ROtorcraft Ship Dynamic Interface Simulation (ROSDIS)

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Abstract. ROSDIS is a research project (National Technology Project) carried out by order of the Royal Netherlands Navy. NLR has been developing a simulation capacity aimed at supporting the current method of determining Ship-Helicopter Operational Limits (SHOLs) in the future through the use of piloted simulation. The goal is to increase the efficiency of flight testing at sea. For both off-line analysis and piloted simulation of the helicopter ship dynamic interface suitable models representative of the helicopter, ship and environment were developed. Over the course of the project, piloted sessions were frequently held in NLR's fixed base simulator, to evaluate the fidelity of the modelling and define further improvements. The most recent session was held with RNLN test pilots of which one was also involved in the actual flight testing at sea. The test setup was such that a comparison with the flight test data was possible (same density mass, wind and ship motion as in flight test).

1. INTRODUCTION

NLR has 40 years of experience in the field of helicopter-ship qualification testing. The NLR approach is based on a thorough understanding of the helicopter performance and control characteristics and the ship's environment. The current SHOL determination method is based on experimentally obtained data of ship and helicopter separately before the Candidate Flight Envelope (CFE) for the helicopter-ship combination is evaluated through flight testing at sea in the final phase. Flight testing at sea, however, is an expensive activity requiring the co-ordination of numerous assets.

A helicopter-ship simulation capacity is thought to be able to support this method since it enables safe exploration of the CFEs in an early stage without depending on the availability of personnel, materiel and the required environmental conditions as strong winds, and low air density. In a simulated helicopter-ship dynamic interface the environmental conditions can be chosen and runs can be repeated numerous times under the exact same conditions. Exploring the CFEs in simulation should enable the flight test engineers to draw up a more refined test program for evaluation at sea. It is therefore thought that simulation can increase the efficiency of the current helicopter-ship flight testing at sea and therefore save on required time and money and will further increase safety during the flight trials.

2. CURRENT SHOL METHOD

The current SHOL determination method (described in detail in ref. 1) is based on experimentally obtained data of ship air wake, ship motion and shore-based helicopter hover performance. These are analysed to draw up the so-called Candidate Flight Envelopes (CFEs) for the helicopter-ship combination which are then evaluated in flight trials at sea to determine the SHOLs.

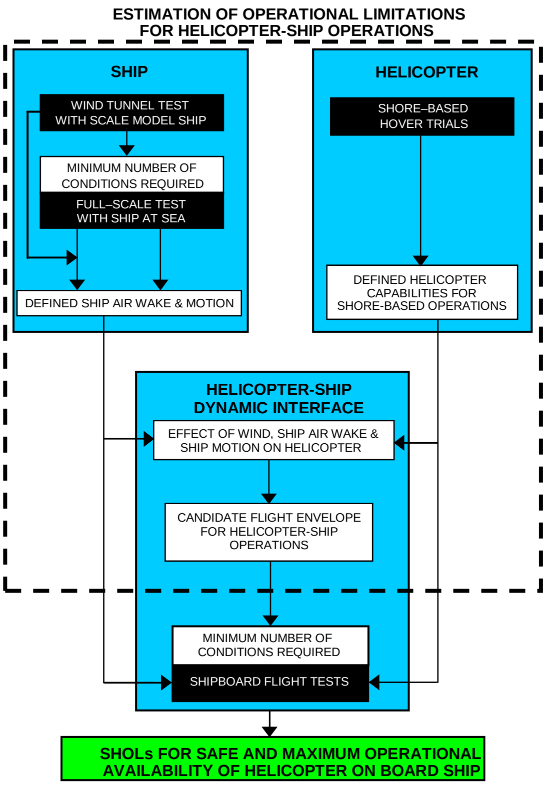


Figure 1 Current SHOL method

The airflow characteristics above the ship's flight deck and along the flight approach paths are measured with a probe on a scaled model in the wind tunnel. These measurements are verified experimentally in full-scale tests on the actual ship. Here also data on ship motion is acquired. The helicopter characteristics in hover (for omni-directional wind speeds) are measured during shore-based trials. The maximum achievable flight envelope is the CFE and is obtained by determining the influence of the ship's air wake on the helicopter capabilities. These CFEs are used for planning the flight test programme at sea. The CFEs are verified during flight test at sea by means of (subjective) pilot ratings and (objective) measurements of helicopter parameters related to ship motion to establish the SHOLs.

