Helicopter-Ship Qualification Testing for the NH90 NFH Helicopter

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Whilst the helicopter is always limited to operations within its flight manual limitations, and may be cleared for ships, each unique ship/helicopter combination needs to be explored in an appropriate manner. The helicopter-ship qualification testing consists initially of shore-based hover trials to document the low speed flight characteristics, as a function of referred weight and relative wind condition, and these data will be combined with airwake data for each ship type to develop the so-called "candidate flight envelope". This candidate flight envelope will be (partially) validated during sea trials for each ship type. This paper describes how a predictive engineering tool, so-called "*SHOL-X*", is applied for the NH90 NFH helicopter-ship qualification testing for the landing platform dock "Hr.Ms. Rotterdam". By using the predictive tool, the helicopter-ship qualification testing is less dependent on the results from several dedicated sea trials. The predictive tool thereby not only reduces time and costs of the test campaigns across the fleet, but also improves the reliability of the finally determined operational envelopes used for in-service operations for many years to come.

Figure 1; NH90 NFH sea trials

INTRODUCTION

The helicopter-ship qualification testing process used for development of the Ship Helicopter Operational Limitation (SHOL) envelopes, for the SH-14D Lynx and AS-532 U2 Cougar, by the Netherlands Ministry of Defense has proven to be a useful approach [1, 2]. In general the qualification process consisted of two independent items resulting in the so-called Candidate Flight Envelope (CFE) for sea trials; namely the determination of the environment near the ship deck and the helicopter low speed flight characteristics during Shore-Based Hover Trials (SBHT). Unfortunately there are some major drawbacks in this helicopter-ship qualification testing process, which include but are not limited to: (1) dependency on encountered environmental conditions, (2) dependency on subjective opinions from few pilots and (3) major costs associated with readiness of both helicopter and ship for long periods. Even despite all the preliminary efforts, the resulting SHOLs are solely based on acceptable test points achieved during dedicated sea trials. However, it occasionally happens that either due to prevailing weather conditions, ship availability and/or aircraft availability the limits of the particular helicopter-ship combination can not be fully explored in some areas or at some masses, thereby restricting the operational capability.

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For the above reasons, it will be a clear advantage for helicopter-ship qualification testing to have a predictive engineering tool, and so be less dependent on the results from several dedicated sea trials. This will reduce time and cost related to the test campaign, and will also improve the reliability of the resulting SHOLs, which are to be used during in-service operations for many years to come. Additionally, it allows assessing the impact of design changes to both helicopter and ship after the SHOLs have been released to service with regard to flight performance and control capability. This paper describes the required steps and flight test results used for the NH90 NFH helicopter-ship qualification testing conducted in The Netherlands for the Landing Platform Dock (LPD) "Hr.Ms. Rotterdam". Thereby, it presents a novel predictive engineering tool, so-called "*SHOL-X*", to be used during the qualification process.

TEST CAMPAIGN

A three-step approach for establishing the SHOL envelope is applied as shown in Figure 2. First the environment in which the helicopter will operate is determined by conducting wind tunnel measurements of the airflow around the ship and full-scale measurements of the airflow above the flight deck with associated ship motion. Shore-based hover trials are carried out to verify and precisely measure helicopter limitations, including handling qualities in cross-wind conditions, engine performance and control margins. Thereafter, when combining the behaviors of the isolated helicopter and the local wind conditions of a particular ship, it results in the CFE. 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 night. This is to determine the effects on the pilot workload of e.g. reduced visibility, ship motion and turbulence. The time required and expenses associated with the helicopter-ship qualification testing are depended on the confidence in the CFE and experience with the helicopter and ship type under test.

A predictive tool, "*SHOL-X*", is developed based on specific rejection criteria for each helicopter type and their dependencies in the ship environment [3]. Being able to decide on effectiveness of helicopter-ship qualification testing campaigns based on outcomes of such a tool is novel. The benefits are numerous like rapid introduction of new helicopter types across the fleet and advanced insight for cost effectiveness of sea trials. The tool can be used for three different aims, as shown in Figure 2, once the CFE is established: (1) complete sea trials for new ships and helicopter types, (2) only sea trials for areas with low confidence in the CFE and/or small safety margins before exceeding rejection criteria, or (3) SHOL certification with a minimum amount of sea trials. In the coming years, during the introduction of the NH90 NFH helicopter across the fleet, it will be decided what these minimum requirements for sea trials need to be.

Figure 2; Flow chart test campaign

HELICOPTER ITEMS

The flow chart for SHOL test campaigns, as shown in Figure 2, distinguishes between environment and helicopter items. In this section examples are shown for processing test data gathered during SBHT and how this data is used by the predictive analysis tool to construct the CFE.

NH90 NFH helicopter

The NH90 NFH is a twin engine, medium weight transport helicopter with a four bladed main rotor turning counter clockwise, 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. These are assisted by a fly-by-wire computer and a hydraulic system. The All Engine Operative (AEO) torque ratings of the NH90 NFH helicopter are 104% for maximum continuous power and 113% for transient power.

Shore-based hover trials

The purpose of the SBHT is to establish aircraft flight characteristics for power required, Trimmed Flight Control Positions (TFCP), aircraft attitude, controllability limits and pilot workload in an omni-directional relative wind envelope to complement the flight manual information. In addition, to the encountered natural wind conditions, a dedicated pace-car is used to set up different relative wind conditions as shown in Figure 3. The flight test data obtained indicates - within the low speed hover envelope - where regions exist where safety margins between available and required aircraft 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, with the achieved Rate of Climb (ROC).

