Lessons Learned from NH90 NFH Helicopter-Ship Interface: Testing across the Complete Dutch Fleet

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In general, the helicopter industry delivers a helicopter that has undergone elaborate in-flight test campaigns performed to demonstrate safe flight within the expected operational envelope. However, establishing the operational potential and limitations for safe shipboard operations is still considered a national responsibility. For some reason, there are still no internationally agreed regulations or standard procedures to establish the required helicopter-ship operational limitations. Consequently the kind of interpretation given to such limitations differs strongly between countries. As it is assumed that each country aims for maximum operational flexibility of a particular helicopter-ship combination, with minimum expenses and without any concessions to flight safety, this paper summarizes the lessons learned from the NH90 NFH helicopter-ship interface testing across the complete Dutch fleet. Aided by a predictive software tool, named "*SHOL-X*", which eliminates subjective elements to the largest possible extend in order to determine operational envelopes for in-service conditions, the Netherlands Ministry of Defence was able to achieve tremendous savings in time and expenses of helicopter-ship qualification. This paper is specifically aimed at pilots and engineers who are involved in flight trials of helicopter-ship combinations as part of a complex flight test programme for which they are required to plan, conduct and report on helicopter-ship operational limitations.

Figure 1; NH90 NFH during sea trials in 2014

NOMENCLATURE

AEO	All Engines Operative
AOB	Angle Of Bank
AOR	Auxiliary Oiler Replenishment
CFE	Candidate Flight Envelope
DIPES	Deck Interface Pilot Effort Scale
FADEC	Full Authority Digital Engine Control
FDO	Flight Deck Officer
LCF	Air Command Frigate
LPD	Landing Platform Dock
MCP	Maximum Continuous Power
MFRI	Multi-purpose Frigate
MPV	Maximum Power Vertical
NFH	NATO Frigate Helicopter
NVG	Night Vision Goggles
OAT	Outside Air Temperature
OGE	Out-of-Ground Effect
OPV	Ocean Patrol Vessel
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 summarize the lessons learned from the NH90 NFH helicopter-ship interface testing performed in the time bracket 2011 and 2014 across the complete Dutch fleet. The applied helicopter ship qualification test programme starts with shore-based hover trials to document the low speed flight characteristics of the helicopter, 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 dedicated sea trials. The CFE is used to increase trial effectiveness as it serves as the starting point for the sea trials. In other words, the CFE allows for an immediate exploration of the potential boundaries of the helicopter-ship operational envelope without unnecessarily wasting time to search the boundaries of the envelope with conservative extensive sea trials.

A predictive engineering tool developed by the main author [1], named "*SHOL-X*", was proposed and used in the qualification process of the NH90 NFH helicopter-ship qualification. "*SHOL-X*" is developed as a generic tool allowing early evaluation of safety limits for operating helicopters to and from ships. In this way, the qualification process is less dependent on the results from dedicated sea trials. Especially, as occasionally has happened during previous test campaigns performed within the Netherlands Ministry of Defence, 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 either due to prevailing weather conditions, ship availability and/or helicopter availability. This resulted in unnecessary restrictions of the operational capability.

The developed predictive tool "*SHOL-X*" not only reduces time and expenses of the test campaigns, but also improves the accuracy of the finally determined operational envelopes to be used for in-service conditions for many years to come. Additionally, it allows assessing the impact of design changes to both the helicopter and ship with regard to flight performance and control capability after the Ship Helicopter Operational Limitations (SHOLs) have 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]. These other methodologies mainly focus on the outcome of sea trials in combination with a subjective understanding of the complex issues involved to set-up a test matrix. However, in none of the other cases an objective approach towards helicopter-ship qualification has been successfully applied.

TEST CAMPAIGNS

A three-step approach for establishing operational envelopes is proposed within "*SHOL-X*" 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 for the ship. This is still followed by a limited validation during full-scale measurements of the airflow above the flight deck. For the helicopter (yellow box in figure), shore-based hover trials are carried out to verify precisely the helicopter limitations, in terms of e.g. handling qualities in cross-wind conditions, engine performance and control margins. Subsequently, 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), for example experience from previous test campaigns with either the helicopter or the ship under test, could be added to optimize the CFE. Finally, based on the CFE, a (partial) flight test campaign on board the ship is conducted, preferably 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 from, for example, visual references, ship motion and turbulence.

