PREDICTION OF REJECTION CRITERIA FOR SHIP HELICOPTER OPERATIONAL LIMITATION QUALIFICATIONS

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The Ship Helicopter Operational Limitation qualification programs are based on so many independent variables that the full operational potential is almost impossible to achieve within the small window allowed for sea trials. It would be a clear advantage to have a predictive engineering tool to perform early evaluation of safety limits for operating aircraft from ships in a wide range of in-service conditions. For this reason a predictive software tool is developed based on specific rejection criteria for each helicopter type and their dependencies in the ship environment. The predictive capacity leads to an improved set-up of the test campaign, whether during shore-based hover trials or sea trials, allowing accurate analyses of data collected. The model could be used for determination of the Candidate Flight Envelope for each ship type allowing larger steps in an incremental approach towards flight envelope restrictions, sensible exclusion of test points and accurate read-across between other helicopter-ship combinations. It should be highlighted that the software model is set up in such away that safe operating envelopes from oil rigs and pinnacles can also be determined.

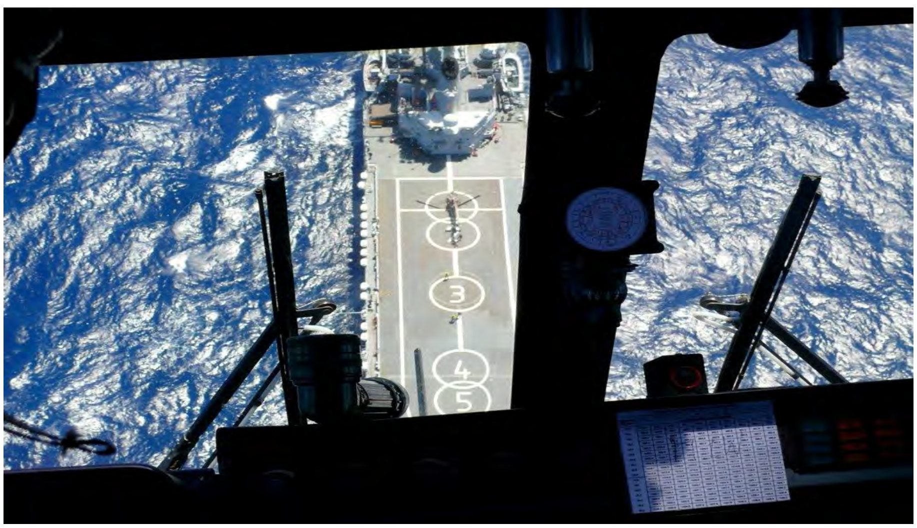

Figure 1; Multi-spot operations

1 Introduction

The qualification process currently used for determination of Ship Helicopter Operational Limitations (SHOL) by the Netherlands Ministry of Defence has proven to be a useful approach. In general the qualification process consists of two independent items resulting in the Candidate Flight Envelope (CFE) for sea trials, namely the determination of the environment near the ship deck and the helicopter flight characteristics during shore-based hover trials [1, 2]. Unfortunately there are some major drawbacks in this current qualification approach, which include but are not limited to: dependency on encountered environmental conditions, dependency on subjective opinions from few pilots and major costs due to a very long planning process in which everything must come together. The resulting SHOL is solely based on acceptable test points achieved during dedicated sea trials. However, it occasionally happens that either

Presented at the European Rotorcraft Forum 36th, Paris, France, September 7-10, 2010.
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due to the prevailing weather conditions or aircraft availability the limits of the aircraft can not be fully explored in some areas or at some masses. Each helicopter-ship combination is based on so many independent variables that the full operational potential is almost impossible to achieve within the small window allowed for sea trials. For this reason the United Kingdom approach uses qualitative methods to assess whether the obtained results are sufficiently comparable to those obtained from other ships. If sufficient comparable data exits, and similar results can be obtained from it, then it may be warranted that based on qualitative analysis the SHOLs are extended, and envelops are determined within reasonable limits [3].

For the above reasons, it will be a clear advantage in the SHOL qualification process, to have a quantitative engineering software 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 accuracy of the resulting SHOL, to be used for in-service operation for many years to come. For this reason the early evaluation of safety limits for operating aircraft from ships in a wide range of sea states and atmospheric conditions must be improved for three main issues:

1. The diversity of data gathered for certification of new helicopter types and new naval platforms generates a laborious task in accurate analyses and development of appropriate SHOL envelopes for all conditions encountered during in-service operations.
2. The planning and expenses associated with the test campaign are enormous, requiring both ship and helicopter to be dedicated for longer periods of time to sea trials instead of primary operational demands. Every resource saved in the test campaign can alternatively be used to meet the requirements of the operational theatre.
3. It has become clear that such operational factors could already be addressed early in the test campaign – which of necessity involves developing a predictive capacity in all the areas which influence operational capability.

2 Test campaign

2.1 General

Deciding on what approach to take in order to achieve the technical test objectives depends on a number of factors such as the resources available. The data does not necessarily need to be obtained from a flight conducted during trials; more so as flight testing is such an expensive activity, other sources of data should invariably be considered first. These sources can be the aircraft manufacturer that has conducted the required tests, earlier test results conducted at the establishment, read across from other similar aircraft, another test organization, or possibly an operator who already has experience with the test article. In each case the evidence and the source should be evaluated carefully to determine to what extent it can be relied upon.

