and helicopter items. In this paragraph examples are shown for processing flight test data gathered during different shore-based hover trials, and how this data is then used to construct the CFE. Once validated, the helicopter flight test results are saved into look-up tables in order to be used for future helicopter-ship qualification trials. There is a distinction expressed in so-called "*rejection criteria*" between performance, control position, helicopter attitude and subjective related issues as explained below [4]. The shore-based hover trials were conducted in 2012 with the NH90 NFH helicopter at two different locations at 10.000 kg, 11.000 kg and 11.750 kg referred weight, the latter simulated by 11.000 kg actual weight at a higher environmental temperature [5].

NH90 NFH helicopter

The NH90 NFH is a twin engine, medium weight transport helicopter with a four bladed counter clockwise turning main rotor, when seen from above, and a bottom-forward rotating tail rotor. Its maximum take-off weight is 11.000 kg. Conventional cyclic, collective and yaw pedals are fitted, assisted by a fly-by-wire computer and a hydraulic system. The helicopter has Rolls-Royce RTM 322-01/9 engines, including Full Authority Digital Engine Controller (FADEC) software. The maximum All Engine Operative (AEO) torque ratings are 104% for Maximum Continuous Power (MCP) and 113% for transient power.

Shore-based hover trials

The purpose of the shore-based hover trials is to establish helicopter flight characteristics for e.g. power required, Trimmed Flight Control Positions (TFCP), helicopter attitude, controllability limits and pilot workload in an omni-directional relative wind envelope. This is done in order to complement the flight manual information. A dedicated pace-car, as shown in Figure 3, is used to set up the required relative wind conditions in addition to the actual wind. The pace-car is equipped with a calibrated speed measurement system, a display on top of the dashboard to present the relative wind to the driver, and a wind vane to provide the pilot with visual reference of the relative wind direction.

Figure 3; Pace-car with NH90 NFH

The flight test data obtained from the shore-based hover trials indicates - within the low speed hover envelope - which regions exist where safety margins between available and required helicopter rejection criteria are marginal or even exceeded. This is required for safety reasons, as in these regions, limitations are likely to be exceeded by the operational aircrew during ship-board operations. Furthermore, there are Maximum Power Vertical (MPV) tests performed at different speeds to express the deltas (i.e. the differences) in torque required, between hover and maximum climb condition, associated to the achieved Rate of Climb (ROC). The climb performance data is used to ensure adequate power margins within the ship's airwake. For subjective ratings, three scales are used: the Deck Interface Pilot Effort Scale (DIPES) is used to describe pilot workload, the A&EE Vibration Assessment Rating (VAR) scale is used to describe vibration levels and the turbulence scale is used to indicate the intensity of the turbulence encountered and its associated helicopter reactions [3]. These subjective ratings should be used with care, however, mainly due to different visual cues between a formation with a vehicle travelling over the runway and a formation with a ship at sea. In addition, natural winds are always accompanied by some degree of turbulence which is not fully replicated by the pace-car tests.

Performance rejection

The results for torque required at 20 knots, as a function of the relative wind direction are shown in Figure 4. The torque required increases for higher referred weight, and depends on the relative wind direction. As the main rotor turns counter-clockwise, when seen from above, more tail rotor thrust is necessary to prevent the nose to turn into the wind for green winds conditions (i.e. winds from the starboard side of the nose of the helicopter). The tendency for the nose of the helicopter to turn into the wind is known as the 'weather-cock effect'. For this reason the torque required at 20 knots is highest at relative winds from the direction green 60 to green 90.

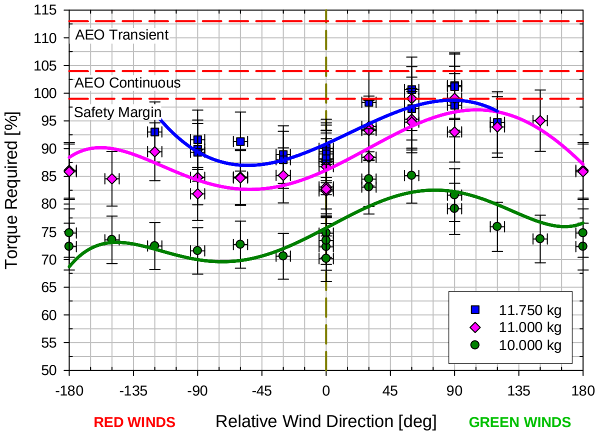

Figure 4; Torque required at 20 knots

Although not shown, for the lower relative wind speeds, the torque required exceeds the 5% safety margin and/or the maximum continuous power limitation of 104% torque. Therefore, these low speed relative wind conditions are removed from the relevant CFE's.

Referred parameters. The flight tests are performed at the required values of referred weights, $W/\sigma\omega^2$, where W is helicopter weight, σ is relative density and ω is the relative rotorspeed. The targeted referred weights are set as the operational weight bands for shipboard operations. The flight test data are converted into referred parameters, so that they can be used to produce information relevant to atmospheric conditions and helicopter masses different from those actually tested. Consequently, with a few exceptions, a relatively small number of tests, at carefully chosen test sites, can produce information relevant to a large part of the helicopter's flight envelope. The main objective is to determine the parameter(s) that will limit the helicopter performance under the atmospheric conditions in a role specification – note that under certain atmospheric conditions, usually hot and high, the engines, rather than the transmission will limit helicopter performance. It is therefore necessary to determine the precise limiting factor(s) for the conditions specified, in order to enable data points flown during different missions of the test campaign to be compared with each other.