3. SIMULATING THE ROTORCRAFT-SHIP DYNAMIC INTERFACE

ROSDIS (ROtorcraft Ship Dynamic Interface Simulation) is a research project (National Technology Project) carried out by order of the Royal Netherlands Navy. NLR has been developing a simulation capacity aimed at supporting the current method of determining Ship-Helicopter Operational Limits (SHOLs) in the future through the use of piloted simulation. The goal is to increase the efficiency of flight testing at sea. The ROSDIS project will end in November 2006 after three years.

The simulation software used in the ROSDIS project is Flightlab, a commercial-off-the-shelf helicopter simulation environment. It provides an integrated environment to rapidly prototype, model, analyse and generate real-time and off-line simulations of non-linear dynamic rotorcraft systems. Flightlab generates non-linear mathematical models of rotorcraft through the use of a family of model components (structural, kinematic, aero-dynamic, control, and solution components). For both off-line analysis and piloted simulation of the helicopter ship dynamic interface suitable models representative of the helicopter, ship and environment were developed. This involves mathematical models, visual models and hardware models.

Figure 2 visualises the development of the sub-models and they way they are related. The models, their definition and their development will be further discussed next.

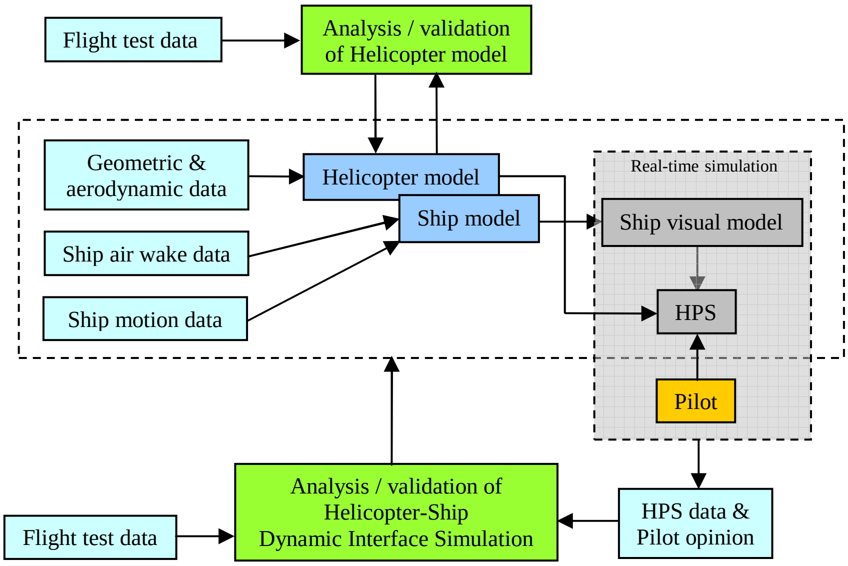


Figure 2: Development of the helicopter-ship dynamic interface simulation

4. SHIP MODELLING

4.1 Ship air wake

As part of the current SHOL method to draw up the CFE, (steady) wake rake measurements are available from wind tunnel measurements, see Figure 3. The ship air wake data was obtained with a wake-rake that was traversed at two heights and four positions, one crossing the spot and the other three downwind from this traverse. The traverses were performed for dead-ahead and 30, 60 and 90 degree wind directions from starboard from which the wake for port winds was derived. In Flightlab the ship air wake was modelled by means of table look-up. The wake traverses were implemented to create a wake field with (full-scale) dimensions of 75m width and 42m height extending to 45m downwind of the spot. The wake structure is rigidly attached to the ship so it follows the ship motions.