If the existing evidence can be considered reliable, it may be used without further testing or, more likely, after executing a limited number of tests, in order to 'spot check' the evidence and increase the confidence of the validity. After reviewing the available dataset the gap towards the minimally required dataset can be established, and it is this gap that the flight trials must address. As such the scope of the test is defined. Based on this pre-work a detailed work breakdown structure can be drafted, including test techniques, test instrumentation, required environmental conditions, trial locations, the order and interdependency of tests, and the allocation of tasks to parts of the organization.

Furthermore, it is important to have a trials closure procedure which ensures that all the data gathered is retained. This data may be required to provide baseline information for comparison purposes when the aircraft is modified in the future. A 'lesson learned' system is also maintained where information concerning mistakes, problems, solutions and good ideas can be retained even though the trials participants may move on.

2.2 Predictive software tool

To allow accurate determination of the SHOL for all conditions encountered during in-service operation a new software tool, to be presented in this paper, is under development with five main application areas:

1. CFE. The software tool can be used for the construction of the CFE in order to indicate dangerous areas and thereby allowing larger steps in difficulty for an incremental approach;
2. Testpoint exclusion. It allows testing for worst case conditions by sensible exclusion of test points in the test matrix (i.e. day/night conditions and multiple spots);
3. Read-across. It can be used for read-across between other helicopter types which are validated to operate from the same ship class;
4. Certification. Once enough confidence is established in the model it can be used for certification purposes without conducting complete and sometimes redundant sea trials;
5. Miscellaneous. Besides SHOL analyses the model can be used for establishing safe operating envelopes from oil rigs and rooftop helipads.

The predictive capacity leads to an improved set-up of the test campaigns conducted for helicopter-ship certification, both conducted during shore-based hover trials and sea trials, allowing accurate analyses of data collected. Its predictive capacity consists in previous existing knowledge related to the certification trials performed for a particular type of helicopter operating on a specific ship and all possible combinations afterwards. Although the data collected for each test point is mainly valid for that particular relative wind condition, underlining the need for 360° testing, it can be easily adapted to represent several environmental conditions and aircraft configurations. The software tool consequently presents the data in a form that makes it easy to determine which pre-set margins are exceeded and for which relative wind conditions this applies as shown in Figure 2. This data is plotted together with the relative wind envelope coming from the flight manual, and the maximum safe operating envelope that allows for lateral positioning above the flight deck and safety considerations for example for tail wind conditions. Consequently, the undisturbed relative wind envelope can be readily drawn around the areas indicating problems, while the ship envelope automatically shows the envelope which could be released for in-service operations for that particular ship type taking anemometer correction into account (known as SHOL).

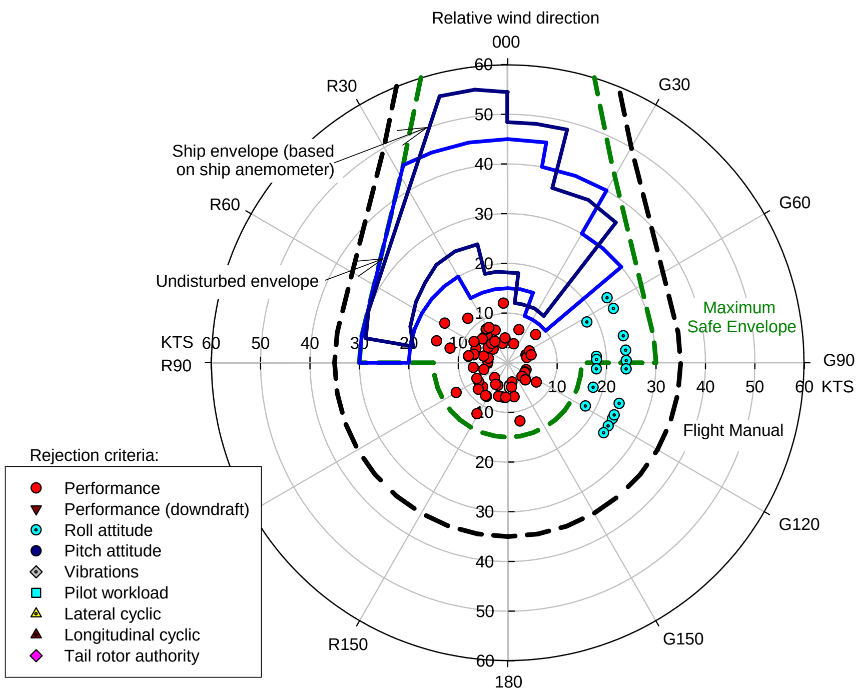

Figure 2; Example predictive software tool plots

3 Rejection criteria

3.1 General

The split between rejection criteria and dependencies in collected test data enables: assessing all other conditions for in-service operations, forms the basis for proper read-across and determines exclusion of test points. For example, the SHOL for a heavy aircraft at night with significant deck motion is considerably smaller, compared to more favorable conditions. The definitions for rejection criteria and dependencies are:

- ***Rejection criteria*** are quantitative and qualitative aircraft parameters which, once exceeded, prevent safe execution of a flight phase.
- ***Dependencies*** are variables in a flight phase which directly influence their related rejection criteria.