Since only the performance of the NH90 NFH is considered in this paper, the linear dimensions of rotor radius and solidity are omitted. The ambient pressure, temperature and density are expressed as ratios of the standard sea level conditions. Likewise, rotor speed is expressed as a percentage of the standard value. These modified groups are termed '*referred*' [6]. For example, the referred parameters for torque required can be determined by the relationship:

$$Q_{ref} = \frac{Q}{\sigma\omega^2} = f\left(\frac{W}{\sigma\omega^2}, \frac{V}{\omega}, \frac{V_c}{\omega}, Z, \frac{\omega}{\sqrt{\theta}}\right)$$

where Q is torque required, V is airspeed, V_c is rate of climb, Z is height and θ is relative temperature. Within the dynamic ship environment, the benefits of ground effect should be considered negligible [7]. Hence, only Out-of-Ground Effect (OGE), low speed, conditions is tested without any vertical speed. The relationship shows that the performance of the helicopter is mainly influenced by the referred weight, the relative wind conditions (airwake in the vicinity of the ship), and rotorspeed setting:

$$Q_{ref} = \frac{Q}{\sigma\omega^2} = f\left(\frac{W}{\sigma\omega^2}, \frac{V}{\omega}, \frac{\omega}{\sqrt{\theta}}\right)$$

For the NH90 NFH at 11.750 kg referred weight (equivalent to 34,8º C at sea level with 11.000 kg maximum take-off weight), the torque required is still the limiting parameter. For this reason, engine gas generator speed (N_g) and engine power turbine inlet temperature (T_{46}) are not further discussed in this paper, as these parameters show similar trends as torque required for an increase in referred weight and relative wind condition.

Error analysis. Errors in flight test measurements introduce the inevitable uncertainty that is inherent in all experimental work. Whenever a measurement can be repeated, this should usually be done several times. Unfortunately, similar conditions are difficult to establish during shore-based hover trials and for all other in-service conditions afterwards. Therefore, making predictions based on only a small set of test points performed during shore-based hover trials must ultimately be accompanied by an uncertainty analysis and the error bands must be shown as error bars in the plotted results. When these uncertainties in the measurements are determined by combining the original fractional uncertainties and squaring them, adding the squares, and taking the square root it is called "summation in quadrature" [8]. This is allowed when the measurements are independent and subject to random uncertainties. Relative errors in referred torque required are determined, for example by [4]:

$$\frac{\delta Q_{ref}}{Q_{ref}} = \sqrt{\left(\frac{\delta Q}{Q}\right)^2 + \left(\frac{\delta \sigma}{\sigma}\right)^2 + \left(2 \times \frac{\delta \omega}{\omega}\right)^2}$$

where δQ, etc., are the uncertainties in the measurements of Q, etc.. The "summation in quadrature" provides an effective check on the significance of error sources and a method for the identification of the most significant errors. This is important as an analysis of measured errors and required computation may affect the choice of instrumentation for a given trial. Although specialized instrumentation may raise the expenses of a trial, the alternative is to repeat the measurements a number of times to acquire an acceptable confidence in the results. However, increased flying time is likely to be a more expensive option than an improved instrumentation fit.

Centre of Gravity

For different Centre of Gravity (CG) positions, test points were flown to determine the associated displacement in pitch attitude, Angle of Bank (AOB), longitudinal and lateral cyclic control position required to maintain trimmed flight condition. For this purpose the cyclic positions and helicopter attitudes were measured in lateral winds up to 40 knots both for green and red winds, and for longitudinal winds from 20 knots tailwind towards 40 knots headwind. The variations in CG were controlled by adding up to 16 sandbags in the cabin of 25 kg each (total 400 kg). The results for displacements in helicopter attitudes and cyclic positions are summarized in Table 1. The data are used to reduce the amount of test points to be flown during the sea trials, whilst ensuring adequate control authority.

Item	Effect
Longitudinal cyclic	± 0,26 %/cm
Pitch attitude	± 0,07 deg/cm
Lateral cyclic	± 0,88 %/cm
Angle of Bank	± 0,23 deg/cm

Table 1; Displacements due to CG

Control rejection

Cyclic position. The results for longitudinal and lateral cyclic position at 20 knots, as a function of the relative wind direction, are shown in Figure 5 and Figure 6 respectively. There are negligible differences in cyclic position with referred weight, although the cyclic position changes with relative wind direction.

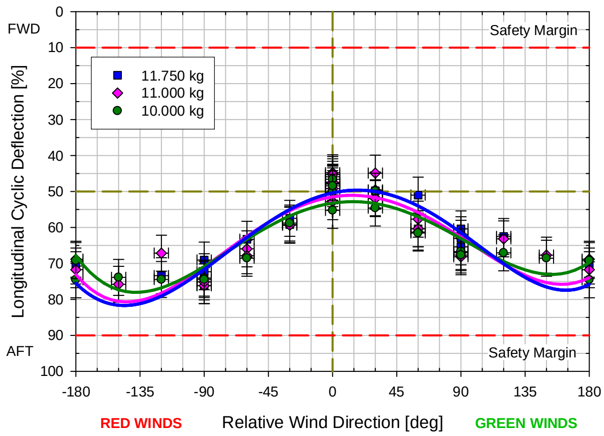

Figure 5; Longitudinal cyclic at 20 knots

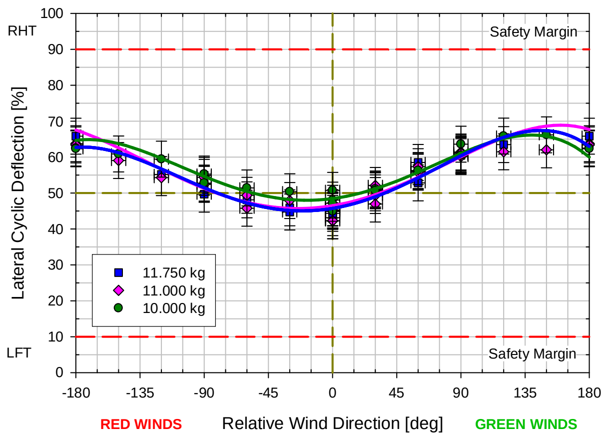

Figure 6; Lateral cyclic at 20 knots

A complete overview of the cyclic positions measured during the shore-based hover trials for all relative wind conditions, and different CG positions, is presented as longitudinal cyclic vs. lateral cyclic, including the cyclic envelope restrictions in Figure 7. The cyclic envelope restrictions result in more stringent margins, then only the 10% safety margin in some areas for a particular longitudinal and lateral cyclic position. No discontinuities, control margins, handling issues or other abnormalities are noted. There are no restrictions in the CFE due to lateral and/or longitudinal cyclic positions.