Figure 3; Pace-car with NH90 NFH

For subjective ratings three scales are used: (1) the Deck Interface Pilot Effort Scale (DIPES) is used to describe pilot workload, (2) the A&EE Vibration Assessment Rating (VAR) scale is used to describe vibration levels and (3) the turbulence scale is used to indicate the intensity of the turbulence encountered and its associated aircraft reactions [4]. The pilot workload ratings should be used with care, however, mainly due to different visual cues between a formation with a vehicle traveling over the runway and a landing on a ship deck at sea. In addition, natural winds are always accompanied by some degree of turbulence which is not fully replicated by the pace-car tests.

Test conditions

The NH90 NFH was assessed for a period of 17 hours and 30 minutes of flight time in a four-day period between 19 and 22 September 2011, at airbase Deelen in The Netherlands [5]. The helicopter was flown with the flight control system in 'ATT' mode (providing roll and pitch attitude hold and heading hold at low speed), the 104% Nr switch engaged, while the Environmental Control System (ECS) was switched off and the landing gear selected down. The aircraft had no external stores and/or other items influencing the performance or handling qualities. The hovering height was approximately 60 ft, which corresponds with about one main rotor diameter to remain out of ground effect. Fuel load and ballast were changed during the course of testing depending on the environmental conditions, to maintain either 10.000 kg or 11.000 kg referred weight, within a margin of 2% by using running rotor refueling. The test for hot & heavy conditions at higher referred weight is still to be scheduled.

The primary data sources used throughout the trial, for post-flight analysis, were recorded aircraft parameters from the MIL-STD 1553B and ARINC-429 data busses. The data-streams were fed, via test connectors in the rear left side of the cabin and test connectors behind the pilot and co-pilot seats, to a generic instrumentation system, and transferred into engineering units according to the Interface Control Document (ICD) [6]. The flight test data were then converted into referred parameters, and used to produce information relevant to atmospheric conditions and aircraft masses different from those actually tested. Consequently, with a few exceptions, a relatively small number of test points at carefully chosen test sites could produce information relevant to in-service conditions for many years to come.

Performance rejection

The results for torque required at 20 knots, as a function of the relative wind direction, for 10.000 kg and 11.000 kg referred weight in ISA conditions at sea level are shown in Figure 4. The torque required is increased for higher referred weight, and dependent on the relative wind direction. As the main rotor turns counter-clockwise, when seen from above, more left pedal 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, known as the 'weather-cock effect', results for green winds in increased tail rotor thrust and thus torque required. For this reason the torque required is highest for green winds.

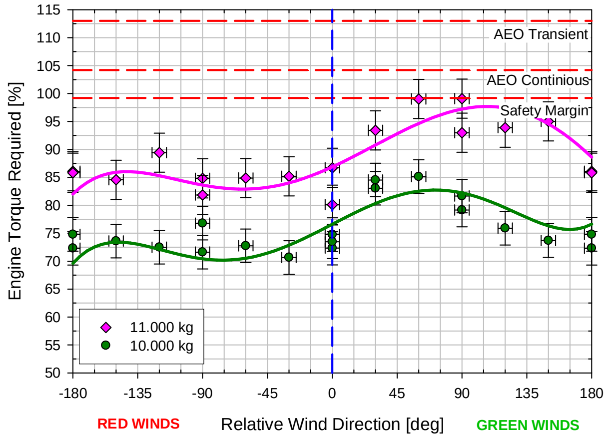

Figure 4; Torque required at 20 knots [5]

For the lower relative wind speeds, below 10 knots, at 11.000 kg referred weight the torque required exceeds the 5% safety margin and/or the maximum continuous power limitation of 104% torque. Therefore the relative wind conditions, below 10 knots, at 11.000 kg referred weight are removed from the CFE.

Error analysis. Errors in flight test measurements introduce the inevitable uncertainty that is inherent in all measurements. Whenever a measurement can be repeated, it should usually be done so several times. Unfortunately, exact similar conditions are difficult to establish during shore-based hover trials and especially for all other in-service conditions afterwards. Therefore, making predictions based on a minimal amount of test points performed during shore-based hover trials is accompanied by the use of error bars. The uncertainty expressed in error bars are determined for torque required by summation "in quadrature" [7]. This is allowed as the measurements are independent and subject to random uncertainties. For example, the referred parameters for referred power required, can be determined by the relationship [8]:

$$P_{ref} = \frac{P}{\sigma\omega^3} = \frac{Q}{\sigma\omega^2} = f\left(\frac{W}{\sigma\omega^2}, \frac{V}{\omega}, \frac{\omega}{\sqrt{\theta}}\right)$$

where P is power required, σ is relative density, ω is relative rotorspeed, Q is torque, W is weight, V is airspeed and θ is relative temperature. Relative errors in referred power required are determined by:

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

where δQ, etc., are the uncertainties in the measurements of Q, etc..

Control rejection

Pedal position. The results for mean pedal position at 40 knots, as a function of the relative wind direction, for 10.000 kg and 11.000 kg referred weight are shown in Figure 5. The pedal position changed with the relative wind direction. The pedal position is independent of referred weight, thus torque required, as the fly-by-wire flight control system acts as a collective-yaw interlink which compensates variations in pedal deflection caused by torque variation. As the main rotor turns counter-clockwise, when seen from above, more left pedal is necessary to prevent the nose to turn into the wind for green winds conditions. The tendency for the nose of the helicopter to turn into the wind, known as the 'weather-cock effect', results for green winds in increased tail rotor thrust and thus torque required. 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 is required to maintain aircraft heading. For red 60 winds with 40 knots at 10.000 kg referred weight, the 10% safety margin is exceeded. Except for red 60 winds with 40 knots, there are no restrictions in the CFE due to mean pedal position.