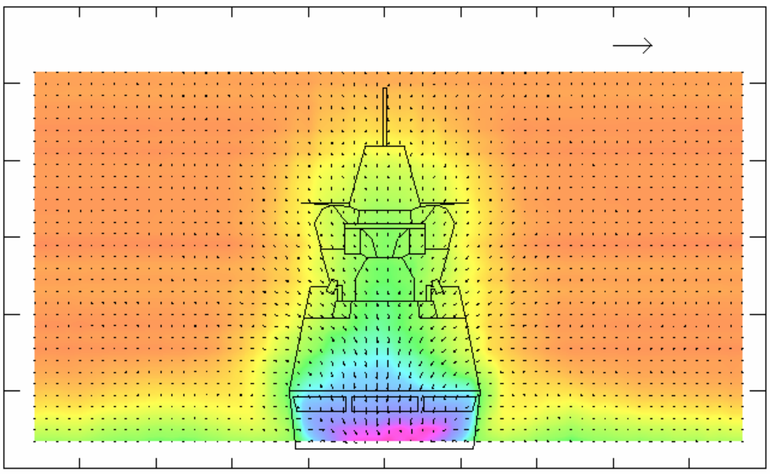


Figure 3: Wind tunnel wake rake measurements (local airspeed disturbance)

The steady ship air wake interference on the helicopter is simulated but no aerodynamic interaction of the helicopter on the ship air wake is modelled, i.e. the rotor down wash does not affect the ship air wake.

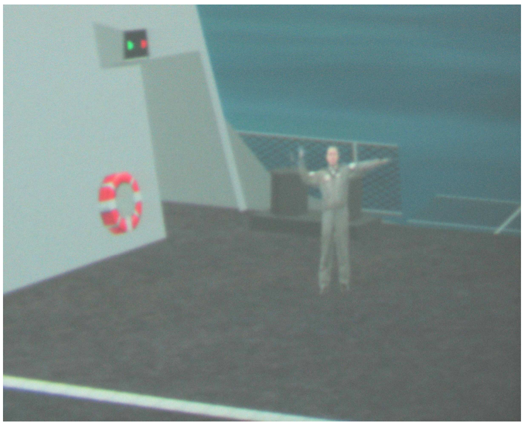
In the final stages of a landing, the atmospheric turbulence increases due to shorter scale length. Also once the helicopter is submerged in the ship air wake, the ship turbulence will be clearly noted. The pilot workload will increase in keeping the helicopter in a stable hover and landing it safely on deck. Since both atmospheric and ship air wake turbulence are presently not modelled, flying the simulator was considered too smooth and therefore too easy since no corrections were required to compensate for turbulence as was encountered during the flight trials. Simulating turbulence would increase pilot workload and control strategy and possibly torque and pedal limits would be earlier encountered. An atmospheric turbulence model is available for evaluation in the final simulator session. However, from flight test experience it is known that the ship air wake turbulence has a larger effect. Additional wind tunnel tests should be carried out to obtain data on ship air wake turbulence through step-by-step measurements.

4.2 Ship motion

The full-scale ship motion measurements comprise speed, heading, pitch and roll angles for various conditions of sea state, relative wave heading, wind speed and wind direction. Heave or vertical deck accelerations are currently not measured by NLR. Exclusion of the heave motion results in a different vertical motion of the spot than in reality since only the vertical motion caused by pitch is represented. Calculation of 6 DoF ship motion is possible with the Fredyn code as used by the RNLN, simulating the ship motion response to incoming waves in the time domain. Wave spectra and ship motion were measured by the RNLN for the subject ship on its maiden trip. A wave spectrum with the same wave direction as estimated during the NLR measurements was tuned as input for the Fredyn code to obtain ship motion with comparable pitch and roll motions as the NLR measurements, now including the heave motion. The effect of including heave will be evaluated in the final session.
During most flight tests, the sea state was such that ship motion never was a limiting factor when drawing up the SHOLs. The SHOLs are therefore presented with the ship motion as measured, without any indication of how more severe ship motion might affect the applicability of the SHOL. Calculated ship motion therefore provides the opportunity to explore the operational limits further than possible in flight test.

4.3 Ship visual model

The Royal Netherlands Navy (RNLN) visual model of the ship as used in the RNLN training simulator was implemented in the NLR simulator. Overall detail and texture of the ship was considered as adequate by the pilots. The sea surface is represented by a flat surface with a texture independent of sea state. Also no ship surface wake is represented. The lack of these visual cues were not considered a hindrance when anticipating the ship motion and heading. Because of the limited field of view in the simulator the centreline was extended on the hangar wall as an extra cue for lateral positioning. The pilots had a tendency to stay too far aft of the landing spot to prevent the view dead ahead being dominated by the hangar wall, losing peripheral view. It was therefore suggested by the pilots to model an open hangar door so more depth and movement cues would be available. This will be realised for evaluation in the final HPS session.
A (stabilized) Glide Path Indicator was added to the model as an extra visual cue.