Rejection criteria and how they are influenced by dependencies are determined for new aircraft or as a consequence of significant changes to an old aircraft which might affect low speed performance or handling qualities. Once validated test results are collected it can be used for future helicopter-ship qualification trials. The software tool is based on processing a network of data, and allows all relevant rejection criteria and dependencies to interact with each other. A summary of the most common rejection criteria and their dependencies is shown in Table 1. There is a distinction made between performance, control position, subjective and aircraft attitude related issues. It further shows at what time during the test campaign data is gathered and processed in the software tool.

3.2 Performance rejections

The transmission and engine performance rejection criteria are summarized as follows [4]:

a. Performance rejection;
b. Performance safety margin rejection.

Item	Rejection criteria	Dependencies	Data gathered
		Performance rejection criteria	
1	Performance	Relative wind (airwake), Referred weight, Configuration	Flight manual, Shore-based trials, Sea trials
2	Performance safety margin	Relative wind (airwake), Referred weight, Visual reference, Ship motion	Shore-based trials, Sea trials
		Control position rejection criteria	
3	Tail rotor authority	Relative wind (airwake), Referred weight, FCMC	Ground assessment, Shore-based trials, Sea trials
4	Lateral Cyclic	Relative wind (airwake), Referred weight, CG, FCMC	Ground assessment, Shore-based trials, Sea trials
5	Longitudinal Cyclic	Relative wind (airwake), Referred weight, CG, FCMC	Ground assessment, Shore-based trials, Sea trials
6	Control safety margins	Relative wind (airwake), Referred weight, Visual reference, Ship motion	Shore-based trials, Sea trials
		Subjective rejection criteria	
7	Vibrations	Relative wind (airwake), Referred weight	Shore-based trials, Sea trials
8	Pilot workload	Relative wind (airwake), Referred weight, Visual reference, Ship motion	Shore-based trials, Sea trials
		Aircraft attitude rejection criteria	
9	Roll attitude	Relative wind (airwake), Referred weight, CG, FOV	Ground assessment, Shore-based trials, Sea trials
10	Pitch attitude	Relative wind (airwake), Referred weight, CG, FOV	Ground assessment, Shore-based trials, Sea trials

Table 1; Rejection criteria and dependencies

a. Performance rejection. Methods for measuring the steady-state performance of gas turbine-engined helicopters commonly use non-dimensional parameters. These parameters consist of groups of relevant dimensional quantities arranged by means of dimensional analysis. Performance flight test have as an objective to determine the relationship between pairs of non-dimensional parameters whilst the others are held constant. This experimental method of testing reduces any limitations in the applicability of performance test data. Data converted into non-dimensional form can be 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 tests, at carefully chosen test sites, can produce information relevant to a large part of the helicopters flight envelope.

Since usually the performance of a single model of helicopter is considered at any given time, the linear dimensions of rotor radius, chord and disk area are omitted. For a similar reason ambient pressure, temperature and density are expressed as ratios of the standard sea level conditions. Likewise, rotor speed is expressed as a percentage of some reference or standard value. This, of course, means that the groups have become dimensional although they still contain the required information. These modified groups are termed '*referred*'. Consider the class book example of helicopter in a climbing flight at low level modeled with the parameters as shown in Table 2 [5]. The dimensional parameters in the last column are: *M* for mass, *L* for length and *T* for time. Note that the local speed of sound has been included as a means of accounting for compressibility effects on the lift and drag characteristics of the rotor blade. So as the performance is influenced by all these parameters:

$$P = f\left(W, V, V_c, Z, a, \rho, \Omega\right)$$

Using dimensional analysis the exact relationship can be determined:

$$P = K\left[(W)^{\alpha}, (V)^{\beta}, (V_c)^{\gamma}, (Z)^{\delta}, (a)^{\varepsilon}, (\rho)^{\eta}, (\Omega)^{\tau}\right]$$

Item	Meaning	Unit	Parameter
P	Power required (Watt)	kgm²/s³	ML^2T^{-3}
W	Weight	kgm/s²	MLT^{-2}
V	Forward speed	m/s	LT^{-1}
V_c	Rate of climb	m/s	LT^{-1}
Z	Height (AGL)	m	L
a	Speed of sound	m/s	LT^{-1}
ρ	Ambient density	kg/m³	ML^{-3}
Ω	Rotor speed	1/s	T^{-1}

Table 2; Dimensional parameters [5]

Substituting dimensions from Table 2:

$$ML^2T^{-3} = K\begin{bmatrix}\left(MLT^{-2}\right)^{\alpha}, \left(LT^{-1}\right)^{\beta}, \left(LT^{-1}\right)^{\gamma}, \\ (L)^{\delta}, \left(LT^{-1}\right)^{\varepsilon}, \left(ML^{-3}\right)^{\eta}, \left(T^{-1}\right)^{\tau}\end{bmatrix}$$

Equating indices:

$$\begin{aligned} M:&\quad 1 = \alpha + \eta \\ L:&\quad 2 = \alpha + \beta + \gamma + \delta + \varepsilon - 3\eta \\ T:&\quad -3 = -2\alpha - \beta - \gamma - \varepsilon - \tau \end{aligned}$$

Now eliminate powers for a, ρ, Ω, thus find values for ε, η, τ:

$$\begin{aligned} \varepsilon &= 2 - \alpha - \beta - \gamma - \delta + 3\eta \\ \eta &= 1 - \alpha \\ \tau &= 3 - 2\alpha - \beta - \gamma - \varepsilon \end{aligned}$$