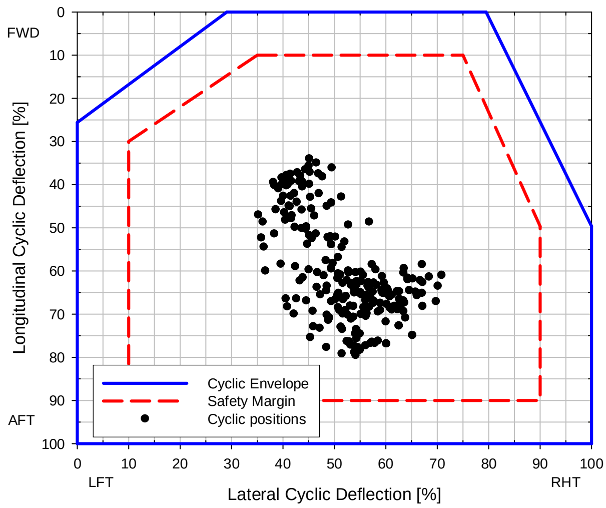

Figure 7; Overview cyclic positions

Tail rotor authority. The results for tail rotor authority at 40 knots, as a function of the relative wind direction are shown in Figure 8. The tail rotor thrust increases for higher referred weights, and depends on the relative wind direction. The tail rotor thrust depends on referred weight, thus torque required, as the tail rotor has to deliver more or less anti-torque to maintain helicopter heading.

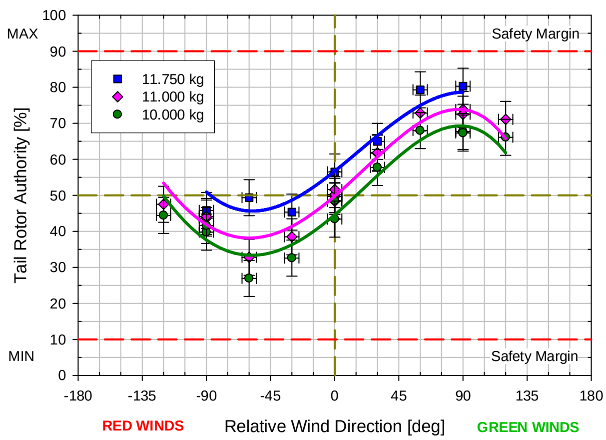

Figure 8; Tail rotor authority at 40 knots

As the main rotor turns counter-clockwise, when seen from above, more tail rotor thrust is necessary to prevent the nose to turn into the wind for green winds conditions. For red wind (i.e. winds from the port side of the nose of the helicopter) conditions the opposite effect occurs and more right pedal, thus less tail rotor thrust, is required to maintain helicopter heading. There are no restrictions in the CFE due to tail rotor authority. Note that the results for tail rotor authority are presented and not pedal positions as, due to the collective-yaw interlink, there are only negligible changes in the pedal position with changes in referred weight.

Helicopter attitude rejection

Pitch attitude. The results for pitch attitude at 30 knots, as a function of the relative wind direction, are shown in Figure 9. There is no unambiguous relation noticeable in pitch attitude with referred weight, although the pitch attitude changes with relative wind direction. The pitch-up attitude, at mid-CG, increases to high pitch attitudes of approx. 10° in a wind direction from green 30 at 30 knots (occasionally increasing towards approx. 12°), whilst knowing that the maximum pitch-up attitude for landing is 12° according to the flight manual [9]. These high pitch-up attitudes result in reduced visual reference with the ship and increase the risk of a tail strike during ship board operations. The green wind conditions with high pitch-up attitudes up to approx. 10° (occasionally increasing towards approx. 12°), around green 30 at 30 knots are removed from the CFE.

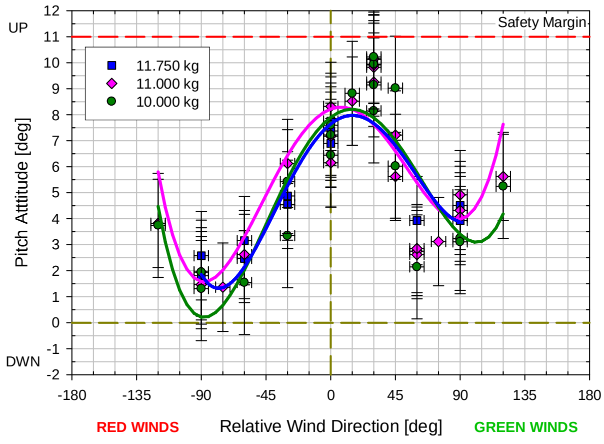

Figure 9; Pitch attitude at 30 knots

Roll attitude. The results for AOB at 40 knots, as a function of the relative wind direction, are shown in Figure 10. There are negligible differences in AOB with referred weight, although the AOB changes with relative wind direction. The changes in AOB towards the right in green winds conditions are relatively small up to approx. 5°. The changes in AOB towards the left for red wind conditions are such that for red 90 winds at 40 knots the AOB is approx. 13° (occasionally increasing towards approx. 15°), and this was considered uncomfortable by the aircrew. The large AOB for red wind conditions, between red 60 and red 120, restricts ship board operations. In these conditions the helicopter touches the flight deck with one main wheel first during landing, especially as the ship will normally be tilting to starboard with red winds, thereby increasing the relative angle between the helicopter and the flight deck even further. The relative wind conditions between red 60 and red 120 with large AOB up to approx. 13°, are only for lower wind speeds partially included in the CFE.

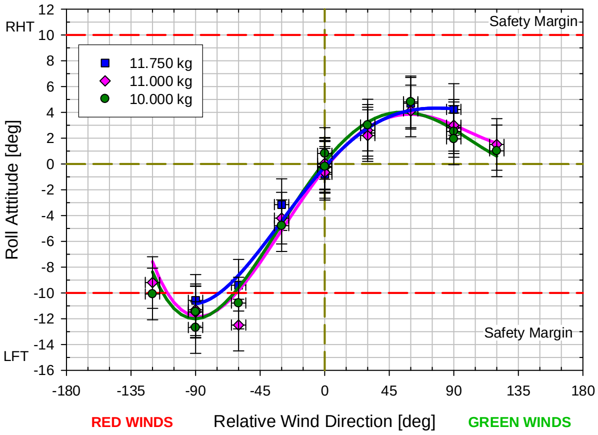

Figure 10; Roll attitude at 40 knots

Subjective rejection

The pilot workload in general was low for all test points performed at different speeds and relative wind azimuths. Only for red 90 relative wind conditions the high AOB was considered uncomfortable by the pilots increasing the workload up to DIPES 3 (highest tolerable pilot compensation required). The VAR level increased up to a moderate level 5 (experienced aircrew was aware of the vibration but it did not affect their work, at least over a short period). There are no restrictions in the CFE due to subjective pilot ratings.

