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PROOF OF CONCEPT FOR A PREDICTIVE SHIP HELICOPTER OPERATIONAL LIMITATION ANALYSIS TOOL

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The requirements for rotorcraft operations in harsh environments along with the large cost reduction in both civil and military services, and the current replacement of large numbers of airframes, are some of the challenges facing the rotorcraft industry today. These days successful completion of the qualification cycle of helicopters operating from ships is still solely dependent on actual data gathering campaigns during expensive sea trials, in which modeling and simulation is hardly used. 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 the developed analysis tool applies maximum and minimum values of local wind conditions near the flight deck to aircraft rejection criteria stored in look-up tables to ensure that there remains sufficient power and control margin to perform safe flight operations throughout. A proof of concept for the predictive software tool is performed in the University of Liverpool's full motion piloted flight simulator, HELIFLIGHT-R, which consists of rotorcraft models interacting with ships airwake and ship motion models. The results of the proof of concept are very promising and presented in this paper.

Figure 1; Deck landing Apache AH-64D

Nomenclature

D	Aircraft drag
g	Acceleration due to gravity
h_R	Height of main rotor hub above fuselage reference point
h_T	Height of tail rotor hub above fuselage reference point
l_T	Distance of tail rotor aft of fuselage reference point
M_a	Mass of helicopter
P	Power required
Q	Torque
Q_R	Main rotor torque
T	Main rotor thrust
T_T	Tail rotor thrust
V	Airspeed
V_c	Rate of climb
W	Aircraft weight
Z	Height
β_{1s}	Lateral blade flapping

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θ	Pitch angle aircraft, Relative temperature
σ	Relative density
ϕ	Bank angle aircraft
ω	Relative rotorspeed

Introduction

These days successful completion of the qualification cycle of helicopters operating from ships is still solely dependent on actual data gathering campaigns during expensive sea trials, in which modeling and simulation is hardly used. When inadequate weather conditions are found, the aircraft must operate within the very restricted general envelope encountered. In contrast, flight simulators and modeling tools have become integral to the manufacturing, training and research communities and their utilization is expanding rapidly. This development underpins the confidence for expanding use of modeling tools in the qualification phase of helicopters operating from ships, to reduce real life testing without any concession in safety. While it may not be necessary for simulation to fully replace at-sea testing, there needs to be an understanding regarding the technical capability of modelling and simulation in order to achieve reliable results for each part of the envelope. In this way, the few remaining points on that envelope could be filled in through live trials, for example, for the most extreme conditions.

The goal of the Dynamic Interface Modeling and Simulation (DIMSS) project which started in 2001 was also to define a process for expanding Wind Over the Deck (WOD) flight envelopes for any ship/helicopter combination using modeling and simulation [1, 2]. In order to demonstrate that the process was effective, a man in the loop flight simulator, which replicated the dynamic interface environment for the LHA class ship and UH-60 Black Hawk helicopter was developed. The process required dynamic interface tests for each ship and helicopter combination to be conducted in the simulator by an experimental test pilot just as they would be using the actual aircraft and ship at sea. The pilot ratings given in the simulator and the aircraft limitations were then used to define the flight envelope. The primary determining factor in the development of WOD launch and recovery flight envelopes was thus the Deck Interface Pilot Effort Scale (DIPES) rating given by the pilot [3]. Unfortunately, the LHA/UH-60A simulation could not be accredited due to a lack of sufficient flight test data for the LHA/UH-60A combination.

For dynamic interface testing, only one pilot usually flies each test condition. Although the opinion of the pilot is formed in collaboration with the observations and the co-pilot, there is only one rating per wind condition per landing spot upon which to define the flight envelope. While it is known that pilots are different, which is no revelation, it does indicate that the pilot(s) used for wind over the deck flight envelope development either at-sea or in a simulator will have an impact on the envelope released for operational use [2]. Using quantitative workload measurements in conjunction with qualitative ratings may provide a better and more effective means for defining a flight envelope. Quantitative measurements would show whether qualitative ratings were made with consistency, and would be a more transparent method for the validation process of the software tool. This paper details the development process of the new modeling tool based on quantitative aircraft parameters, and a proof of concept at the flight simulation facility of the University of Liverpool, HELIFLIGHT-R [4].