The time required and expenses associated with each test campaign are dependent on the confidence in the CFE and the experience with the helicopter and ship type under test. The predictive capabilities of "*SHOL-X*" are based on specific rejection criteria – these have to be defined for each helicopter type under study - and their dependencies on the ship environment [1]. The tool can be used for two goals: (1) determine the CFE and (2) analyze the onboard flight test results, which enables SHOL development with only a bare minimum amount of effort during already expensive sea trials. The main benefits of this tool is that it allows a rapid introduction of new helicopter types across the fleet, drastically increasing the cost effectiveness of SHOL development, and achieving maximum operational flexibility for the ship.

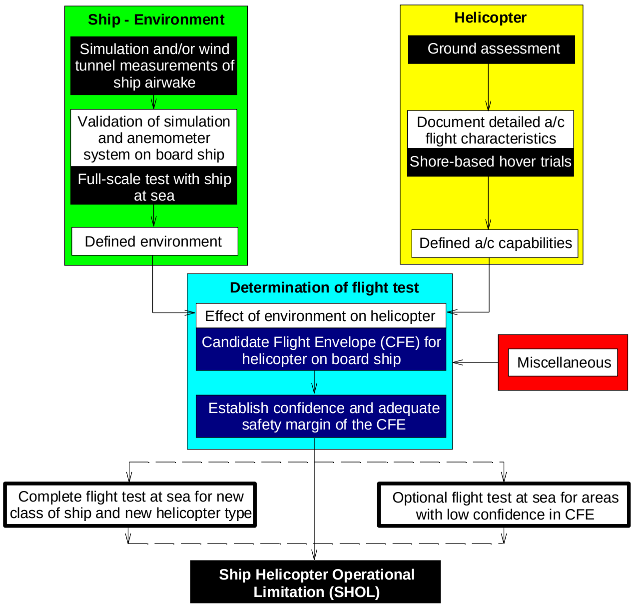

Figure 2; Flow chart SHOL development

ENVIRONMENT ITEMS

The first step in the flow chart for SHOL development, as shown in Figure 2, distinguishes between environment and helicopter items. In this section processing airwake data in the vicinity of the flight deck is discussed. It is important to distinguish between three different wind conditions:

1. **Relative wind**. The shore-based hover trials are performed in undisturbed relative wind, which is also 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 encounter during ship board operations.

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 ship's superstructure. This disturbed wind is what the helicopter encounters when operating from the flight deck and is known as local wind. Unfortunately, both the undisturbed relative wind and local wind conditions are unknown for the operational crew after the test campaign once the operational envelopes are released, as the indicated wind by the ship's 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 should be made towards the indicated wind speed on board the ship to ensure a usable CFE.

To establish the relation between the three different winds conditions, wind tunnel measurements are conducted for every ship type at various points above the flight deck and in the helicopter 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. In case of any doubt about the reliability of the indicated wind by the ship's 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 correlation with the undisturbed relative wind for post-flight analysis.

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. Areas with vertical airflow components are expressed in angles, φ, from the horizontal plane. The areas with a large negative angle (i.e. downward airflow velocities) in combination with high wind speeds may create problems in performance requirements.

Ship's 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, yet 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 and the effect on the local wind at the flight deck.

Some examples of disturbances at the port anemometer location for the Landing Platform Dock (LPD No.1), Air Command Frigate (LCF), Ocean Patrol Vessel (OPV), M-Frigate (MFRI), Auxiliary Oiler Replenishment (AOR) and the Landing Platform Dock (LPD No.2) ships are shown for wind speed coefficient C_v and airflow deviation χ as a function of the relative wind direction in Figure 3 and Figure 4 respectively. The differences in wind speed coefficient are up to approximately 0.3, hence for 30 knots already a difference exists of up to 9 knots between the actual and indicated wind speed between these ship types. Furthermore, the differences in wind direction are up to approximately 30º in azimuth. Therefore, when the relation between undisturbed relative wind and indicated wind is unknown, it is questionable whether efficient sea trials could be performed.