Vertical climb performance

The helicopter's maximum achievable vertical climb performance was assessed, using a technique known as MPV, for different airspeeds starting at approx. 5 knots increasing to approx. 50 knots as shown in Figure 11. Vertical flight was established using ground references in combination with Doppler information presented on the flight navigation display with the hover page selected. The maximum achievable ROC increased with an increase in true airspeed, and decreased with an increase in referred weight. For each test point the achieved ROC is expressed against the deltas (i.e. the differences) in torque required, between hover and maximum climb condition as shown in Figure 12. For some reason, the achieved ROC per 1% torque increment decreases with an increase in true airspeed, and indicates minimal changes between the different referred weights. For the construction of the CFE, the values for achieved ROC per torque increment are correlated with the downward flow components of the airwake in the vicinity of the ship to assure that the power available is not exceeded in the approach and/or the departure paths.

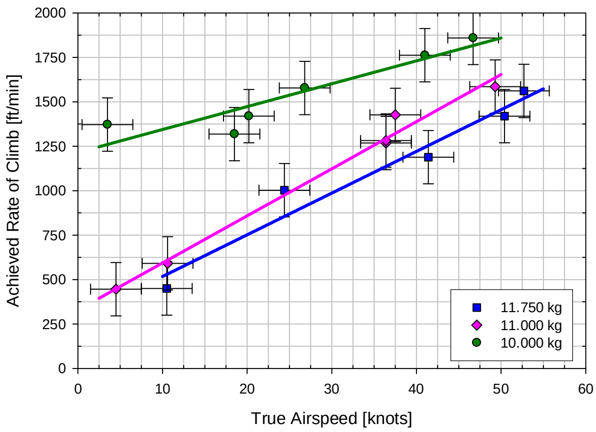

Figure 11; Achieved ROC

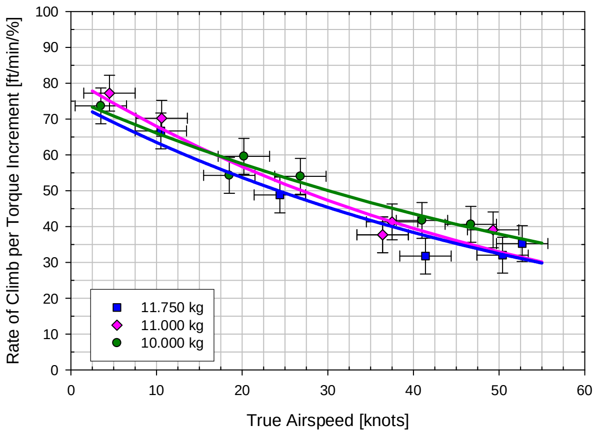

Figure 12; ROC per torque increment

Key facts helicopter

The following key facts for the helicopter flight characteristics related to ship-board operations are observed:

1. The flight test data should be converted into referred parameters, so that it can be used to produce information relevant to atmospheric

conditions and helicopter masses different from those actually tested;

2. The precise limiting factor(s) for the specified operational conditions should be known, to enable data points flown during the test campaign to be correlated with each other;
3. The flight test data should be accompanied by a solid uncertainty analysis;
4. If the main rotor turns counter-clockwise, when seen from above, more torque required is necessary to prevent the nose to turn into the wind for green winds conditions;
5. An increase in referred weight results into an increase for torque required, engine gas generator speed, engine power turbine inlet temperature and tail rotor thrust. As a result, for higher referred weights, an associated minimum relative wind speed is required to perform flight operations;
6. An increase in referred weight has negligible influence on AOB, pitch attitude, lateral cyclic, longitudinal cyclic and pedal position.

ENVIRONMENT ITEMS

The flow chart for helicopter-ship test campaigns, as shown in Figure 2, distinguishes between environment and helicopter items. In this paragraph, examples are shown for processing airwake data in the vicinity of the flight deck. It should be noted that the results of the shore-based hover trials are based on the relative wind conditions encountered by either hovering in natural wind conditions or by using a pace-car, however, near and above the flight deck the relative wind is disturbed by the large ship's superstructure. This disturbed wind is what the helicopter faces when operating from the flight deck and is known as local wind. The local wind conditions were determined by wind tunnel measurements at a constant speed of 30 m/s with a 1:75 scale model, and validated by full-scale measurements on board the ship at different location and heights above the flight deck [10,11]. The wind tunnel measurements were in good agreement with the full-scale measurements on board the ship.

Unfortunately, both the undisturbed relative wind and local wind conditions are unknown for the operational crew after the test campaign, as the indicated wind by the ship anemometers is their only reference source. The latter is unreliable since by mounting anemometers on a ship with a bluff body, the local air flow at the anemometer location also deviates from the undisturbed relative wind conditions. For this reason, the undisturbed relative wind should be known to the test team, and applicable corrections made to the indicated wind speed on board the ship. In case of any doubt about the reliability of the indicated wind by the ship anemometers, a reference anemometer should be positioned at the bow of the ship as much as possible outside ship influences, to provide real-time correlation with the indicated wind, and to provide correlation with the undisturbed wind for post-flight analyses. Therefore, it is important to distinguish between three different wind conditions:

1. **Relative wind**. The shore-based hover trials are performed in undisturbed relative wind, and this is the free air stream near the ship.
2. **Indicated wind**. The relative wind with the anemometer indication errors taken into account. The operational envelopes are based on this wind condition.
3. **Local wind**. The local wind conditions are different for each position near and above the flight deck. These are the wind conditions the helicopter will face during ship board operations.

To establish the relation between these three different winds conditions, wind tunnel measurements are conducted for every ship type at various points above the flight deck, and in the approach and departure paths. The aim of wind tunnel measurements is to correlate for each landing spot the local wind and the indicated wind by the anemometers, as shown for deviations in wind speed and wind azimuth at different heights above the landing spot in Figure 13 and Figure 14 respectively.