Substituting the result for η into the equation for ε and the result for ε into the equation for τ gives:

$$\begin{aligned} \varepsilon &= 5 - 4\alpha - \beta - \gamma - \delta \\ \eta &= 1 - \alpha \\ \tau &= -2 + 2\alpha + \delta \end{aligned}$$

Hence:

$$P = K\begin{bmatrix}(W)^{\alpha},(V)^{\beta},(V_c)^{\gamma},(Z)^{\delta},(a)^{(5-4\alpha-\beta-\gamma-\delta)}, \\ (\rho)^{(1-\alpha)},(\Omega)^{(-2+2\alpha+\delta)}\end{bmatrix}$$

Gives:

$$P = K\left[\left(\frac{W\Omega^2}{\rho a^4}\right)^{\alpha},\left(\frac{V}{a}\right)^{\beta},\left(\frac{V_c}{a}\right)^{\gamma},\left(\frac{Z\Omega}{a}\right)^{\delta},\left(\frac{\rho a^5}{\Omega^2}\right)\right]$$

Where $\omega = \Omega/\Omega_0$ and $\sigma = \rho/\rho_0$, while noting that the reference values Ω_0 and ρ_0 are themselves constant:

$$P = K\left[\left(\frac{W\omega^2}{\sigma a^4}\right)^{\alpha},\left(\frac{V}{a}\right)^{\beta},\left(\frac{V_c}{a}\right)^{\gamma},\left(\frac{Z\omega}{a}\right)^{\delta},\frac{\sigma a^5}{\omega^2}\right]$$

Noting that a is a function of ambient temperature $a = \sqrt{\gamma RT} = K_1\sqrt{T} = K_2\sqrt{\theta}$ and $\theta = T/T_0$, gives:

$$P = K\begin{bmatrix}\left(\frac{W\omega^2}{\sigma\theta^2}\right)^{\alpha},\left(\frac{V}{\sqrt{\theta}}\right)^{\beta},\left(\frac{V_c}{\sqrt{\theta}}\right)^{\gamma}, \\ \left(\frac{Z\omega}{\sqrt{\theta}}\right)^{\delta},\frac{\sigma\theta^2\sqrt{\theta}}{\omega^2}\end{bmatrix}$$

Reorganizing and collecting like terms by extracting $\omega/\sqrt{\theta}$ produces the $'W/\sigma'$ referred power relationship:

$$P = K\begin{bmatrix}\left(\frac{W}{\sigma\omega^2}\cdot\frac{\omega^4}{\theta^2}\right)^{\alpha},\left(\frac{V}{\omega}\cdot\frac{\omega}{\sqrt{\theta}}\right)^{\beta}, \\ \left(\frac{V_c}{\omega}\cdot\frac{\omega}{\sqrt{\theta}}\right)^{\gamma},\left(Z\cdot\frac{\omega}{\sqrt{\theta}}\right)^{\delta},\sigma\omega^3\cdot\left(\frac{\sqrt{\theta}}{\omega}\right)^{5}\end{bmatrix}$$

Collecting $\omega/\sqrt{\theta}$ as common factor in the above expression results in:

$$P = K\begin{bmatrix}\left(\frac{W}{\sigma\omega^2}\right)^{\alpha},\left(\frac{V}{\omega}\right)^{\beta},\left(\frac{V_c}{\omega}\right)^{\gamma}, \\ Z^{\delta},\sigma\omega^3,\left(\frac{\omega}{\sqrt{\theta}}\right)^{4\alpha+\beta+\gamma+\delta-5}\end{bmatrix}$$

Finally the $'W/\delta'$ power required relationship becomes:

$$\frac{P}{\sigma\omega^3} = K\begin{bmatrix}\left(\frac{W}{\sigma\omega^2}\right)^{\alpha},\left(\frac{V}{\omega}\right)^{\beta},\left(\frac{V_c}{\omega}\right)^{\gamma}, \\ Z^{\delta},\left(\frac{\omega}{\sqrt{\theta}}\right)^{\lambda}\end{bmatrix}$$

Hence we can write, whilst knowing the relationship between performance and torque (Q):

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

Note that the forward speed and rate of climb have been expressed as advance ratios. Since measuring air density is difficult, an alternative grouping can be obtained by replacing σ with δ/θ. This is called the $'W/\delta'$ referred power relationship which, although easier to use since it lacks air density, cannot be used for rotorcraft with fixed rotor speed [5].

The selection of specific values or ranges for each non-dimensional parameter will depend on the required results, the available flying time and the likely atmospheric conditions at the test site. The climb performance is 'spot checked', while the steady state data is collected during pace-car trials through 360º in ±15º and ±5 knot increments up to the maximum permitted side and tail wind limits (as the flight manual does only provide performance data for dead ahead wind conditions). This is done at values of referred weights, $W/\sigma\omega^2$, which have been chosen as the operational weight bands for use on board ships. Within the ship environment the benefits of ground effect are considered negligible, hence only OGE low speed conditions are tested. The test data can be presented and adjusted with the software tool so that it shows the problem areas for all azimuths as shown in Figure 3. For the areas where the required performance exceeds the maximum achievable limit it will be rejected and excluded from the SHOL.