Test methodology

The data gathering process for Ship Helicopter Operational Limitation (SHOL) programs is divided into two separate elements, environment and helicopter as shown in Figure 2 [5]. The environment side takes into account local airwake conditions near the flight deck influenced by the superstructure, and the required anemometer corrections due to position errors. The helicopter side accurately summarizes aircraft low speed flight characteristics to indicate areas exceeding rejection criteria while taking adequate safety margins into account. The SHOL analysis tool then enables the accurate construction of a Candidate Flight Envelope (CFE) for all in-service conditions thereby indicating confidence levels for each area in the predicted envelope. For areas with enough confidence a SHOL envelope can be certified without conducting complete sea trials, while for the remaining areas where operational demands require a larger envelope only partial sea trials are considered on a cost-effectiveness basis. Therefore the SHOL analysis tool can be used for:

1. Larger steps in an incremental approach towards flight envelope restrictions during sea trials;
2. Sensible exclusion of test points and indicating the priority of test points to be flown;
3. Read-across between other helicopter-ship combinations;
4. Certify envelopes by software analyses without conducting full sea trials.

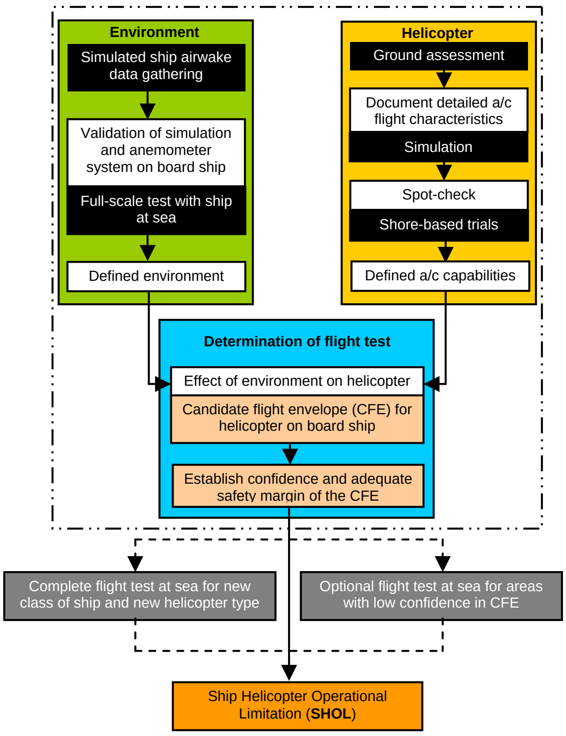

Figure 2; Flow chart SHOL qualification

In the following paragraphs examples are shown for processing objective test data gathered during shore-based hover trials and how this data is used by the predictive analysis tool to construct the CFE. Of course the same methodology is used for data gathered during sea trials to allow allowing assessment of all in-service conditions.

Rejection Criteria

The predictive analysis tool is under development based on specific rejection criteria for each helicopter type and their dependencies in the ship environment, and so be less dependent on the results from several dedicated sea trials. The subdivision between rejection criteria and dependencies in test data enables: assessing other possible conditions for in-service operations, forms the basis for proper read-across and enables accurate exclusion of test points. The definitions for rejection criteria and dependencies are [6]:

- ***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 and/or handling qualities. The initial collected helicopter data is saved into lookup tables and used for future helicopter-ship qualification trials, as the steady-state aircraft characteristics are valid for trimmed hover conditions in a unique solution [7]. The predictive software tool processes in a network the collected data, and allows all relevant rejection criteria and dependencies to interact with each other. There is a distinction made between performance, control position, subjective and aircraft attitude related issues. It also shows that in addition to the steady-state characteristics an additional safety margin is applied to allow aircraft handling while influenced by any relevant dependencies in the ship environment [6].

Unique Trimmed Solution

The helicopter is required to perform as a dynamic system within the user-defined Operational Flight Envelope (OFE), known as SHOL, or that combination of relative wind or other limiting parameters that bound the vehicle dynamics, required to fulfill the user's function. Beyond this lies the manufacturers-defined Safe Flight Envelope (SFE), this sets the limits to safe flight, normally in terms of the same parameters as the OFE, but represents the physical limits of structural, aerodynamic, powerplant, transmission or flight control capabilities. The margin between the OFE and the SFE needs to be large enough so that inadvertent transient excursions beyond the OFE are tolerable. For this reason there is at least a standard safety margin of 5 kts applied for construction of the CFE to the relative wind speeds presented in the low speed hover envelope as determined by the manufacturer. In addition to the 5 kts margin the CFE is made such that test points flown during Shore-Based Hover Trials (SBHT) already exceeding the safety margins in steady-state trimmed condition are excluded [8].