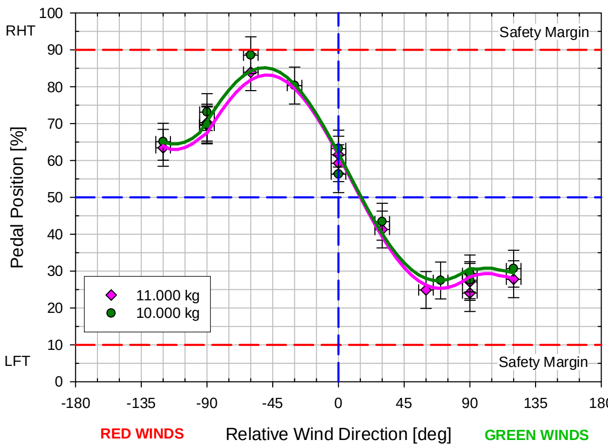

Figure 5; Mean pedal position at 40 knots [5]

Cyclic position. The results for longitudinal and lateral cyclic position at 20 knots, as a function of the relative wind direction, for 10.000 kg and 11.000 kg referred weight are shown in Figure 6 and Figure 7 respectively. There is no difference in cyclic position between both referred weights, although the cyclic position changes with relative wind direction.

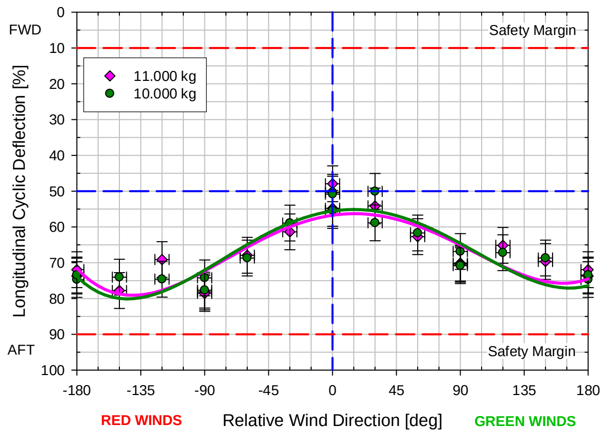

Figure 6; Longitudinal cyclic at 20 knots [5]

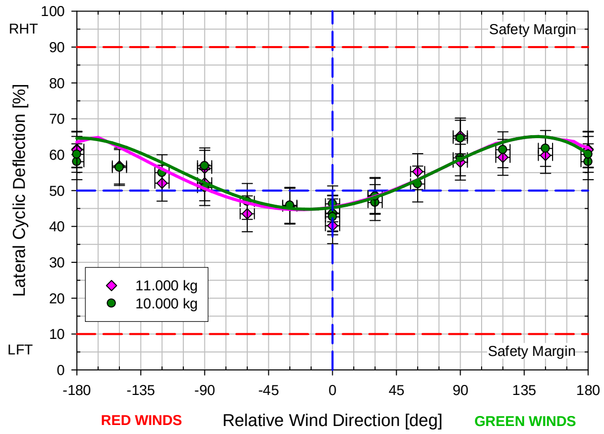

Figure 7; Lateral cyclic at 20 knots [5]

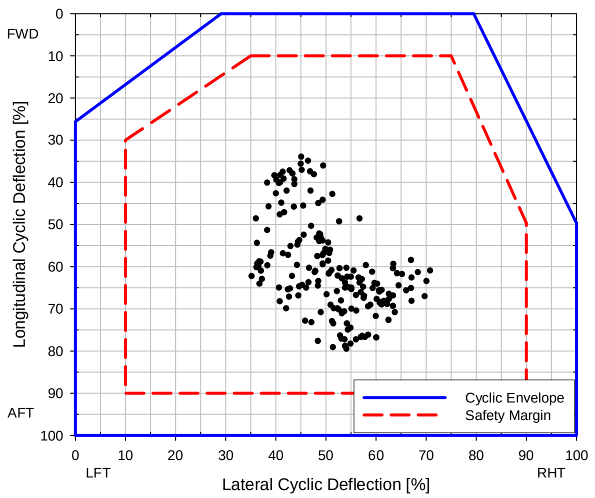

Figure 8; Overview cyclic positions [5]

A complete overview of the cyclic positions measured during the SBHT for all relative wind conditions, and different Centre of Gravity (CG) positions, is presented as longitudinal cyclic vs. lateral cyclic, including the cyclic envelope restrictions as shown in Figure 8. There are no restrictions in the CFE due to lateral and/or longitudinal cyclic positions for the test conditions tested.

Aircraft attitude rejection

Roll attitude. The results for Angle of Bank (AOB) at 40 knots, as a function of the relative wind direction, for 10.000 kg and 11.000 kg referred weight are shown in Figure 9. The AOB changed with wind direction towards the right for green winds and towards the left for red winds. The changes in AOB towards the right in green winds conditions are relatively small up to a maximum of 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 large AOB was considered uncomfortable by the aircrew. The large AOB up to approx. 13°, for red wind conditions, between red 60 and red 120 could restrict ship board operations as the helicopter touches the flight deck with one main wheel first, especially as the ship will normally be tilting in the opposite direction towards starboard with red winds, thereby increasing the relative angle between the helicopter and the flight deck even more. The red wind conditions with large AOB up to approx. 13°, between red 60 and red 120, were (partially) included in the CFE, although were approached carefully to assess the impact on safety during ship board operations.