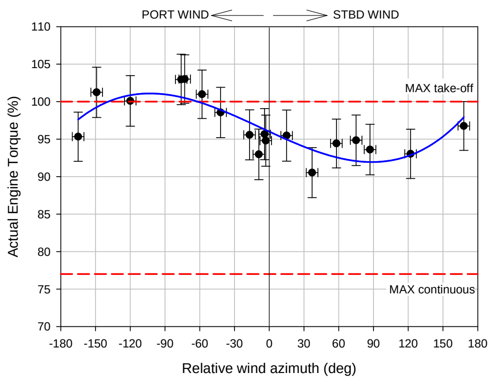

Figure 3; Example performance issues

It is often an objective of a flight test to determine the parameter that will limit the performance of a helicopter under the atmospheric conditions specified in a role specification. Under certain atmospheric conditions, usually hot and high, the engines, rather than the transmission will limit the performance. It is therefore necessary to determine the precise limiting factor for the conditions specified. The analysis is relatively simple but requires access to engine performance data. The analysis continues by obtaining the actual limiting values from the aircraft manual, called Q_{LIMIT}, T_{LIMIT} and N_{LIMIT}. Using the pressure height and specified air temperature these values are calculated as follows [5]. Transmission Limited Referred Power (TLRP):

$$TLRP = \frac{Q_{LIMIT}\omega}{\delta\sqrt{\theta}}$$

The Engine Temperature Limited Referred Power (ETLRP) is determined using a figure of referred power $P/\delta\sqrt{\theta}$ against referred engine temperature T/θ, as shown for T6 in Figure 4, and the value:

$$ETLRP = \frac{T_{LIMIT}}{\theta}$$

The Engine Speed Limited Referred Power (ESLRP) is determined using a figure of referred power $P/\delta\sqrt{\theta}$ against referred engine speed $N/\sqrt{\theta}$, as shown for Nh in Figure 5, and the value:

$$ESLRP = \frac{N_{LIMIT}}{\sqrt{\theta}}$$

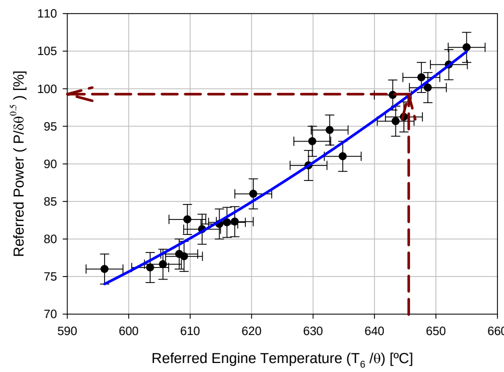

Figure 4; Example engine test data – temp

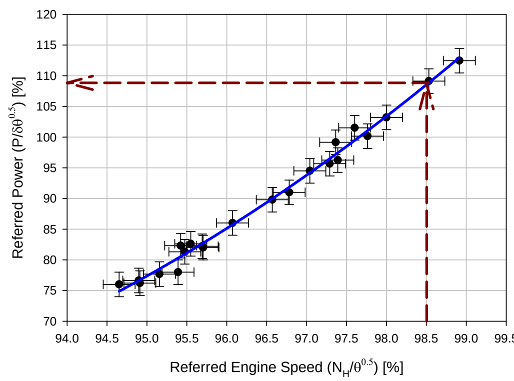

Figure 5; Example engine test data – speed

If either the ETLRP or the ESLRP is less than the TLRP then the performance will be engine limited under the conditions specified. It is now possible to determine the maximum performance available, for each referred weight band for SHOLs, for the most conservative parameter. Choose the Lowest limited Referred Power, now called LRP_{MIN}, and calculate the Maximum Available Referred Power (MARP) from:

$$MARP = \frac{P_{MAX}}{\sigma\omega^3} = \frac{LRP_{MIN}}{\left(\omega/\sqrt{\theta}\right)^3}$$

Using a graph of referred power required $P/\sigma\omega^3$ against referred weight $W/\sigma\omega^2$, as shown in Figure 6, determines the maximum referred weight for hover OGE using the MARP found earlier. This value is used to determine a variety of performance limiting parameters and is plotted as shown in Figure 7, indicating limiting parameters for other possible environmental conditions.

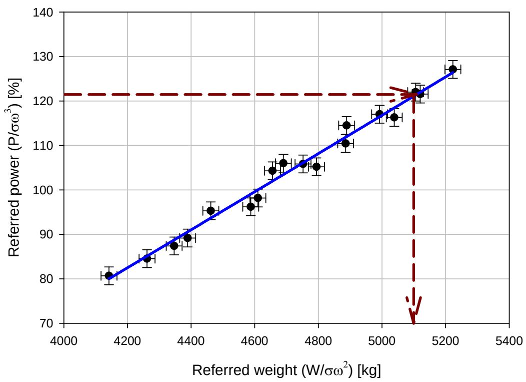

Figure 6; Example limiting performance

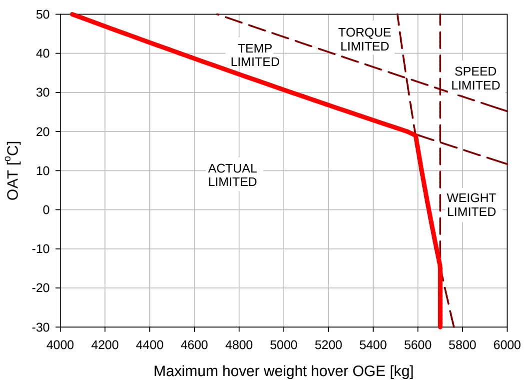

Figure 7; Example limits in hover

b. Performance safety margin rejection. The steady-state aircraft performance is calculated with the equations previously described. However, in addition to the steady-state performance an additional safety margin is required to allow the aircraft to be handled while influenced by any relevant dependencies. It is possible that the aircraft can be operated for particular relative wind conditions during daytime, while for identical nighttime conditions, where the visual reference to judge ship motion is decreased, and thus the pilot needs an extra safety margin. The explanation for using and the data gathering procedure for dependencies are described later in this article.