Trim is concerned with the ability to maintain flight equilibrium with controls fixed. For hover is distinguished by the four 'outer' flight-path states, and this is a consequence of having four independent helicopter controls – three for the main rotor and one for the tail rotor. The rotorspeed is not normally controllable by the pilot, but is set to lie within the automatically governed range. For a helicopter, the so-called inner states – the fuselage attitudes and rates – are uniquely defined by the flight path states in a trim condition. The shore-based hover trials rely on steady-state test points which are known to have a unique relation [7]. There are several reasons the Flight Test Engineer desires unaccelerated state:

1. Performance is evaluated in steady-state flight conditions;
2. Steady-state flight is interesting to handling qualities engineer, whose task is to evaluate the stability and controllability of an aircraft;
3. For shipboard operations it is mainly used to assess the remaining control margins before exceeding rejection criteria and/or loss of control.

A simple trim concept of a helicopter in steady-state hover condition is shown in Figure 3 [9]. The balance of forces in the vertical direction gives the thrust approximately equal to the weight:

$$T \approx W$$

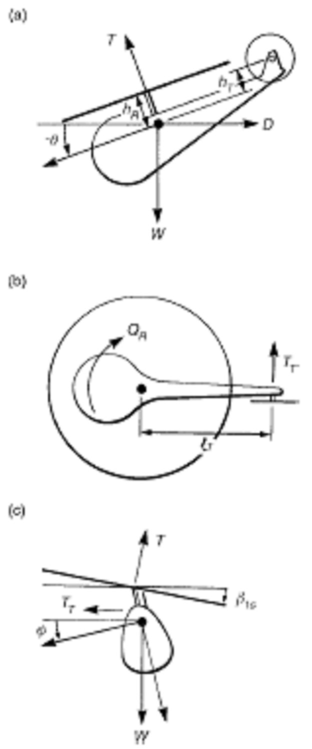

Figure 3; Simple consideration of trim [9]

This condition actually holds true up to moderate forward speeds for most helicopters. Balancing the forces along the forward fuselage axis gives the approximate pitch angle as the ration of drag to thrust:

$$\theta \approx -\frac{D}{T}$$

Since the thrust remains essentially constant in trimmed flight, the pitch angle follows the drag and varies as the square of forward speed. In this simple model, the absence of any aerodynamic pitching moment from the fuselage or tail requires that the hub moment is zero, or that the disc has zero longitudinal flapping. The tail rotor thrust can be written as the main rotor torque divided by the tail arm:

$$T_T \approx \frac{Q_R}{l_T}$$

The tail rotor thrust therefore has the same form as the main rotor torque, with the bucket at minimum main rotor power. The balance of rolling moment from the main and tail rotors, to give the lateral disc flapping:

$$\beta_{1s} \approx \frac{h_T T_T}{h_R T}$$

Thus, the disc tilts to port, for anticlockwise rotors, and the disc tilt varies as the tail rotor thrust. The balance of side-force gives the bank angle:

$$\phi \approx \frac{T_T}{M_a g}\left(1-\frac{h_T}{h_R}\right)$$

In practice, the two terms in the numerator are of the same order and the neglected in-plane lift forces have a significant influence on the resulting bank angle. From the force and moment balance can be derived the required control angles – main/tail rotor collectives producing the required thrusts and lateral cyclic from the lateral disc tilt. With this simple trim concept it is shown that there is a relationship between different parameters used to trim the aircraft, and once the trimming is done correctly it can be considered in a unique solution [7, 9]. A general example of limiting factors for hover conditions for a counter-clockwise helicopter is shown for different relative wind conditions in Figure 4. The exact areas where these rejection criteria are exceeded in steady-state trimmed condition are investigated initially during the SBHT and where required confirmed by sea trials.

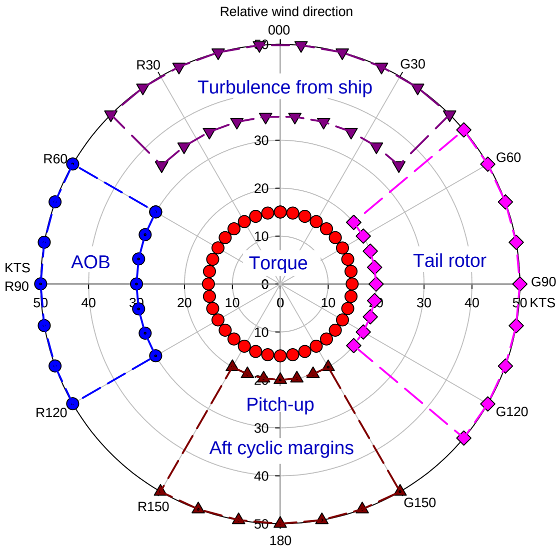

Figure 4; Example limiting factors

Referred Parameters

The objective of flight tests is often to determine the parameter that will limit the performance of a helicopter under the atmospheric conditions specified in a role specification. Although, it should be kept in mind that 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 to enable data points flown during different mission of the test campaign to be compared with each other. Once the precise limiting factors are known referred parameters are used [6, 10]. The use of referred parameters enables the combination of test points flown in different environmental conditions or to make predictions for environmental conditions that were not achievable at the test location. For example for torque, whilst knowing the relationship between power required and torque (Q):