The port anemometer is selected for red winds (i.e. winds from the left side of the ship's centreline) and the starboard anemometer is selected for green winds (i.e. winds from the right side of the ship's centreline), 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 the event that an anemometer system is out-of-service, it is advised to provide either red or green winds for flight operations to ensure that the windward anemometer system could be used, or to use the emergency SHOL envelope. The emergency SHOL envelope should contain sufficient margins to allow shipboard operations with the downwind anemometer system selected.

As the disturbances at the anemometer locations are already known for each ship type, a Wind Correction Algorithm (WCA) is applied on most ships in the Royal Netherlands Navy. The WCA correctly calculates 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 onboard the ship and less variation is present in the indicated wind information.

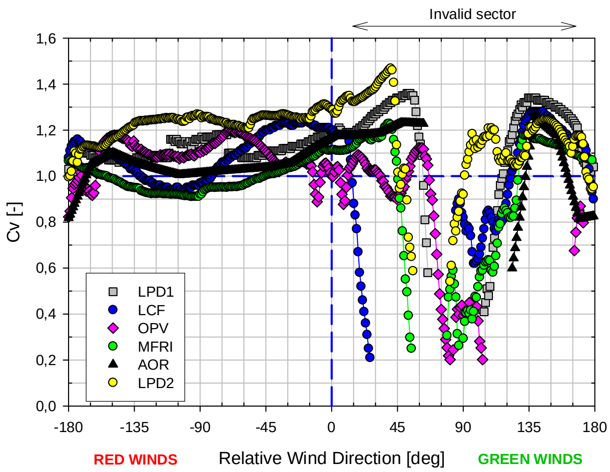

Figure 3; Port anemometer locations, *Cv*

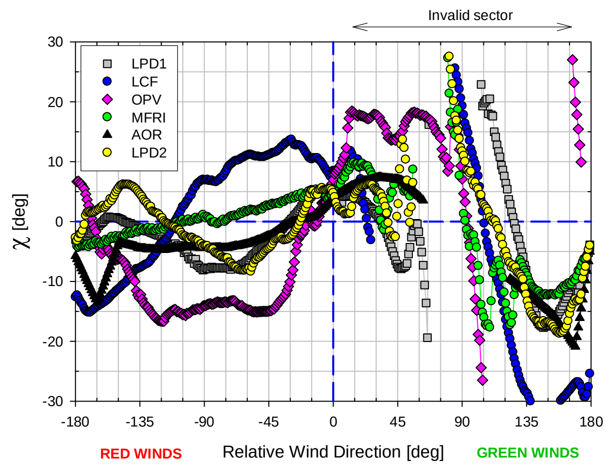

Figure 4; Port anemometer locations, χ

Lessons learned: Ship Environment

Based on the above discussions, the following lessons learned for the ship environment related to shipboard 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.

HELICOPTER ITEMS

The first step in the flow chart for SHOL development, as shown in Figure 2, distinguishes between environment and helicopter items. In this section processing flight test data gathered during different shore-based hover trials is discussed, and how this data is then used to construct the CFE. Once available, the helicopter flight test results are saved into look-up tables in order to be used for future helicopter-ship interface trials. There is a distinction expressed in the so-called "*rejection criteria*" between performance, control position, helicopter attitude and subjective related issues [1,4]. The shore-based hover trials were conducted 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 high Outside Air Temperature (OAT), equivalent to 34.8º C at sea level with 11 000 kg maximum take-off weight [5,6]. 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 (relative to international standard atmosphere), and ω is the relative rotorspeed (relative to a standard rotor speed value). These targeted referred weights are set as the operational weight bands for shipboard operations.

NH90 NFH helicopter

The NH90 NFH is a twin engine, medium weight maritime 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 Engines 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 example, 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, which only provides torque required for dead-ahead conditions. A dedicated pace-car, as shown in Figure 5, 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 5; 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 shipboard 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 relative to the achieved rate of climb. The climb performance data are used to ensure adequate power margins are maintained, once influenced by the ship's airwake.

For subjective ratings, three scales are used [3]: 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. These subjective ratings should be used with care, as there are 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.

Referred parameters. 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. As such, 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 compare data points flown during different missions of the test campaign with each other.