3.3 Other rejection criteria

The control position, subjective and aircraft attitude rejection criteria are summarized as follows [4]:

1. Control position rejection:
    a. Tail rotor authority;
    b. Lateral cyclic position;
    c. Longitudinal cyclic position;
    d. Control safety margins.
2. Subjective rejection:
    a. Aircraft vibrations;
    b. Pilot workload.
3. Aircraft attitude rejection:
    a. Roll attitude;
    b. Pitch attitude.

1. Control position rejection. The low speed envelope Trimmed Flight Control Positions (TFCP) are measured during pace car trials. The TFCP and transients in control position should stay within margins of the control authority to enable the aircraft to be maneuvered towards a trimmed position and maintain it. The aircraft inertia, control power and the expected degree of dependencies will all affect the control margin required and could increase the required control safety margin. For ease of understanding a minimal 10% control margin is internationally used as being representative for this value, although this margin is increased for certain scenarios i.e. increased ship motion and nighttime conditions. An example plot for tail rotor authority is shown in Figure 8.

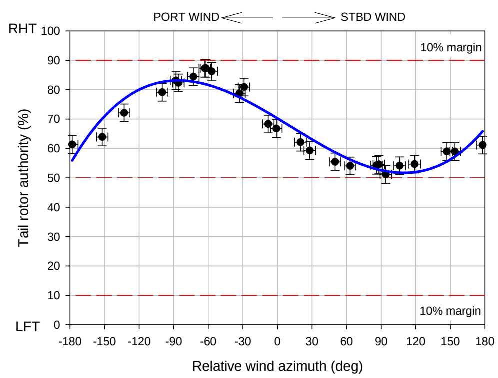

Figure 8; Example tail rotor authority

2. Subjective rejection. The pilot workload is determined during pace car trials, together with an aircraft vibration assessment, to assess the workload associated with obtaining and maintaining a trimmed flight condition as shown in Figure 9. For this purpose the Aeroplane and Armament Experimental Establishment Vibration Assessment Rating (VAR) scale and Deck Interface Pilot Effort Scale (DIPES) are used [6]. It should be kept in mind that within the ship environment pilot workload is also dependent on the relative location between helicopter and ship with its associated visual cues and ship motion. Although the visual cues are mostly dependent on the type of landing and take-off procedure used and not on the relative wind conditions, it does require some testing during sea trials. Furthermore the more pilots used for the trials the more objective the results are with at least a minimum of two test pilots.

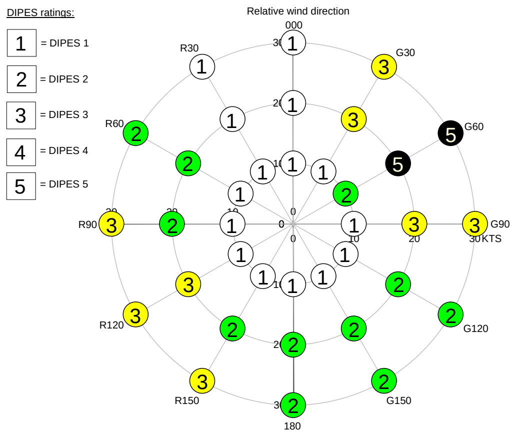

Figure 9; Example pilot workload

3. Aircraft attitude rejection. The trimmed aircraft attitudes for the low speed regime are determined during shore-based hover trials. In correlation with the Field Of View (FOV) diagram determined during ground assessment, it is decided which maximum roll attitude and pitch attitude are possible with enough visual reference for the pilot with the landing site to conduct safe operations. An example plot for roll attitude is shown in Figure 10.

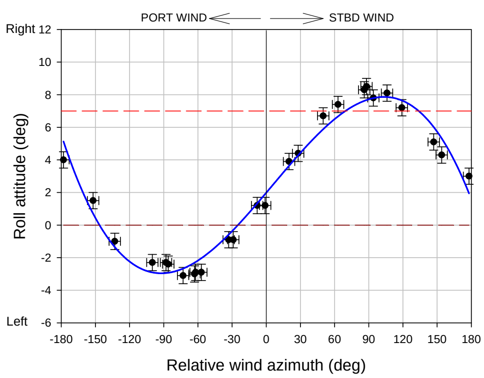

Figure 10; Example roll attitude

3.4 Rejection dependencies

The rejection criteria are influenced by their respective dependencies as summarized in Table 1 [4]:

a. Relative wind (airwake);
b. Referred weight;
c. CG position;
d. Visual reference;
e. Ship motion;
f. Aircraft configuration;
g. Field of View;
h. Flight Control Mechanical Characteristics.

a. Relative wind (airwake). Changing relative wind conditions has considerable influence on rejection criteria. For this reason all low speed testing is conducted for different speeds at 360º to establish those differences. Once these differences are known a unique relation for each relative wind condition can be determined and saved into lookup tables [7, 8]. Now only the relation between ship anemometer and local wind speed across the flight deck, in the approach and in the departure path should be determined for each ship type and the appropriate rejection criteria for each relative wind condition is found in the lookup tables.