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

Within the ship environment the benefits of ground effect are considered negligible [11]. Hence only Outside Ground Effect (OGE) low speed conditions are tested without any vertical speed:

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

This equation confirms that the performance of the helicopter is mainly influenced by the relative wind conditions (airwake), referred weight and the rotorspeed setting. The associated error bars are determined by summation of instrumentation errors and fractional errors "in quadrature" [6, 12]. Where δx is called the uncertainty, or error, in the measurement of x.

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

This is important as an analysis of measured errors and required computation may affect the choice of instrumentation for a given trial. Although specialist instrumentation may raise the cost of a trial the alternative is to repeat the measurements the required number of times to acquire an acceptable confidence in the results. Increased flying time is likely to be a more expensive option than an improved instrumentation fit.

The HELIFLIGHT-R simulator

A proof of concept for the predictive SHOL analysis tool was performed in the Flight Science & Technology Research Group at University of Liverpool's full motion piloted flight simulator, HELIFLIGHT-R, which consists of rotorcraft models interacting with ships airwake and ship motion models. The simulator includes a time-accurate airwake model of a Type 23 frigate with an atmospheric boundary layer profile, and a realistic sea surface with ship visual model [13]. A UH-60 Black Hawk model with shipboard landing capability with a maximum gross weight of 22,000 lbs provided in FLIGHTLAB was used. The HELIFLIGHT-R simulator, as shown in Figure 5, could be summarized as follows [4]:

- A 12 ft visual dome mounted on a six degree of freedom motion platform;
- A cockpit equipped with two wide screen 19" LCDs to represent the primary flight information, engine information and navigation information;
- The Crew Station uses a 4-axis (longitudinal and lateral cyclic, collective and pedals) electric control loading system that back-

drives the pilots' controls and allows fully programmable force-feel characteristics;

- Three high resolution LCOS projectors, with a 1400 x 1050 resolution, equipped with wide angle lenses provide a wide field of view of 210° horizontally by +30°/-40° vertically;
- FLIGHTLAB modeling and simulation software is at the centre of operation of the new facility. FLIGHTLAB provides a modular approach to developing flight dynamics models, producing a complete vehicle systems model from a library of predefined components, allowing analysis with pilot-in-the-loop real time simulation.

Figure 5; Approach towards ship

The Type 23 frigate, as shown in Figure 6, had the following dimensions relevant for shipboard operations:

- 35 ft hover above sea level during approach, the result of a deck height of 15 feet;
- 52.9 ft deck width, 436 ft length ship and 4.900 tons.

Figure 6; Type 23 frigate

The relevant limitations for the proof of concept tests are summarized as follows:

- Airwake not coupled to ship motion;
- Pilot In Command (PIC) flew from the left seat during a Fore-Aft Approach from port side;
- The simulated helicopter should be considered as Black Hawk look-alike (provided by FLIGHTLAB version 3.2) and not as the real UH-60 Black Hawk;
- Once the helicopter touched down on the deck, there was an un-developed ground contact model. To prevent any vibration, the simulator was frozen by the IOS operator ±3 ft before touch-down.

Proof of concept

The test conditions were flown by an experimental test pilot of The Netherlands Defence Helicopter Command. For the proof of concept a similar test set-up was used as for actual test campaigns by performing SBHT before the CFE was constructed. The SBHT consisted of documenting Trimmed Flight Control Positions (TFCP) for different azimuths and speeds, as shown in Figure 7, at 21.000 lb and 23.000lb referred weights to indicate i.e. remaining control margins for each test point.