Since only the performance of the NH90 NFH is considered in this paper, the linear dimensions of rotor radius and rotor 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*' [7]. For example, the referred parameters for the torque required can be expressed by the relationship:

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

where Q_{req} is torque required, V is true airspeed, V_c is rate of climb, Z is height, θ is relative temperature and ζ is the relative wind direction from the nose of the helicopter. Within the dynamic ship environment, the benefits of ground effect should be considered negligible for planning purposes [8]. Hence, only Out-of-Ground Effect (OGE), low speed, conditions are tested without any vertical speed. The before mentioned expression then shows that the performance of the helicopter is predominantly influenced by the referred weight, the relative wind speed and direction (airwake in the vicinity of the ship), and the rotorspeed setting:

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

Note that, although not further discussed, for the NH90 NFH at 11 750 kg referred weight, the torque required is still the limiting performance parameter and thus not the engine gas generator speed N_g or engine power turbine inlet temperature T_{46} [6].

Error analysis. Errors in flight test measurements introduce the inevitable uncertainty that is inherent to 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, then by combining the original fractional uncertainties, squaring them, adding the squares and then taking the square root of the result (i.e. "summation in quadrature"), the final 'error' becomes a reliable indicator of overall uncertainty [9]. This is allowed when the measurements are independent and subject to random uncertainties. Relative errors in referred torque required are determined, for example by [1]:

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

where δQ_{req}, etc., are the uncertainties in the measurements of Q_{req}, 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 costs of a trial, the alternative is to repeat the measurements a number of times to acquire acceptable confidence in the results. However, increased flying time is likely to be a more expensive option than an improved instrumentation fit.

Lessons learned: Helicopter

Based on the above discussions and the key facts mentioned in reference [4], the following lessons learned for the helicopter flight characteristics related to shipboard 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 comprehensive 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 in an increase in 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 Angle Of Bank (AOB), pitch attitude, lateral cyclic, longitudinal cyclic and pedal position.

CANDIDATE FLIGHT ENVELOPE

Once the environment and helicopter items are determined and validated, the final reliable data are saved into look-up tables. Thereafter, when combining the behaviour of the isolated NH90 NFH 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 serves as the starting point for sea trials. In fact, the CFE is the preliminary SHOL 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 [4]:

- Torque required for the lower relative wind speeds;
- Pitch attitudes around green 30 at 30 knots;
- Roll attitude in red wind conditions;
- 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 a mid centre of gravity in Figure 6 to Figure 8 respectively. For all three referred weights, 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. 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.