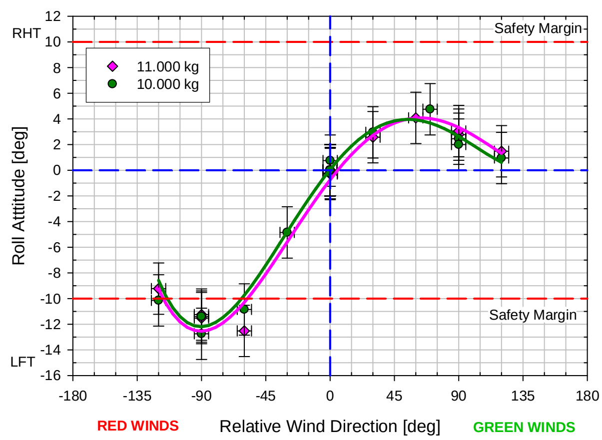

Figure 9; Roll attitude at 40 knots [5]

Pitch attitude. The results for pitch attitude at 30 knots, as a function of the relative wind direction for 10.000 kg and 11.000 kg referred weight are shown in Figure 10. The pitch-up attitude is at 20 knots tailwind approx. 4° and increases with longitudinal speed towards approx. 7,5° at 40 knots headwind. The increase of pitch-up attitude with airspeed is in contradiction with an expected decrease in pitch attitude with airspeed by the pilot, and could result in difficulties with speed selection in the low speed region. The pitch-up attitude, at mid-CG, increases even further 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° to avoid a tail strike.

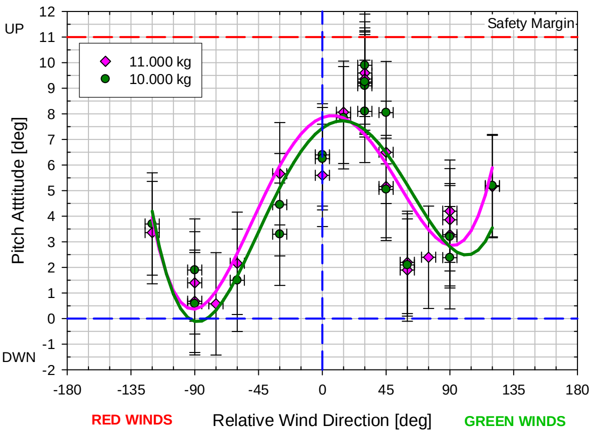

Figure 10; Pitch attitude at 30 knots [5]

The high pitch-up attitudes, up to approx. 10° in a wind direction from green 30 at 30 knots, could result in reduced visual reference with the ship and/or in a tail strike during ship board operations, especially as the LPD "Hr.Ms. Rotterdam" has a 1,7° up-slope of the flight deck towards the stern of the ship, thereby increasing the relative angle between the helicopter and the flight deck even further. The wind conditions around green 30 with 30 knots were removed from the CFE.

Fish tailing

For winds in the port sector, between red 30 and red 120 above 20 knots, so-called "fish tailing" characteristics were noticed. The fish tailing results in uncontrollable heading changes of ± 6°, AOB changes of ± 3°, and increased pedal activity with ± 14% (1,6 cm) pedal inputs at 0,5 Hz. These areas in the port sector could be included in the CFE, although it should be noted that fish tailing effects could be stimulated in the ship's airwake, thereby making heading control even more difficult. For this reason an additional safety margin of 14% was applied towards the mean pedal position when constructing the CFE.

Centre of Gravity

For different CG positions test points were flown to determine the associated displacement in pitch attitude, AOB, longitudinal and lateral cyclic control position required to maintain trimmed flight condition. The CG changed longitudinally from 58% towards aft 99%, and laterally from 26% towards right 76% from the maximal deviations allowed within the CG envelope. The cyclic positions and aircraft 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 aircraft 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, while ensuring safe operations with full control authority throughout the CG envelope for operational aircrew.

Item	Effect
Longitudinal cyclic	± 0,65 %/cm
Pitch attitude	± 0,15 deg/cm
Lateral cyclic	± 0,80 %/cm
Angle of Bank	± 0,25 deg/cm

Table 1; Changes due to CG [5]

Subjective rejection

The pilot workload in general was low, only for red 90 relative winds the high AOB was considered uncomfortable by the pilot 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 as short period). There are no restrictions in the CFE due to subjective pilot ratings.

Vertical climb performance

The aircraft's vertical climb performance was assessed, using a technique known as MPV, for different airspeeds starting at 10 knots increasing to 50 knots, both for 10.000 kg and 11.000 kg referred weight 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 pilot was flying the vertical climb manually without using the autopilot upper mode functions. For each test point the achieved ROC is expressed against the deltas in torque required, between hover and maximum climb condition. These values for ROC vs. torque increments 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 of the ship.