b. Referred weight. Testing conducted at the desired referred weight is ensured by fuelling and ballasting the aircraft. The ballast schemes must allow the basic weight of the aircraft to be high enough to cover a number of operating weights by altering fuel state and allow for variation due to different ambient conditions on any one day. External ballast or internal water tanks are required as it can be jettisoned should the aircraft encounter a problem which threatens the safety of the aircraft. This, in combination with fuel state to alter weight, offers the most flexible scheme to cover all the referred weight requirements. The aim is to have the aircraft at its maximum permitted operating weight as soon as possible, as these points will be read down to lower weights and once limits have been established at the higher weight the aircraft can be made lighter to further explore the envelope until new limits are reached. Within the ship environment the referred weight is also influenced by the exhaust path fumes of the ship, which could result in a locally increased OAT.

c. Center of Gravity (CG) position. Testing conducted at the desired CG is ensured by properly ballasting the aircraft. Internal ballast is used to alter CG position, which offers the most flexible scheme to cover all CG requirements. There is potential for reducing the amount of low speed testing required at extremes of CG and/or predicting likely problem areas (in terms of control margins and aircraft attitude) by applying CG corrections from tested conditions towards maximum possible deviations due to CG changes [9] as shown in Figure 11. It should be stressed that these CG correction coefficients are, and should, be applied to all maneuvers conducted in the low speed regime to assess control margins. Sloping ground operations in particular are investigated by assessing the cumulative effect of windspeed, CG, deck motion and the landing itself. This is accomplished by computing the appropriate steady-state control position for hovering with a particular relative wind at a particular CG and adding to this the amount of transient into-slope cyclic required.

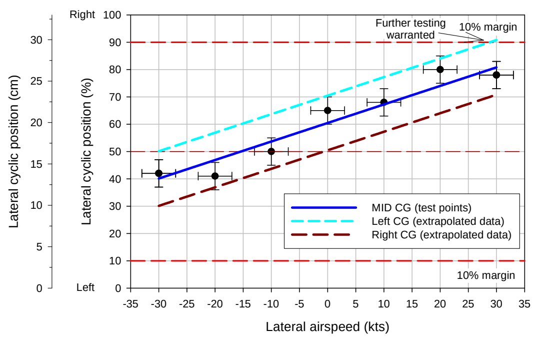

Figure 11; Example CG corrections

d. Visual reference. Some items assessed during sea trials are: horizon bar, deck lighting, deck markings and visual references for different relative positions with the ship. These visual references available to the pilot influence the workload [10]. Although it should be kept in mind that within the SHOL only take-off and landing phases with good visual references close to the superstructure are considered, while these visual references are mainly depended on the type of take-off or landing and not the relative wind condition. Therefore, assigning visual cue ratings for each take-off and landing would complicate the test campaign unnecessarily. For this reason, the SHOL qualification still only differentiates between daytime and nighttime conditions. For nighttime 5% increased safety margins for both power and controls are used (and no tail wind is allowed), while nighttime test points are automatically read-across to daytime conditions. It is investigated with further research if more differentiation then only daytime and nighttime conditions would be beneficial.

e. Ship motion. Ship motions are resulting from amongst others sea state, relative wind/wave direction, loading and ship's speed. During sea trials a certain number of take-off and landings are made for similar relative wind conditions with different ship motion characteristics to establish a relationship with required safety margins for torque and flight controls. This relationship is then applied to assess safety margins up to maximum ship motion for all other test points included in the SHOL. It is investigated with further research how ship motion could be more easily categorized (i.e. displacement, frequency, acceleration) to allow accurate read-across between ship types.

f. Field Of View (FOV). The FOV assessed during ground assessment is aircraft dependent as shown in Figure 12. The FOV in combination with aircraft attitude could results in loss of the landing site and those conditions are rejected.

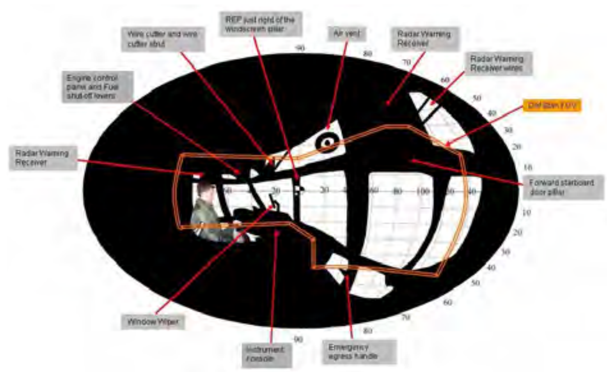

Figure 12; Example FOV diagram

g. Flight Control Mechanical Characteristics (FCMC). The limitations for FCMC are aircraft dependent and are first evaluated during ground assessment. Thereafter, control positions required in flight in combination with pilot percentiles are assessed as shown in Figure 13.

h. Aircraft configuration. The different aircraft configurations could change aerodynamic characteristics and handling qualities. The penalties for performance are determined by the manufacturer and are usually detailed in the flight manual. Testing is preferably conducted in the 'worst-case' configuration for regular in-service operation. This allows the test data to be automatically read-across to all other configurations without any issues.