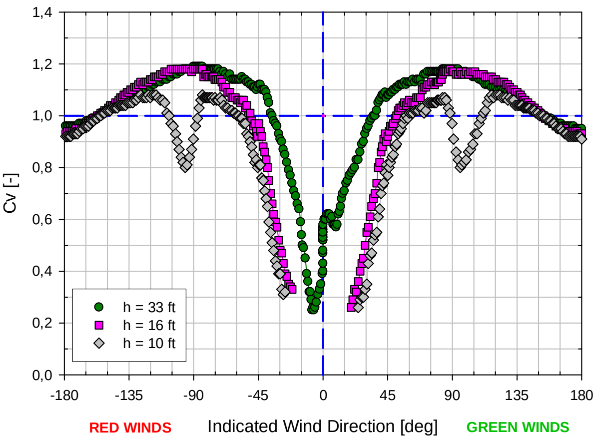

Figure 13; Speed deviation, *Cv*

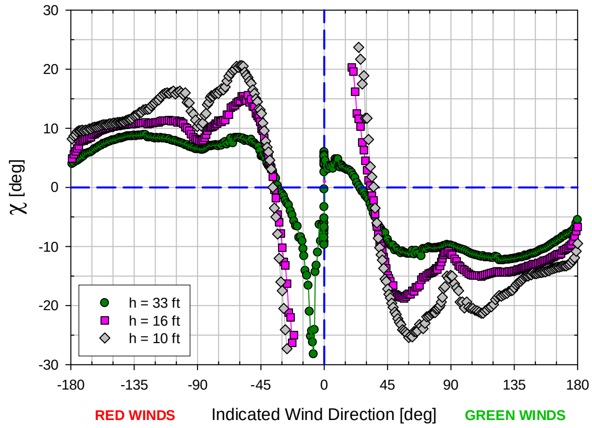

Figure 14; Azimuth deviation, χ

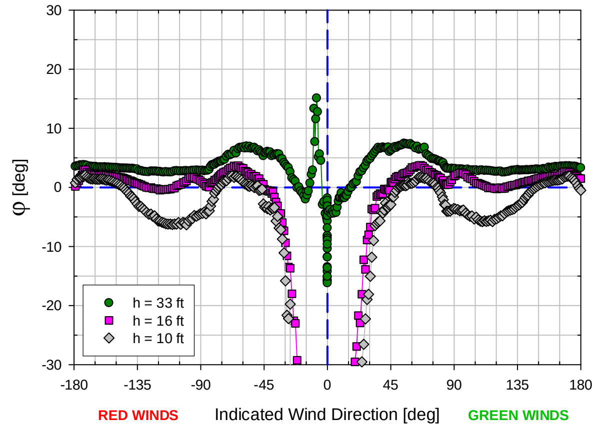

Figure 15; Vertical flow, φ

The local wind speed is correlated with the indicated wind speed by the following equation:

$$C_v = V_{loc} / V_{an}$$

where C_v is called the wind speed coefficient, V_{loc} the local wind velocity and V_{an} the indicated wind speed by the anemometer system. In case $C_v < 1$, the indicated wind speed is higher than the local wind speed which the helicopter faces when operating from the flight deck, and vice versa. The local wind direction is correlated with the indicated wind direction by the following equation:

$$\chi = \beta_{loc} - \beta_{an}$$

where χ is the airflow deviation, β_{loc} is the local wind direction and β_{an} the indicated wind direction by the anemometer system. Both for green and red wind conditions, the local winds have a larger angle when seen from the bow of the ship, as indicated by the anemometers (the wind moves inboard behind the hangar).

Areas with vertical airflow components are expressed in angles, φ, from the horizontal plane as shown at different heights above the landing spot in Figure 15. The areas with a large negative angle (i.e., downward airflow velocities) in combination with high wind speeds may create problems in performance requirements. Note that although not shown, the limitations due to downward airflow velocities are most pronounced on the leeward side of the ship, for example port side with green wind conditions, as the wind falls down after being disturbed by the ship's superstructure. In most cases these downward airflow velocities are the cause of the SHOL boundaries for leeward take-offs and landings.

Ship anemometers

The operational envelopes are based on the indicated wind as presented by the anemometers on board each ship. These anemometer systems are usually positioned somewhere in the mast of the ship or on the roof of the bridge, as much as possible outside airwake disturbances caused by the ship, thus far away from the flight deck. In order to correlate helicopter flight characteristics with a particular ship type, it is essential to understand the disturbances in airflow at each anemometer location in relation to the undisturbed relative wind. Some examples of disturbances at the port anemometer location for the Landing Platform Dock (LPD1), Air Command Frigate (LCF), Ocean Patrol Vessel (OPV), M-Frigate (MFRI) and the Auxiliary Oiler Replenishment (AOR) ship are shown for wind speed and wind direction in Figure 16 and Figure 17 respectively. The differences in wind speed coefficient are up to approx. 0,3, thus for 30 knots already a difference of up to 9 knots between the actual and indicated wind speed between these ship types. The differences in wind direction are even up to approx. 30º in azimuth. Therefore, in case the relation between undisturbed relative wind and indicated wind is unknown, it would be questionable whether efficient sea trials could be performed.

The port anemometer is selected for red winds and the starboard anemometer is selected for green winds, to ensure that the windward anemometer is used during flight operations. If for whatever reason, the port anemometer is selected for green wind conditions, the "invalid sector" is presented and the readings would be unreliable. In case an anemometer system would be unserviceable, it advised to provide either red or green winds for flight operations to ensure the windward anemometer system could be used, or to use the emergency SHOL envelope. The emergency SHOL envelope should contain sufficient margins to allow ship-board operations with the downwind anemometer system selected.