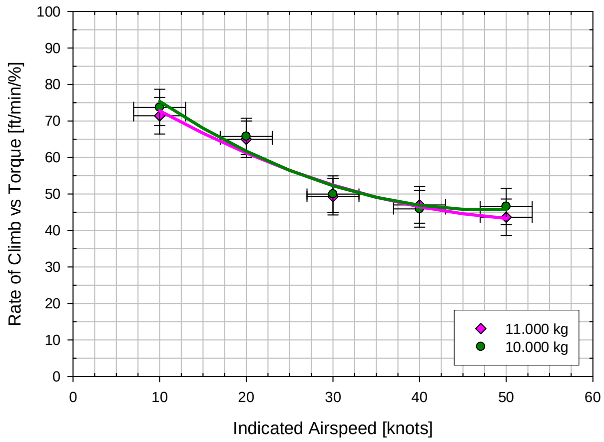

Figure 11; Vertical climb performance [5]

ENVIRONMENT ITEMS

The flow chart for SHOL test campaigns, as shown in Figure 2, distinguishes between environment and helicopter items. In this paragraph, it is explained how airwake data is used by the predictive tool to construct the CFE. The results of the SBHT are based on relative wind conditions encountered by either hovering in natural wind conditions or by using a pace-car, although near and above the flight deck the relative wind is disturbed by the large 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 and confirmed by full-scale measurements [9]. Unfortunately, both the relative wind and local wind conditions are unknown for the operational crew after the trials, as the indicated wind by the ship anemometers is their only reference source. Furthermore, by mounting anemometers on a ship with a bluff body, the local air flow (speed and direction) at the anemometer location also deviates from the undisturbed wind conditions. Therefore, it is important to distinguish between three different wind conditions:

1. **Relative wind**. The shore-based hover trial is based on these wind conditions and it is the free air stream near the ship.
2. **Indicated wind**. The relative wind with the anemometer errors taken into account. The SHOLs are based on these wind conditions.
3. **Local wind**. The local wind conditions are changing for each position near and above the flight deck. These are the wind conditions the helicopter encounters during ship board operations.

To establish the relation between these three different wind conditions, there are wind tunnel measurements 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 establish the relationship for each landing spot between the measured local flow properties in the helicopter flight area and the data measured at the anemometer positions. An example is shown for wind speed and azimuth deviations due to the ship's superstructure, as a function of the relative wind direction, in Figure 12 and Figure 13 respectively.

The measured data above the flight deck is reworked towards indicated wind speed by the following equations:

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

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. The horizontal flow deviation is calculated by:

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

where χ is the horizontal flow deviation, β_{loc} is the local horizontal wind direction and β_{an} the indicated wind direction by the anemometer system. Vertical flow components in the flight area are only expressed in local angles from the horizontal plane, φ_{loc}, as the anemometer systems applied on the ship do not account for vertical flow angles as shown in Figure 14.

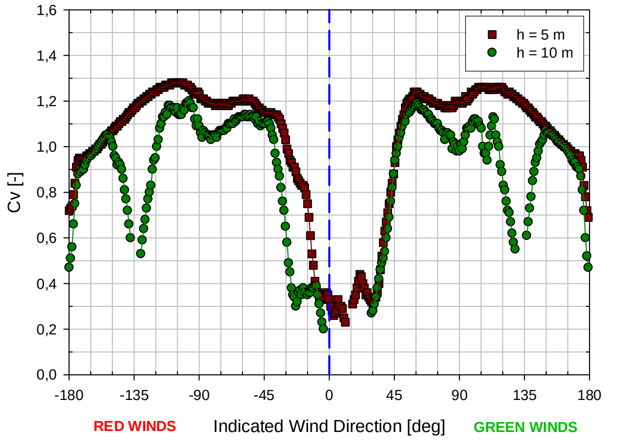

Figure 12; Speed deviation spot 1 [9]

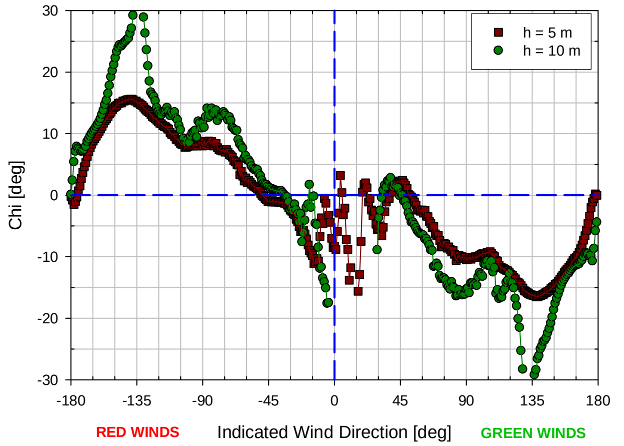

Figure 13; Azimuth deviation spot 1 [9]

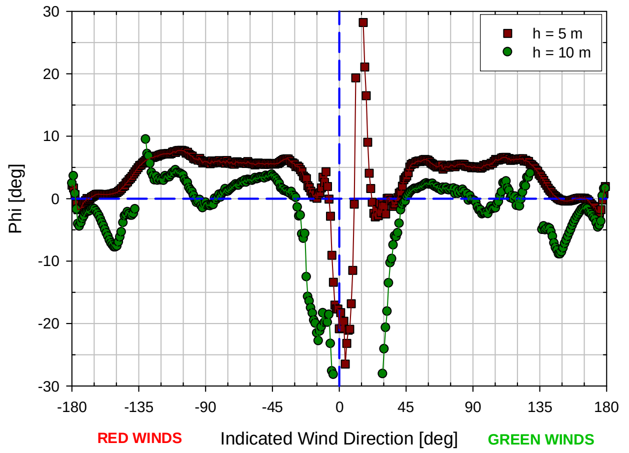

Figure 14; Vertical flow component spot 1 [9]