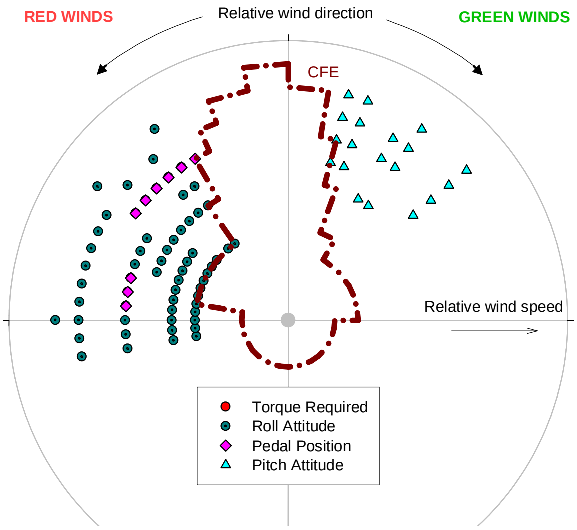

Figure 6; CFE 10 000 kg referred weight

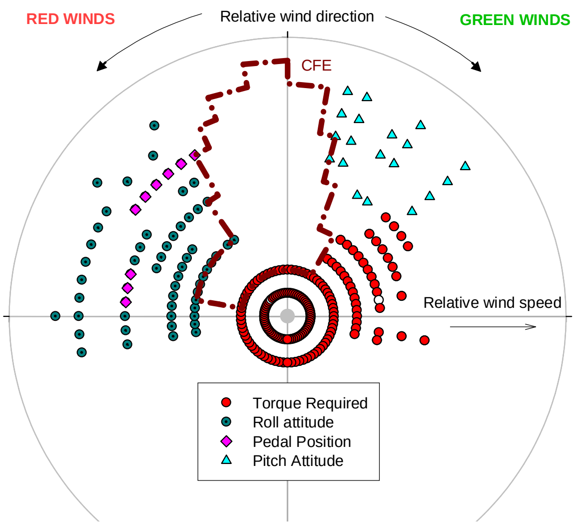

Figure 7; CFE 11 000 kg referred weight

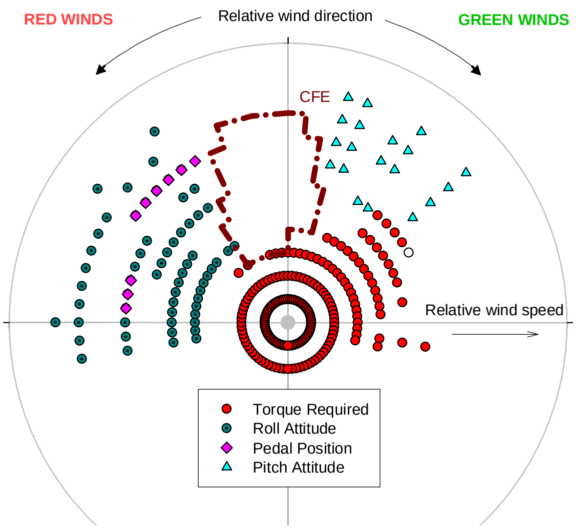

Figure 8; CFE 11 600 kg referred weight

Lessons learned: CFE

Based on the above discussions and the examples Figure 6 to Figure 8, the following lessons learned 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 the sea trials is to determine the effects on pilot workload from, for example, 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. For this higher referred weight the boundaries of the SHOL envelope are established first, and once determined, the original lower referred weight is re-selected and these boundaries are expanded further outwards. This method results in a so-called "*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, is shown in Figure 9 to Figure 11 respectively. 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 12 to Figure 14 respectively.