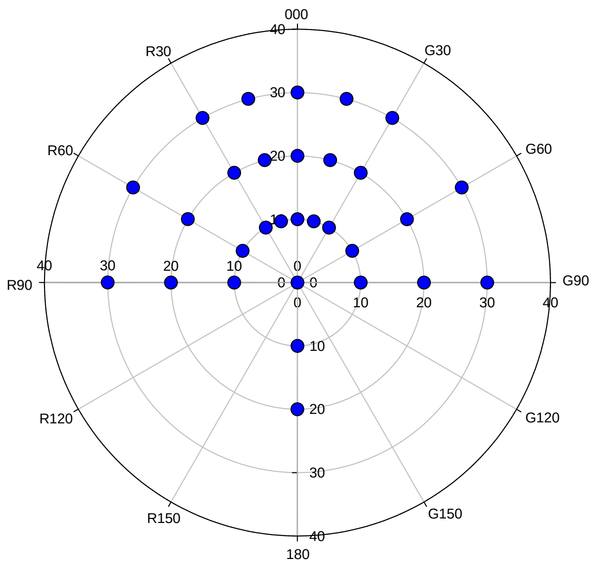

Figure 7; SBHT test points flown

In addition data was captured for changes in control position for different center of gravity locations by flying only in longitudinal or lateral directions. Furthermore, the relation between torque required and corresponding vertical velocity was determined during Maximum Power Vertical (MPV) climb conditions. This enables the vertical velocity components of the airwake near the flight deck to be expressed as additional torque requirements to maintain height above the flight deck. Finally for the Type 23 frigate randomly selected test points were flown for data gathering to validate the predictions made by the SHOL analysis tool.

Safety margins

The safety margins were applicable for the UH-60 Black Hawk for determining the CFE based on the steady-state aircraft parameters in hover condition, to allow the aircraft to be handled while influenced by any relevant dependencies in the ship environment.

Torque safety margins:

- All testpoints were validated against static torque values of 100% as maximum;
- Torque limits were corrected for relative density variations in ambient and target conditions, and variation between target and actual referred weights;
- Steady state power margins were 5% (day) or 10% (night). When conducting night operations ship motion cues would be reduced and in general require larger control corrections to accommodate for delayed response to changes in aircraft clearance and closure rates;
- A steady state exceedance was defined as an exceedance of this margin for a dwell time in excess of 5 seconds; i.e. grater than 5 sec between 95%-100% (day) and 90%-100% (night);
- Transient margin from 100% to 125% was not utilized.

Control position safety margins:

The standard international safety margin of 10% was applied for all control positions during daytime and an additional safety margin of 5% was applied for night time conditions (15% total).

Discussion test results

Torque. At higher wind speeds, the torque required varies with wind direction as shown in Figure 8. In winds from starboard (green winds) more torque is required than in winds on the nose and from port (red winds). In this example torque required is highest at the relative wind conditions tested from the direction G60 to G90. This has amongst other reasons to do with the tail rotor which has to deliver more thrust to compensate the weathercock effect of the fuselage as more left power pedal is required to maintain heading for an anti-clockwise rotating main rotor. In winds from port, the tail rotor is assisted by the weathercock effect of the fuselage, so less thrust is required. Furthermore torque required is dependent on the aircraft referred weight and relative wind speed which is in correlation with the performance graphs provided in the Flight Manual.

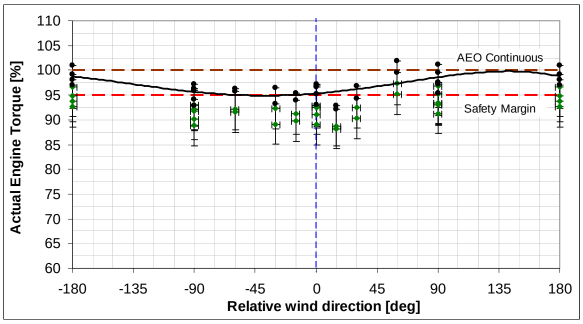

Figure 8; Example torque at 10 kts

Pedal position. The mean pedal position is plotted as a function of relative wind direction as shown in Figure 9. It shows that in green winds increasing left pedal deflection is required to maintain helicopter heading, while in red winds less left pedal deflection is required. In this example pedal position is similar to torque required, highest at tested relative wind conditions from the direction G60 to G90. Pedal deflection is thus dependent on wind speed and wind direction similar as for torque. The tail rotor pitch would have been a better parameter for remaining control margin then pedal position, due to interactions with the collective-yaw interlink.

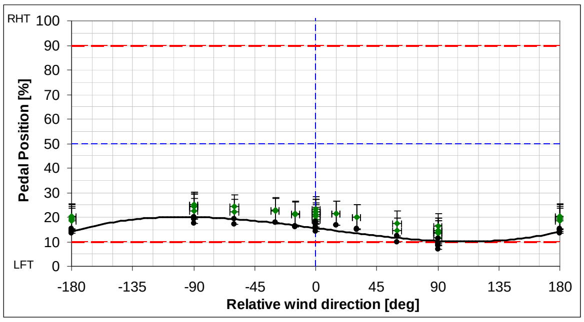

Figure 9; Example pedal position at 10 kts

Roll attitude. The aircraft attitudes in correlation with the Field Of View (FOV) indicate which maximum roll attitudes are achievable for safe operations from the flight deck while maintaining enough visual reference to the landing site. At higher wind speeds, roll attitude varies with wind direction as shown in Figure 10. In red winds more Angle of Bank

(AOB) to the left is required than in winds on the nose and for green winds some AOB to the right is required. In this case the maximum AOB occurs for R90 winds and that is quite large, especially as the test pilot during the proof of concept was flying from the left seat during an approach towards the ship from port side. This resulted in issues especially with a moving ship, and as the ship was tilting to starboard with red winds the relative angle was increased between the helicopter and the flight deck.