For head winds in the sector ± 30°, the airwake over the flight deck is strongly influenced by the superstructure of the hangar. The hangar generates an elliptical recirculation zone, of which the longitudinal axis is roughly two to three times the hangar height and the lateral axis is the width of the hangar. This recirculation zone is characterized by reduced wind speed, an unstable flow pattern and a large negative vertical flow component. Note that the landing spots are two meters towards the port side of the ships centerline, as the minimum speed and strongest vertical flow components occur around green 15 instead of dead ahead. For quartering winds between ± 30° and ± 60° the sharp hangar edge will generate a dominant vortex which will roll over the flight deck and in combination with the steep gradient in wind speed at the edge of the recirculation zone, it hampers flight operations. The beam winds and tail winds are generally influenced by vortexes generated by the sharp deck edge, although flight operations are conducted in these areas with lower wind speeds, the vortexes are of less intensity to hamper flight operations.

Unfortunately, it is a restriction that no wind tunnel data is available for the departure path to the leeward side of the ship, and thus not included in the data processing. Based on previous knowledge with the SH-14D Lynx it is known that there are large downdrafts on the leeward side of the LPD “Hr.Ms. Rotterdam” [10]. A maximum angle of green 10 at higher relative wind speeds, slightly widening for lower wind speeds, is applied for safety considerations from previous experience to construct the CFE. This underlines the requirement to have an accurate and complete data set to construct a CFE, and reduce any subjective elements in its construction.

CANDIDATE FLIGHT ENVELOPE

Once the helicopter and environment issues are known and clearly documented these results are combined to construct the CFE. The predictive tool “*SHOL-X*”, presents the CFE in a polar plot that makes it easy to indicate which rejection criteria are exceeded and for which relative wind conditions this applies as shown for 10.000 kg and 11.000 kg referred weight at mid-CG in Figure 15 and Figure 16 respectively. The rejection criteria are plotted together with the maximum hover envelope mentioned in the flight manual [11], and the maximum safe operating envelope that allows for lateral positioning above the flight deck. The rejection criteria indicated are:

- Power required at 11.000 kg referred weight, below 10 knots relative wind, exceeded the 5% safety margin for maximum continuous power;
- High pitch-up attitudes up to approx. 10° (occasionally increasing towards approx. 12°) around green 30 with 30 knots;

- Large left AOB up to approx. 13° (occasionally increasing towards approx. 15°) for red winds from abeam;
- Right pedal position exceeding the 10% safety margin, while taking fish tailing characteristics into account for red winds.

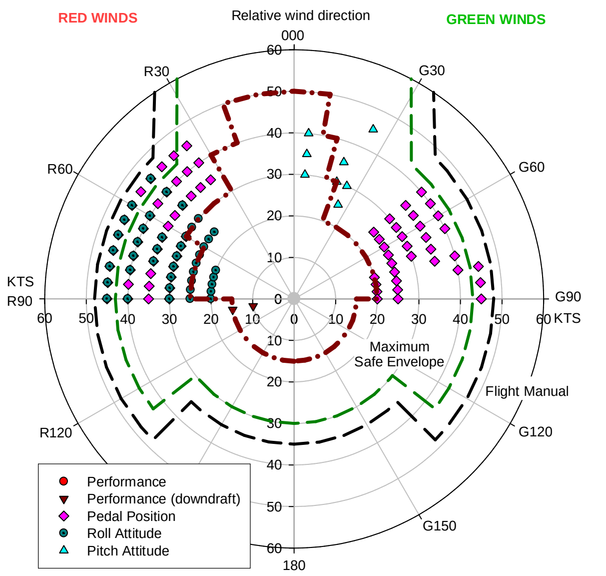

Figure 15; CFE 10.000 kg referred weight

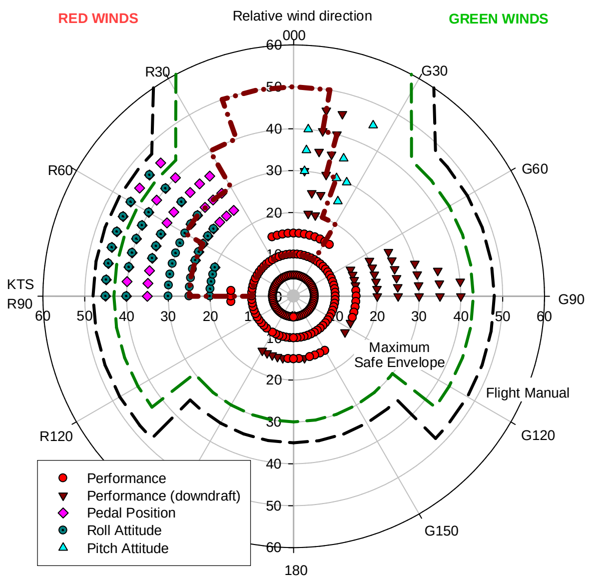

Figure 16; CFE 11.000 kg referred weight

Note that the differences in rejection criteria between 10.000 kg and 11.000 kg referred weight are mainly due to torque required. This is confirmed by the results from the SBHT in which the trend lines for cyclic position, mean pedal position and aircraft attitude could be considered similar. From this point, it is just a matter of drawing a CFE excluding rejection criteria, while taking also safety considerations into account for tail wind conditions in order to judge closure rates in the approach towards the ship. Some rejection criteria data points are still included in the envelope. Those areas should be approached in an incremental manner and the main focus of the sea trials. The resulting CFE is the basis for preparation and execution of test campaigns on board ships to establish SHOLs during sea trials.