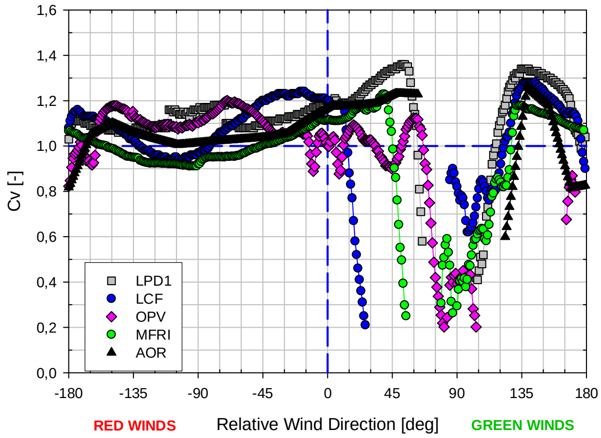

Figure 16; Port anemometer locations, *Cv*

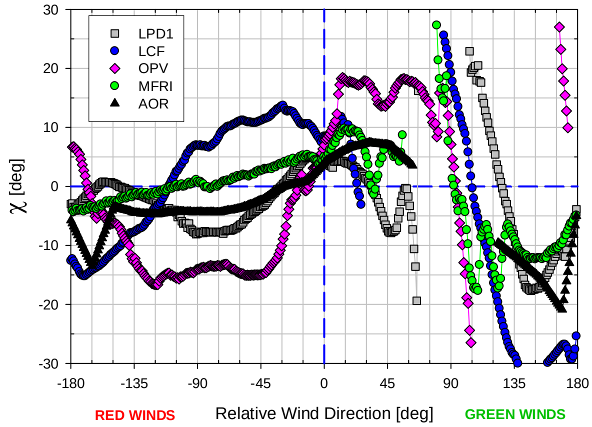

Figure 17; Port anemometer locations, χ

Note that as the disturbances at the anemometer locations are already known for each ship type, a Wind Correction Algorithm (WCA) is applied on most ships. The WCA calculates correctly the relative wind from the anemometer readings that are subject to local disturbances at the anemometer locations, and in addition applies damping to these relative wind data streams. As a result, undisturbed relative wind is presented and less variation is present in the indicated wind information.

Key facts Environment

The following key facts for the ship environment related to ship-board operations are observed:

1. A distinction should be made between relative, indicated and local wind conditions;
2. The relation between undisturbed relative wind and indicated wind should be known for each ship type, as there are large variations;
3. The port anemometer should be selected for red winds and the starboard anemometer selected for green winds, to ensure that the windward anemometer is used during flight operations.

CANDIDATE FLIGHT ENVELOPE

Once the helicopter and environment items are determined and validated, the data are saved into look-up tables. Thereafter, when combining the behaviour of the isolated helicopter and the local environment conditions of a particular ship, it results in the CFE. The CFE is a diagram giving the likely combinations of indicated wind speed (in radial coordinates) and direction (in angular coordinates) for safe take-offs and landings from a particular ship. The CFE is used to increase trial effectiveness as it functions as the starting point for sea trials. In fact, the CFE is the preliminary envelope, whilst the SHOL is the result of sea trials and is the ultimate version defining the safe operational limitations. The following rejection criteria are relevant for construction of the CFE's for the NH90 NFH:

- Torque required for the lower relative wind speeds;
- Pitch attitudes around green 30 at 30 knots;
- Roll attitude in red wind conditions;
- Although not previously discussed, for some reason right pedal position exceeds the 10% safety margin in red wind conditions;
- From previous sea trials it is known that for some reason, torque required exceeds the rejection criteria in the red 90 azimuth (input miscellaneous items in CFE);
- The boundaries for a hot & heavy envelope should have an additional safety margin due to a somewhat more sluggish helicopter response (input miscellaneous items in CFE).

The predictive tool, "*SHOL-X*", correlates these rejection criteria with the environmental conditions on board each ship type as shown for the fore-aft procedure at 10.000 kg, 11.000 kg and 11.600 kg referred weight at mid-CG in Figure 18 to Figure 20 respectively. Note that the shore-based hover trials were performed up to 11.750 kg referred weight, whilst the CFE were only developed up to 11.600 kg referred weight. A somewhat lower maximum referred weight was chosen for the hot & heavy conditions on board ships, to allow flight operations conducted within the speed bracket of the ship's cruise engines in calm wind conditions. Otherwise, the ship's high speed gas turbines must always be available in calm wind conditions to operate the helicopter, which unless operational scenarios dictate is not desirable.

The rejection criteria are plotted together with the maximum hover envelope mentioned in the flight manual (black dotted line in figure) [9], and a maximum safe operating envelope with a 5 knots safety margin that allows for lateral positioning above the flight deck without exceeding flight manual limitations (green dotted line in figure). For all three referred weight, the rejection criteria for roll attitude (red wind conditions), pitch attitude (green wind conditions) and pedal position (red wind conditions) are restricting the CFE (brown dotted line in figure) in similar relative wind conditions. The differences in the CFE's are mainly in the lower speed regions, due to an increase in torque required for the higher referred weights.

Key facts CFE

The following key facts for the construction of the CFE are observed:

1. The predicted CFE is a flight envelope giving the likely combinations of indicated wind speed and direction for safe take-offs and landings from each particular ship type, and is used to increase trials effectiveness as it functions as the starting point for sea trials;
2. The differences in CFE due to increasing referred weight are mainly due to performance related issues;
3. The boundaries for a hot & heavy envelope should have an additional safety margin due to a somewhat more sluggish helicopter response.

SEA TRIALS

The main focus of sea trials is to determine the effects on pilot workload for e.g. visual references, ship motion and turbulence. The sea trials consist of take-off and landings, at least two per test conditions at the boundaries of the envelope, for different procedures, spots, referred weights and ship motion. Once enough confidence and routine is established for shipboard operations at the lower referred weight around a number of test points, a higher referred weight is selected.