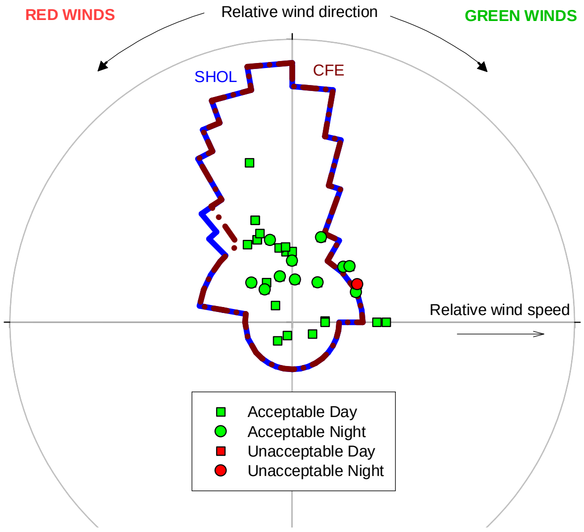

Figure 9; Subjective 10 000 kg ref weight

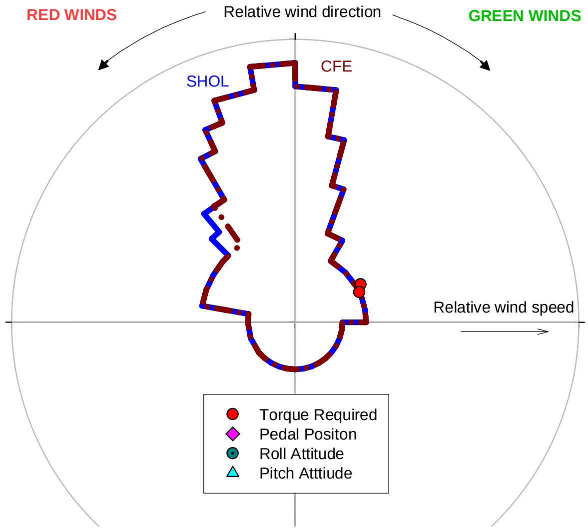

Figure 12; Objective 10 000 kg ref weight

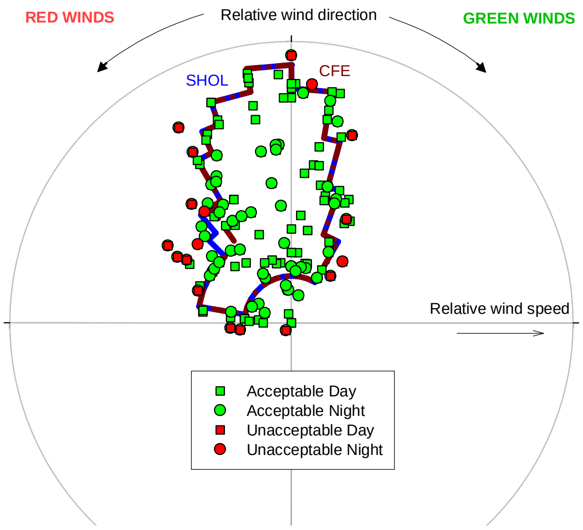

Figure 10; Subjective 11 000 kg ref weight

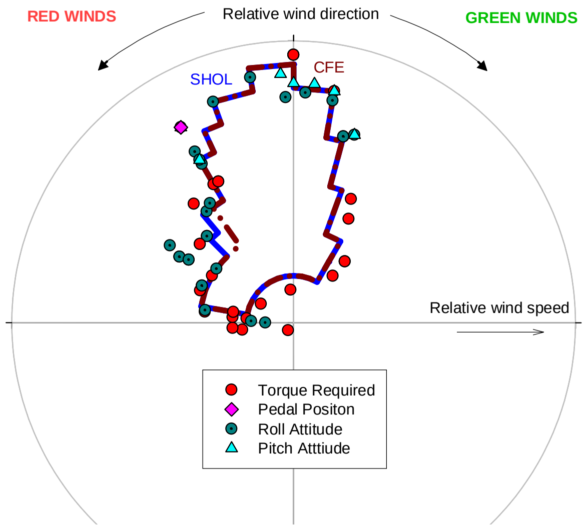

Figure 13; Objective 11 000 kg ref weight

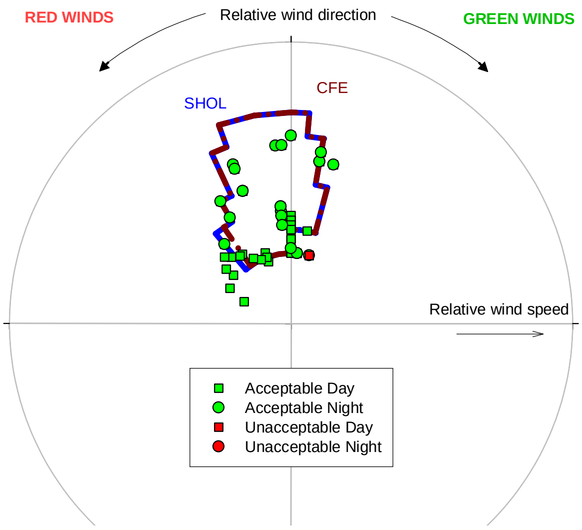

Figure 11; Subjective 11 600 kg ref weight

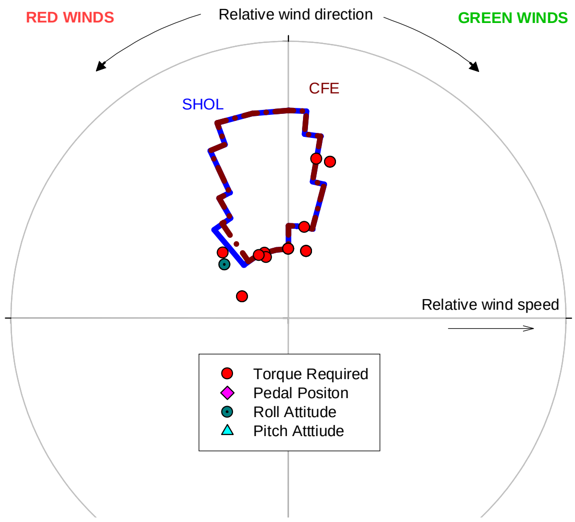

Figure 14; Objective 11 600 kg ref weight

The 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 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 whether there is still room for expansion of the envelope.

In the examples, 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 turbulence caused by the ship's superstructure, which also causes large pitch and roll attitude deviations of the helicopter. 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 fully 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 having enough confidence in the CFE, the NH90 NFH has been released to service. This was only achievable because a comparison between both subjective and objective test results could be made, providing an optimal insight of the boundaries for the SHOL envelope. This indicates the importance of the software tool "*SHOL-X*" as a predictive tool for all follow-up helicopter-ship qualification testing. The order of magnitude in savings for the sea trials in time required and flight hours consumed for it are roughly 66%. This is equivalent to a reduction in time required for the sea trials from a three week period towards a seven day period, and a reduction from at least 45 flight hours towards a maximum of 15 flight hours required.