SEA TRIALS

The NH90 NFH was assessed, during sea trials on board the LPD "Hr.Ms. Rotterdam", for a period of 35 hours and 35 minutes of flight time in a two week period between 3 and 13 October 2011, near the coast of Den Helder in The Netherlands [12]. In total 21 test sorties comprising a total of 504 deck landings, of which 416 day and 88 night (aided/unaided), were flown in conditions up to and including sea state 4. The LPD "Hr.Ms. Rotterdam" as shown in the landing phase in Figure 17, is a 166 m long ship with 12.750 tons displacements in use for amphibious operations. The flight deck, of 66 x 25 m, had two landing spots, of which spot 1 was forward closed to the hangar and spot 2 was aft. The flight tests were performed at 10.000 kg and 11.000 kg referred weight. The aircraft had no external stores and/or other items influencing the performance or handling qualities.

Figure 17; LPD "Hr.Ms. Rotterdam"

Test results

The tests consisted of take-off and landings, at least two per test conditions, for different procedures, spots, referred weights and ship motions. A test condition was only considered successful in case the pilot gave an acceptable workload rating, and when the objective data during post-flight analysis indicated sufficient safety margins. The DIPES scale was used to describe pilot workload and the turbulence scale was used to indicate the intensity of the turbulence encountered and its associated aircraft reactions [4]. A detailed overview of all the acceptable and unacceptable test points, for the fore-aft port procedure, combined for spot 1 and spot 2 at 10.000 kg or 11.000 kg referred weight are shown in Figure 18 and Figure 19 respectively. In addition each figure shows the established SHOL envelope during the sea trials.

The test results show that 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. 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 do not have to be tested over again. An overview of the objective rejection criteria exceeded during the sea trials as determined during post-flight analysis, combined for spot 1 and spot 2 at 10.000 kg or 11.000 kg referred weight are shown in Figure 20 and Figure 21 respectively. For 10.000 kg referred weight there are a limited number of rejection criteria exceeding safety margins, although for 11.000 kg referred weight the limitations are much more pronounced.

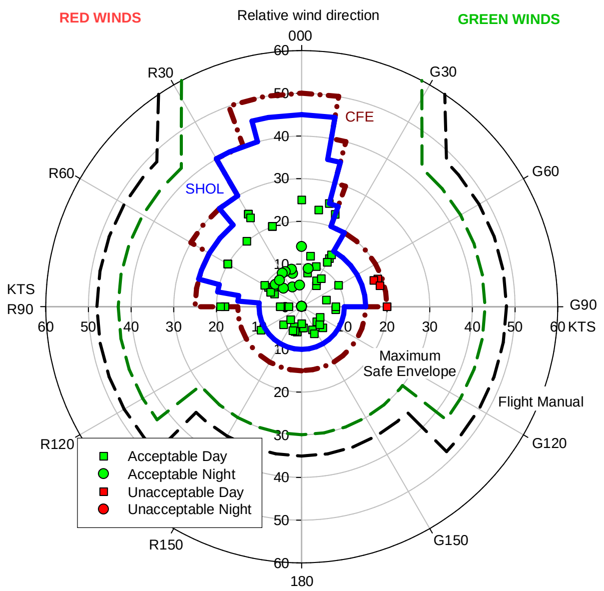

Figure 18; Subjective 10.000 kg ref weight [12]

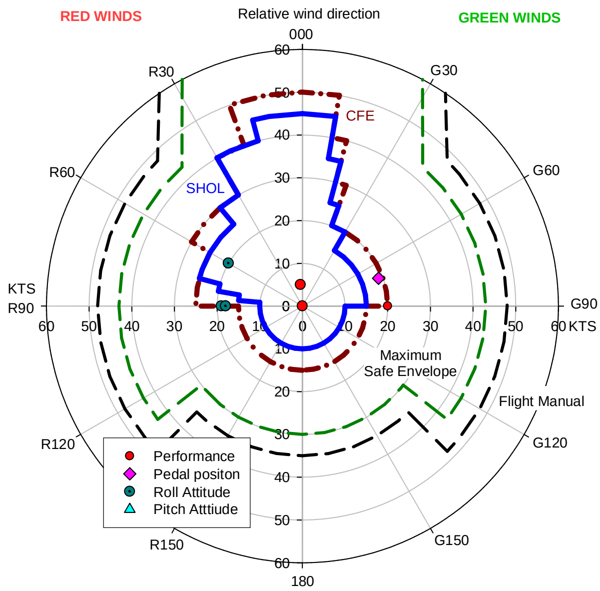

Figure 20; Objective 10.000 kg ref weight [12]