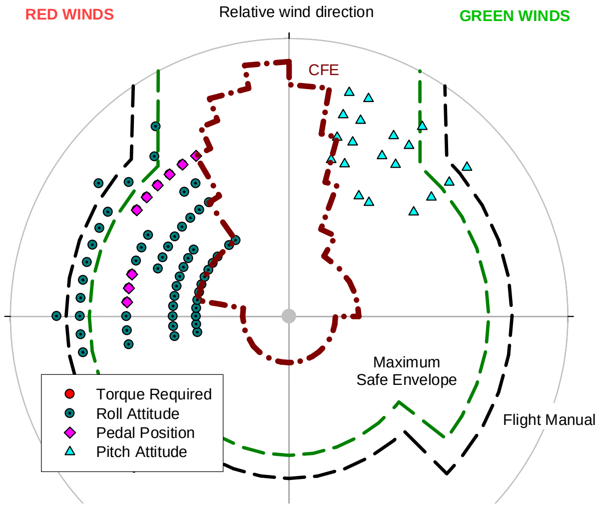

Figure 18; CFE 10.000 kg referred weight

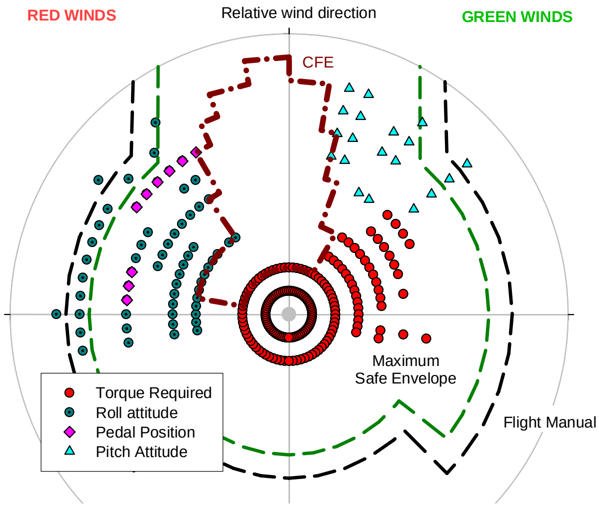

Figure 19; CFE 11.000 kg referred weight

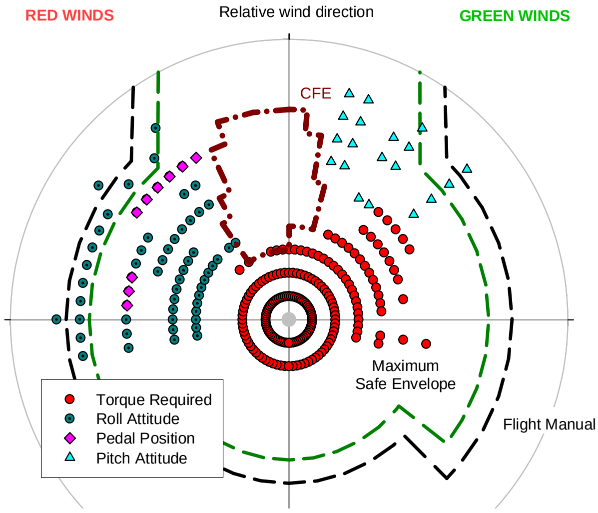

Figure 20; CFE 11.600 kg referred weight

For this higher referred weight the boundaries of the SHOL envelope are established first, and once determined, the lower referred weight from which was started is re-selected and these boundaries are expanded further outwards. This method results in a "wedding cake" strategy in which the results for the higher referred weight are also valid for the lower referred weight and the latter do not have to be tested again. A test condition is only considered successful in case the pilot gives an acceptable workload rating, while at the same time the objective data during post-flight analysis indicates sufficient safety margins.

An overview of acceptable and unacceptable test points as rated by the pilot, for the fore-aft daytime procedure, are shown in Figure 21 to Figure 23 respectively [12,13]. There is a distinction made between day and night test points, and both the CFE (brown dotted line in figure) and the SHOL envelope (blue line in figure) are shown. An overview of exceeded objective rejection criteria are shown in Figure 24 to Figure 26 respectively [12,13]. These objective criteria are only indicated if safety margins are exceeded. The safety margins for the respective parameters were initially established during the shore-based hover trials, and were fine-tuned during various sea trials. The indicated objective rejection criteria are used to accurately define the boundaries of the SHOL, and to assess whether actual limits are approached or there is still room for expansion of the envelope.

The roll attitude of the helicopter is the main limitation in red wind conditions, whilst torque required is the main limitation for take-offs towards the leeward side of the ship and the lower boundaries of the envelope. The upper boundaries are due to pilot workload in the turbulence caused by the ship's superstructure, which also causes large pitch and roll attitude deviations. Note that, in all cases, the objective test data is more consistent and restrictive in defining the boundaries of the operational envelope than the subjective ratings given by the pilot. The upper boundaries of the hot & heavy envelope could not be tested during the test campaign, due to a lack of sufficient wind. However, after applying additional safety margins towards the flight test data for 11.000 kg referred weight, and enough confidence in the CFE, the NH90 NFH has been released to service. This is only achievable in case a comparison between both subjective and objective test results could be made, providing an optimal insight of the boundaries for the SHOL envelope, indicating the importance of the software tool "*SHOL-X*".

Key facts sea trials

The following key facts for the execution of the sea trials are observed:

1. A "wedding cake" strategy should be used in which the results for the higher referred weight are also valid for the lower referred weights;
2. A test point should only be considered successful in case the pilot gives an acceptable workload rating, while at the same time objective data indicates sufficient safety margins;
3. There is always a minimum amount of sea trials required for each ship type to assess pilot workload for e.g. visual references, ship motion and turbulence;
4. A CFE should be used as the starting point for sea trials to drastically increase cost effectiveness of the test campaign;
5. The objective test data is usually more consistent and restrictive in defining the boundaries of the operational envelope than the subjective ratings given by the pilot.

CONCLUSIONS

The key facts of ship helicopter operational limitation development are summarized. So far, tremendous savings in time and expenses of helicopter-ship qualification have been achieved in the Netherlands, whilst aided by the predictive software tool "*SHOL-X*". This tool is used to determine the CFE and to analyze the onboard flight test results, and thus enables helicopter-ship qualification testing with only a bare minimum amount of effort during expensive sea trials. Thereby, the tool eliminates subjective elements as much as possible in the construction of operational envelopes for in-service conditions in a world-wide theatre. In case the methodology is applied correctly, a generic operational envelope could be developed for each helicopter type, which could easily be applied to different ship types. As it is assumed that each country aims for maximum operational flexibility of each particular helicopter-ship combination, with minimal expenses and without any concessions in flight safety, this paper has the ambition to function as the starting point for international regulations or standard procedures to conduct helicopter-ship qualification.