Visual references

An important item of the sea trials is to assess the adequacy of the visual references on board each ship. The visual references are important for the pilot to position the helicopter above the landing grid such that, if fitted, the deck lock system could be immediately engaged once landed on-deck. Some examples of the lessons learned in visual references are summarized in this section.

Deck markings. The flight deck markings (white lines painted on the flight deck) should be matched with the take-off and landing procedures (e.g. fore-aft, oblique and cross-deck). For example, in Figure 15 an oblique line is missing in a 45° azimuth from the ship's heading. In this case, a simple solution would be to paint a line at 45° from the ship's heading starting from the landing grid running towards the deck edge. Other meaningful deck markings are the so-called "*bumline*" running from left to right across the flight deck to judge fore-aft position, and a vertical line on the hangar door to judge lateral position.

Figure 15; Missing 45° line on the deck

Night vision compatibility. The light settings of the ship should allow both for aided and unaided flight operations. In Figure 16 an example is shown of the green Stop & Go light taped, as even in the minimum light setting the green light was too bright for the Night Vision Goggles (NVG). Thus, it is required to ensure that the light setting of the ship could be readily adapted to both aided and unaided flight operations.

Figure 16; Taped green Stop & Go light

Field of View. The field of view from the cockpit should be free of obstructions, where possible, to allow the pilot maximum visual references with the ship. Unfortunately, the horizontal bar of the cockpit door window in the right hand side resulted, in multiple occasions, in temporarily loss of visual reference with the Flight Deck Officer (FDO) as shown in Figure 17. The FDO provides take-off and landing instructions to the pilot and losing sight considerably increases pilot workload. It is required during the development phase of a (maritime) helicopter to optimize the field of view such that various take-off and landing procedures are achievable with adequate visual references throughout.

Figure 17; Obstruction horizontal bar in door

Ship motion

In general, ship motion is predominantly important once the helicopter is on-deck and not for take-off and landing. The pilot always tries to touch down or take-off the helicopter when the ship is in a quiescent state with minimal deck motion. Once landed and tied-down to the flight deck with lashings, the helicopter is dependent on the behaviour of the ship in the environment. In case the ship motion drastically increases the tension on the lashings may become excessive, and the lashings could ultimately break with a risk for the helicopter to turn-over to the side. Operational aspects to consider with increased ship motion are limitations for spinning-up and stopping of the main rotors, and for moving the helicopter from the hangar towards the landing spot and vice versa. For this reason, operational envelopes should also be established for the helicopter once secured on the flight deck, for spinning-up and stopping the main rotors and for moving the helicopter into and out of the hangar. These deck handling envelopes should preferably be larger than the ship motion limitations for take-off and landing. Note that the development of deck handling envelopes could be supported with simulation tools and mock-ups of the helicopter to determine the maximum operational capability without the risk of damaging the helicopter.

Turbulence

The turbulence levels associated with the ship airwake generally increase in intensity with relative wind speed, and vice versa, as shown in Figure 18. In addition the turbulence levels are related to the relative wind direction, as shown for red quartering winds, where the turbulence levels are generally higher than for head winds at the same relative wind speed. The areas with increased turbulence levels in the vicinity of the ship cause torque spikes, increased control activity, considerable pitch and roll motion of the helicopter and higher pilot workload. The turbulence level is the main cause of the upper boundaries of the operational envelopes.