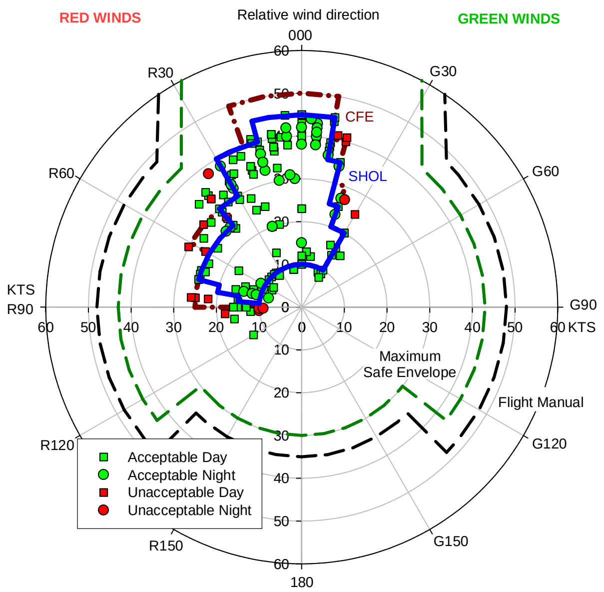

Figure 19; Subjective 11.000 kg ref weight [12]

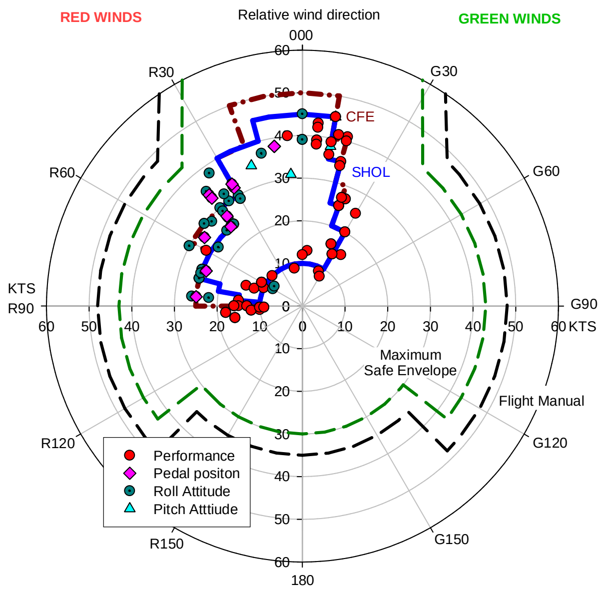

Figure 21; Objective 11.000 kg ref weight [12]

In line with the predictions of the CFE, there are for red winds large left AOB and considerable right pedal required restricting the SHOL envelope. For green winds torque required at the leeward side of the ship is restricting the SHOL envelope. This possibility for comparison between subjective and objective test results gives an optimal overview for the reasons of SHOL envelope boundaries. Thereby, it indicates whether actual limits are approached or that there is still room for expansion. For the examples shown above, the port side of the envelope was somewhat more restrictive as expected, although the forward sector could likely be expanded towards 50 knots relative wind speed and at 10.000 kg referred weight the aft sector expanded towards 15 knots relative wind speed. Note that, in all cases, the objective test data is more restrictive for the boundaries of the envelope than the subjective ratings given by the aircrew. As this is the first NH90 NFH sea trial in The Netherlands, the test experience allows setting the rejection criteria correctly for future trials.

For completion an overview of the turbulence levels encountered, both for 10.000 kg and 11.000 kg referred weight at spot 1 is shown in Figure 22. The turbulence level is increasing with airspeed in the forward sector, and for red winds from abeam. For the fore-aft port procedure the turbulence level by itself was in none of the cases restricting the envelope.

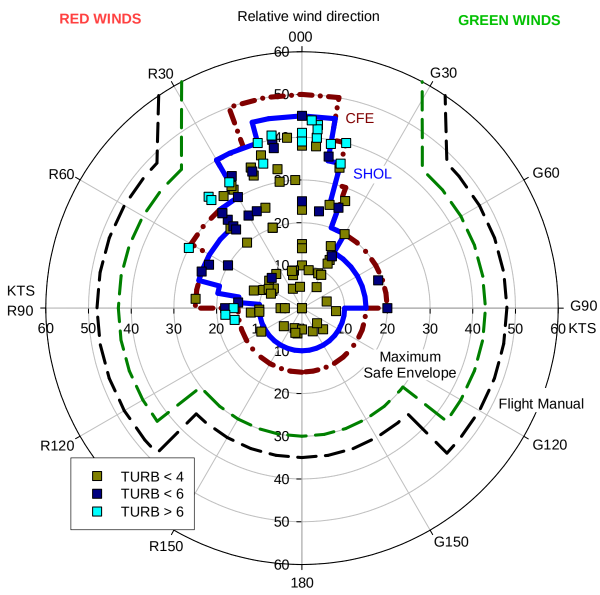

Figure 22; Overview turbulence spot 1 [12]

CONCLUSIONS

A novel predictive engineering tool, so-called "*SHOL-X*", relying on actual flight test data is developed based on specific rejection criteria for each helicopter type and their dependencies in the ship environment. The idea represents a practical assimilation and organization of actual data to be used to predict how to get through a complex matrix of test conditions to define an acceptable operational envelope for shipboard operations. The predictive tool is used for determination of the candidate flight envelope for each ship type allowing e.g. larger steps in an incremental approach towards flight envelope restrictions and sensible exclusion of test points. The predictive tool not only reduces time and costs of the test campaign, but also improves the reliability of the finally determined SHOL used for in-service operation for many years to come by enabling comparison between both objective and subjective flight test data. The accuracy of the predictive tool will be precisely determined during the introduction of the NH90 NFH helicopter in the coming years. Once enough confidence is established in the predictions made by "*SHOL-X*", it will be decided to which extend the Netherlands Ministry of Defense can use this tool for certification purposes while conducting a minimum amount of sea trials, and what these minimum requirements for sea trials need to be.

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