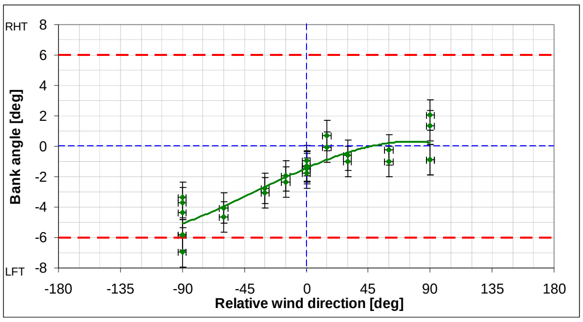

Figure 10; Example AOB at 30 kts

Summary. It is outside the scope of this article to explain all the aircraft characteristics of the shore-based hover trials. Examples shown are just an indication of the kind of data gathered and how it is processed. The software tool presents the data of shore-based hover trials in a polar plot that makes it easy to indicate which safety margins are exceeded and for which relative wind conditions this applies as shown for both objective and subjective rejection criteria in Figure 11 and Figure 12 respectively.

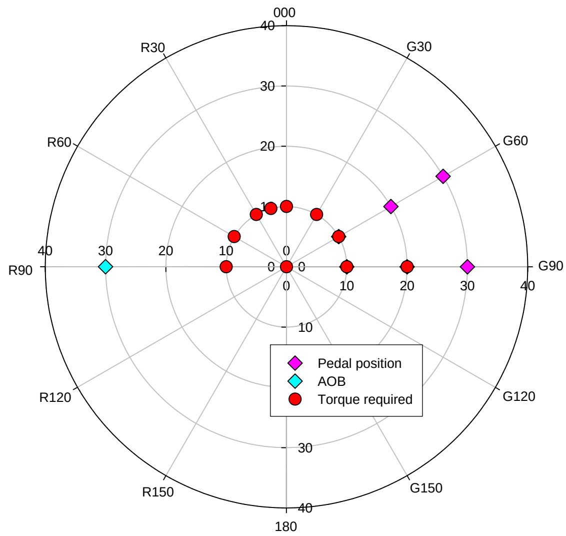

Figure 11; Exceeded margins SBHT

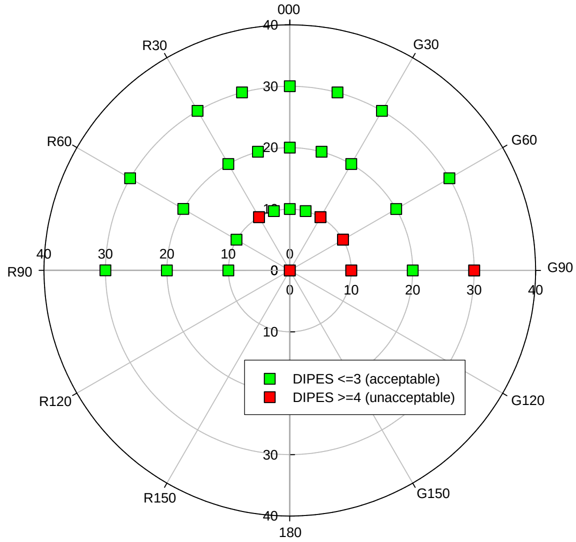

Figure 12; Subjective issues SBHT

The polar plot shows that in line with the previously presented data below 10 kts performance limits are approached or even exceeded taking the error bars into account. Furthermore R90 roll attitude is relatively large and from G60 to G90 pedal position is approaching limitations. It should be noted that the subjective ratings are not exactly in correlation with the objective rejection criteria, although a DIPES rating of 4 or higher always coincides with objective rejection criteria and objective data is thus more restrictive. This concludes the analyses of helicopter related items expressed in rejection criteria determined during shore-based hover trials. It is now a matter of relating the relevant rejection criteria with local wind conditions for each ship type to construct the CFE.