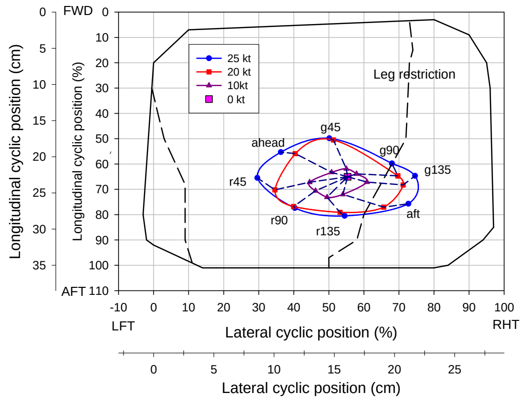

Figure 13; Example FCMC

4 Anemometers

The local wind across the helicopter deck (speed and direction) may strongly deviate from the undisturbed natural wind as the flow gets influenced by the ship's superstructure. For this reason airflow trials along and across the flight deck at various landing points and approach and departure paths are conducted on every ship type. First in the windtunnel (and/or CFD) and thereafter at the actual ship prior to helicopter tests. The aim of these tests is to establish the magnitude of errors in the ship's anemometer system in relation to local wind speed, and to indicate areas of turbulence and down draughting air which may create problems and thus should be approached in cautious and progressive way. This information is vital since, unless the system is of sufficient accuracy, helicopter operations from that ship will not be recommended. It also shows the variation in local wind between landing spots which is used for read-across between spots to reduce the amount of testing. When sea trials are conducted a reference anemometer is always installed on the ship which is an economical way of obtaining the result in a form which is of use during post trial analysis.

Normally the ship is equipped with two anemometers; one on the port side and one on the starboard side of the ship. The system is duplicated for redundancy but also to obtain an unambiguous reading for all wind directions. This is required as anemometer corrections are subjected to several practical deviations, which in turn will lead to erroneous interpretation when not properly handled. These deviations are categorized as follows [11]:

- **System errors.** These are the calibration and system deviations, including deviation caused by up- and down flow. These deviations are determined on a test bench and in a wind tunnel.
- **Position errors.** By mounting a system on a bluff body, the local air flow (speed and direction) at the system's location will deviate from the free air stream. These deviations are measured beforehand in a wind tunnel. The position errors are given separately for the port anemometer and the starboard anemometer system.
- **Alignment error.** This error is caused by misalignment of the system with respect to the centerline of the ship.

For practical purposes it is convenient to couple the measured local flow properties in the helicopter flight area and the data measured at the anemometer positions as follows:

$$C_v = V_{loc} / V_{an}$$
$$\chi_v = \beta_{loc} - \beta_{an}$$

Airflow results are presented for speed and azimuth corrections in Figure 14 and Figure 15 respectively. Those corrections are added to all the results obtained during shore-based hover trials to determine the CFE.

5 Conclusion

A predictive software tool, relying on actual test data, is developed based on specific rejection criteria for each helicopter type and their dependencies in the ship environment. The predictive capacity involves an improved set-up of the test campaign, both conducted during shore-based hover trials and sea trials, allowing accurate analyses of data collected. The model could then be used for determination of the Candidate Flight Envelope for each ship type allowing larger steps in an incremental approach towards flight envelope restrictions, sensible exclusion of test points and accurate read-across between other helicopter-ship combinations. The software model thereby not only reduces time and cost of the test campaign, but also improves the accuracy of the finally determined SHOL used for in-service operation for many years to come.

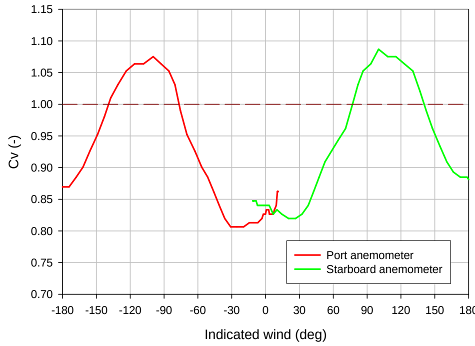

Figure 14; Example speed corrections

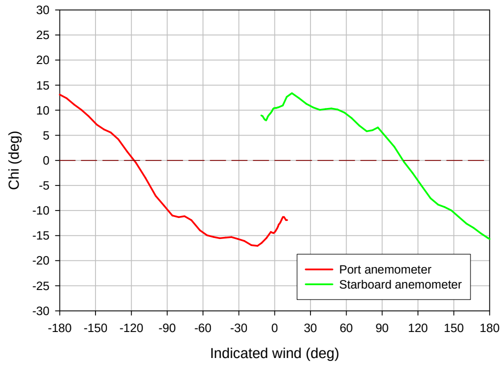

Figure 15; Example azimuth corrections

6 Future work

It is investigated if more differentiation then only daytime and nighttime conditions is beneficial to determine safety margins and how ship motion could be more easily categorized (i.e. displacement, frequency, acceleration) to allow accurate read-across between ship types. Furthermore, the accuracy of the predictive software tool will be determined during the introduction of the NH-90 the coming years. Once enough confidence is established it will be decided to which extend the model could be used for certification purposes without conducting complete and sometimes redundant sea trials.

Acknowledgements

The PhD research is conducted and sponsored by the Netherlands Defense Academy (NLDA). The following persons advise during the research Prof. Th. van Holten and dr. M.D. Pavel from Delft Technical University, Prof. J.V.R. Prasad from Georgia Institute of Technology, Prof. G.D. Padfield from University of Liverpool, dr. T.W.G. de Laat from NLDA. Their contribution to the research is very much appreciated.

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