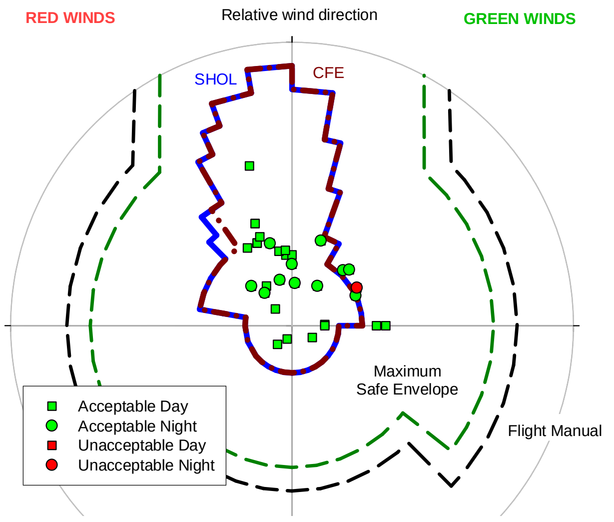

Figure 21; Subjective 10.000 kg ref weight

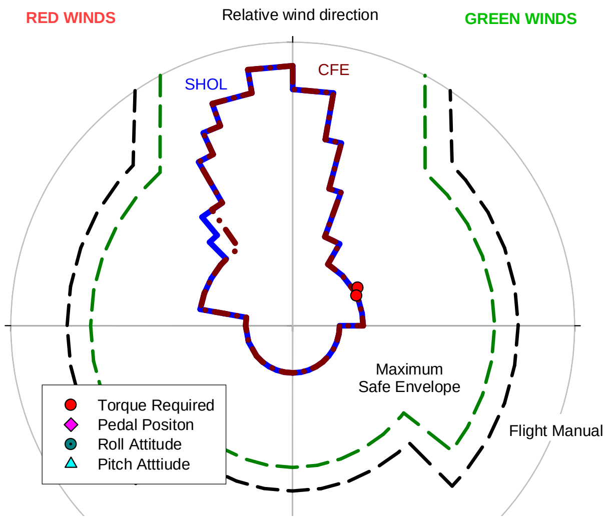

Figure 24; Objective 10.000 kg ref weight

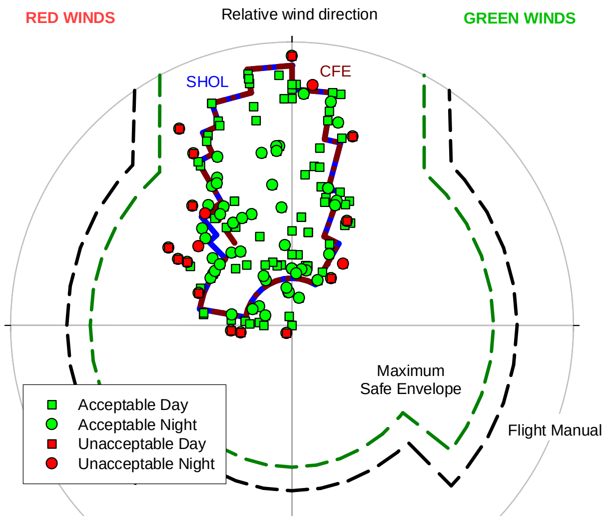

Figure 22; Subjective 11.000 kg ref weight

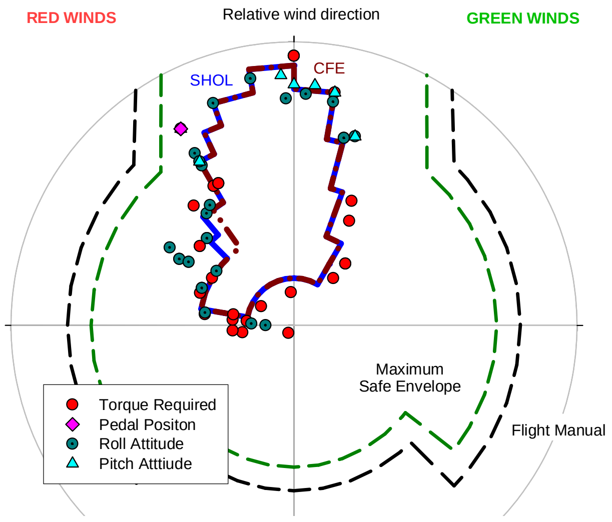

Figure 25; Objective 11.000 kg ref weight

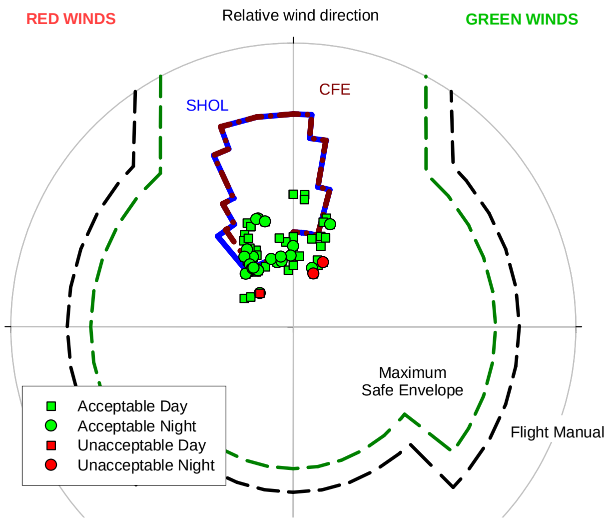

Figure 23; Subjective 11.600 kg ref weight

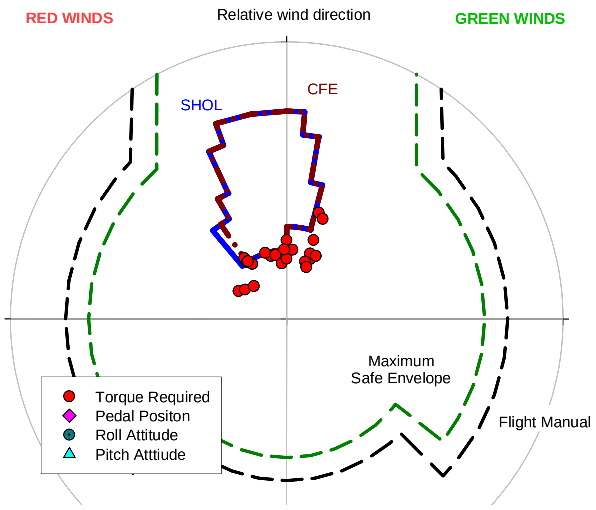

Figure 26; Objective 11.600 kg ref weight

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