Environment items

The results of the shore-based hover trials are based on the relative wind conditions encountered by i.e. hovering in natural wind conditions or by using a pace-vehicle. Near and above the flight deck the relative wind is disturbed by the ship's superstructure. This disturbed wind is what the helicopter faces when operating from the flight deck and is known as local wind. These local wind conditions are determined by simulation and/or full-scale measurements. Unfortunately both these wind conditions are unknown for the operational crew after the trials, as ship anemometers are 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 will also deviate from the free air stream. Therefore it is important to distinguish between three different wind conditions:

1. **Relative wind**. The shore-based hover trial is based on undisturbed relative wind 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 this wind condition.
3. **Local wind**. The local wind conditions are changing for each position near and above the flight deck. These are the wind condition the helicopter will face during ship board operations.

Candidate Flight Envelope

Once the helicopter and environment issues are determined and clearly documented these results are combined to construct the CFE. It is now a matter of correlating between relative and local wind conditions across the flight deck, in the approach and in the departure path for each different ship type. This is done by constructing lookup tables expressed in relative wind conditions with shore-based hover trial results, whilst knowing that for each relative wind condition there is a unique trim position [7, 9]. Furthermore lookup tables expressed in relative wind conditions are constructed for mean, maximum and minimum values of local wind present in the approach, take-off and landing phase of the ship.

The predictive analyses tool transparently processes these data such that for each relative wind condition, the maximum and minimum values in azimuth, speed and vertical flow deviations in local wind are applied to the rejection criteria. Thereby ensuring that during in-service conditions, the helicopter has sufficient power and control margins to perform a safe take-off and landing. Consequently, the software tool gives the indicated wind envelope which could be released for in-service operations for that particular ship type taking anemometer correction into account as shown for the UH-60 Black Hawk in Figure 13. There are only four relevant rejection criteria indicated, as the others are not approaching any safety margins. It shows that even though some rejection criteria are indicated these areas are still included in the CFE. Those areas should be approached in an incremental approach and the main focus of the sea trials as these will probably set the boundaries of the SHOL envelope.

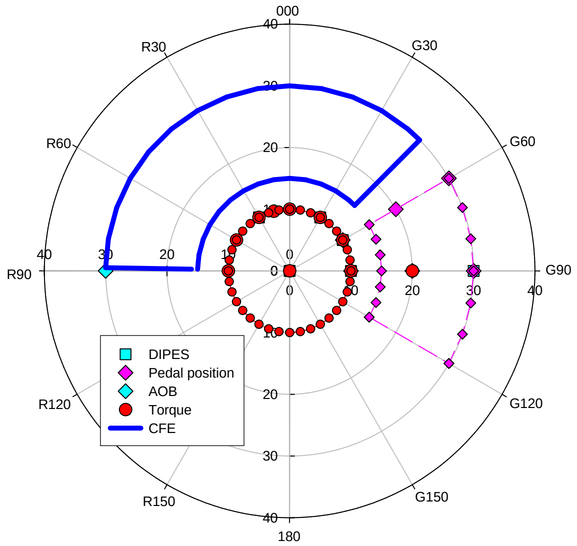

Figure 13; CFE for 23.000 lb

SHOL envelope

The SHOL envelope determined in the simulator for a Fore-Aft Port (FAP) approach, flown from the left seat, with a high referred weight of 23.000 lbs is shown in Figure 14. It clearly indicates that the prediction made by combining both objective and subjective SBHT results gives a very accurate prediction of the finally determined SHOL as these are set as the envelope boundaries.

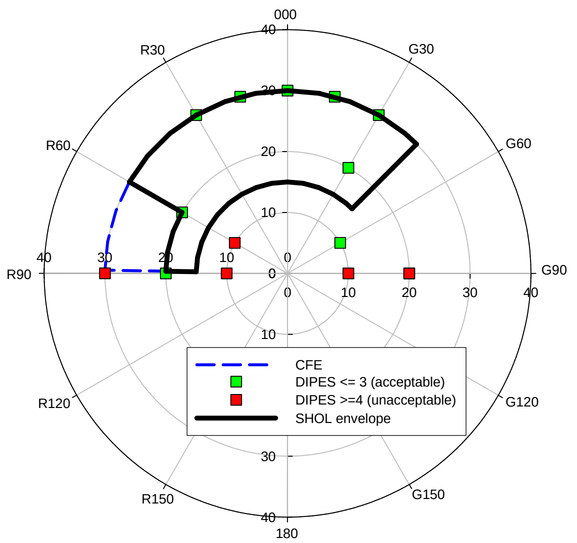

Figure 14; Result SHOL trial

These boundaries are set by taking the next acceptable data point in speed and/or azimuth condition. The combination of objective and subjective data is in line with the methodology briefly addressed in the DIMMS project [2]. It states that in accordance with dynamic interface test procedures, data points where control margins of less than 10% control movement remaining, were reassigned a DIPES rating of 5 and considered to be outside the acceptable envelope. However, the advantage of the novel SHOL analyses tool is that these data points could be identified and even removed where necessary before conducting expensive sea trials, thereby increasing trial efficiency, but most important increase flight safety.