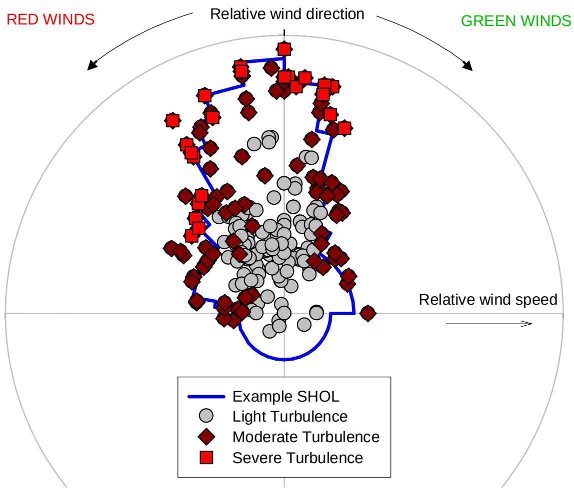

Figure 18; Example turbulence levels airwake

Combined sea trials results

The combined results of the SHOLs for each ship type within the Dutch fleet have a large similarity shown by the blue line in Figure 19. This indicates that when the anemometer corrections are made correctly the SHOL boundaries are mainly helicopter related and thus not ship related. The discrepancies in the upper boundaries of the envelope are caused by i.e. the differences in turbulence level for each ship type with increasing relative wind speed, and the boundary layer effect. The variations in turbulence are caused due to for example the height of the hangar and/or the distance between the landing spot in relation to the hangar. The variations in boundary layer are caused due to the height of the anemometers above sea level which are not compensated for by the WCA. In general, the higher the anemometers are above sea level, the higher the exponential increase in indicated wind speed, whilst the local wind speed at the height of the flight deck remains similar. The discrepancies in the starboard boundaries of the envelope are mainly caused by the strength of the downdraft on the leeward side of the ship, thus primarily the dimensions of the ship. The port and lower boundaries of the envelope in this example are caused by differences in the anemometer readings between the various ships (as not all ships were yet equipped with a WCA).

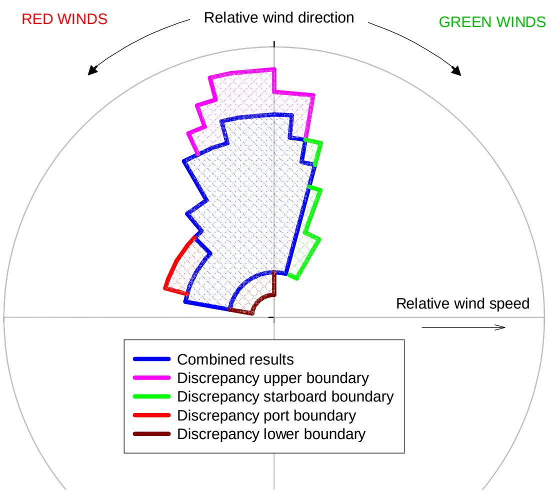

Figure 19; Combined sea trial results

It is a fundamental prerequisite of efficient helicopter-ship interface testing to understand that the operational limitations are mainly caused by the helicopter flight characteristics, and not the ship type, once the anemometer corrections are applied correctly towards the undisturbed relative wind. This allows for quick exploration of the potential boundaries for each ship type without wasting time to pursue the boundaries with a conservative incremental approach. In this way, potential losses are avoided of valuable time and/or useful environmental conditions which could not be compensated for at a later stage of the test campaign.

Lessons learned: Sea Trials

Based on the above discussions, the following lessons learned from the sea trials are observed:

1. A so-called "*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 the effects on pilot workload, for example, visual references, ship motion and turbulence;
4. 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;
5. When the anemometer corrections are made correctly the SHOL boundaries are mainly helicopter related and thus not ship related.

CONCLUSIONS

The lessons learned in establishing NH90 NFH shipboard operational limitations are summarized in this paper. When the described methodology is applied correctly, and when the anemometer corrections are made for each ship type, the operational boundaries of the SHOL envelope are mainly helicopter related and thus not ship related. In addition, due to an accurate prediction of the CFE potential losses are avoided of valuable time and/or useful environmental conditions which could not be compensated for at a later stage of the test campaign. Aided by a predictive software tool, named *"SHOL-X"*, which eliminates subjective elements to the largest possible extend in order to determine operational envelopes for in-service conditions, the Netherlands Ministry of Defence was able to achieve tremendous savings in time and expenses of helicopter-ship qualification test campaigns. The order of magnitude in savings for the sea trials in time required and flight hours consumed for it are roughly 66%. This is equivalent to a reduction in time required for the sea trials from a three week period towards a seven day period, and a reduction from at least 45 flight hours towards a maximum of 15 flight hours required. 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 to flight safety, this paper has the ambition to function as the starting point for international regulations or standard procedures to conduct helicopter-ship interface testing.

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