Another reason for combining objective and subjective data is that presently the primary determining factor in the development of SHOL envelopes is a workload rating given by the pilot. For dynamic interface testing, there is usually only one pilot that flies a particular test condition. Although the opinion of the pilot is formed in collaboration with the observations and the co-pilot, there is only one rating per wind condition per landing spot. That only one pilot flies a particular test condition is in contradiction to another conclusion drawn from the DIMMS project, where multiple pilots flew the same test conditions resulting in as many different envelopes for the same landing spots [2]. In general the differences in ratings between the pilots were one DIPES point or less. However, there were some significant differences that cannot be ignored. The pilots most likely were using a different landing and/or takeoff profile in order to manage limiting aircraft parameters more effectively. This drawback of solely using subjective opinions in SHOL development is confirmed by the test point at G60 that was rated a DIPES 4 during both the SBHT and sea trials at 21.000 lbs, while it was assigned a DIPES 3 for 23.000 lbs. Although the difference is only one DIPES point, it means that this test point would have been included in the SHOL envelope. The chances that the same test pilot could rate it a DIPES 4 the next time the test point is flown, or an operational fleet pilot would not be able to land in that condition are too large and therefore the test point was excluded from the SHOL based on objective criteria.

Conclusions

A predictive engineering 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 and processing of data collected. The model could be used for determination of the CFE 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 by combining both objective and subjective parameters improves the exactness of the SHOL envelope used for in-service operation for many years to come without making any concessions in safety.

Future Work

The accuracy of the predictive software tool will be precisely determined during the introduction of the NH90 helicopter the coming years. Once enough confidence is established it will be decided to which extent the model could be used for certification purposes without conducting complete and sometimes redundant sea trials.

Acknowledgements

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References

1. Advani, S.K. and C.H. Wilkinson, *Dynamic Interface Modelling and Simulation - A Unique Challenge*, in *Royal Aeronautical Society on Helicopter Flight Simulation*. 2001: London.
2. Roscoe, M.F. and C.H. Wilkinson, *DIMSS - JSHIP's Modeling and Simulation Process for Ship / Helicopter Testing & Training*, in *AIAA Modeling and Simulation Technologies Conference and Exhibit*. 2002: Monterey, California.
3. Geyer, W.P., K. Long, and D. Carico, *Helicopter / Ship Qualification Testing, Part II: American Clearance Process*, in *RTO-AG-300 Vol.22*, RTO/NATO, Editor. 2003.
4. White, M., et al., *Acceptance Testing of a Rotorcraft Flight Simulator for Research and Teaching: The importance of Unified Metrics*, in *35th European Rotorcraft Forum*. 2009: Hamburg.
5. Hoencamp, A., *An Overview Of SHOL Testing Within The Royal Netherlands Navy*, in *European Rotorcraft Forum 35th*. 2009: Hamburg, Germany.

6. Hoencamp, A., *Predictions of rejection criteria for ship helicopter operational limitation qualifications*, in *Heli Japan*. 2010: Saitama, Japan.
7. Dreier, M.E., *Introduction to Helicopter and Tiltrotor Flight Simulation*, ed. J.A. Schetz. 2007: AIAA Education Series, ISBN 978-1-56347-873-4.
8. Hoencamp, A., *Concept of a Predictive Analysis Tool for Ship Helicopter Operational Limitations of Various In-Service Conditions*, in *American Helicopter Society 67th Annual Forum*. 2011: Virginia Beach, VA.
9. Padfield, G.D., *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modeling*. 2007 ed. Vol. Second Edition. 2007: Blackwell Publishing, ISBN 978-1-4051-1817-0.
10. Cooke, A. and E. Fitzpatrick, *Helicopter Test & Evaluation*. 2002: Blackwell Science, ISBN 0-632-05247-3.
11. Hoencamp, A., T. van Holten, and J.V.R. Prasad, *Relevant Aspects of Helicopter-Ship Operations*, in *European Rotorcraft Forum 34th*. 2008: Liverpool, United Kingdom.
12. Taylor, J.R., *An introduction to error analysis: the study of uncertainties in physical measurements*. ISBN 0-935702-75-X. Vol. second edition. 1997: University Science books.
13. Forrest, J.S. and I. Owen, *An investigation of ship airwakes using Detached-Eddy Simulation.* Elsevier, 2010. Computers & Fluids 39: p. 656-673.