Also a manually controlled dynamic Flight Deck Officer (FDO) was created to assist the pilot in the final phase of the landing and in the take-off (Figure 4). FDO commands are given mainly based on the longitudinal and lateral distance of the helicopter to the spot. Like in flight test, commands for altitude were not very often required since the horizon bar provides a good visual reference for this. Unlike in reality, the ‘FDO’ (simulator operator) cannot anticipate the ship motion which in one case has resulted in the operator signalling ‘down’ when the roll angle was considered too large by the pilot.

Figure 4: Flight Deck Officer.

5. HELICOPTER MODELLING

A Lynx flight mechanics model was developed to enable comparison with flight test data. Considering the fact that the limits for torque and pedal are the main limiting parameters for the Lynx helicopter when close to a moving ship with a disturbed air flow field, a good match with flight test data needs to be obtained, especially for these parameters.

5.1 Model components

A graphical representation of the Lynx model in Flightlab is shown in Figure 5. Visible are the blade masses, the landing gear, main rotor blades, tail rotor and stabilisers. The centre of gravity is represented with the body axes. Main rotor and tail rotor hinges are visible as coloured rings.

The model uses a blade element representation of the main rotor and an enhanced Bailey model (‘disk rotor’) for the tail rotor. The main rotor blade elements use the quasi-steady aerodynamics including stall delay, with a look-up table for the airfoil characteristics. For the main rotor inflow calculation the six state Peters-He model is used with interference on the tail rotor, fin and fuselage. The fuselage and stabiliser aerodynamics are represented by look-up tables.

A model of the stabilisation part of the AFCS, the Automatic Stabilisation Equipment (ASE) has been created. Not modelled in detail yet are the airfoils of the fin and the BERP profile data of the main rotor. Instead generic data tables for the NACA0012 airfoil have been used for the fin. For the rotor the NPL9615 profile of the old metal blades has been used. Landing gear characteristics include the oleo spring characteristics of the Lynx with tuned damping for correct ground handling.

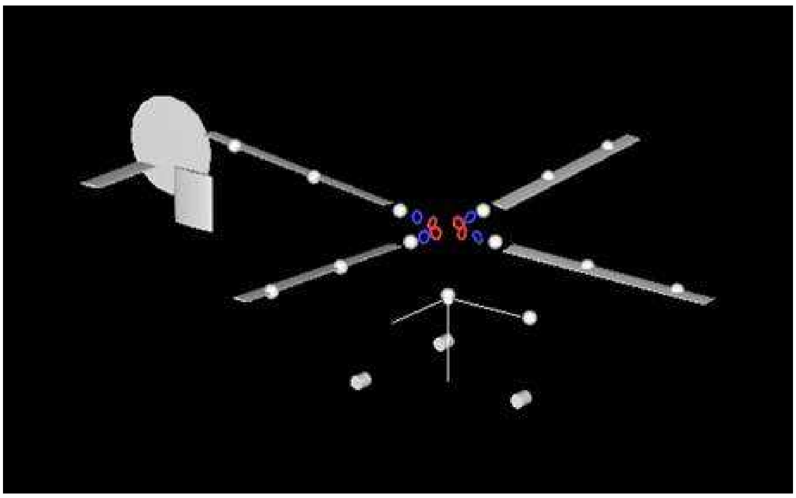


Figure 5 Graphical representation of the FLIGHTLAB Lynx helicopter model

5.2 Validation process

The validation process of the Lynx flight mechanics model consists of the following steps:

1. Trim validation
2. Dynamic validation
3. Subjective tuning (pilot opinion)

As part of the trim validation, pedal deflection for the important low speed region is shown in Figure 6. Flight test data as obtained during shore-based hover trials is compared with simulation results of the Lynx model with a disk tail rotor receiving main rotor interference. The data was measured for three different mass density ratios and wind speeds (10, 19 and 30 knots, hence the centre gap). The simulation was performed for these same conditions. The match for port winds is reasonable. Pedal for starboard forward winds are up to 10% higher in simulation, but the pronounced area of high pedal deflection around 50 kts starboard wind direction above 10 knots is clearly not reproduced by the model. This area of inadequate yaw control is typical to the relative low wind speed envelope. Pedal for red aft winds are overpredicted by about 5%.

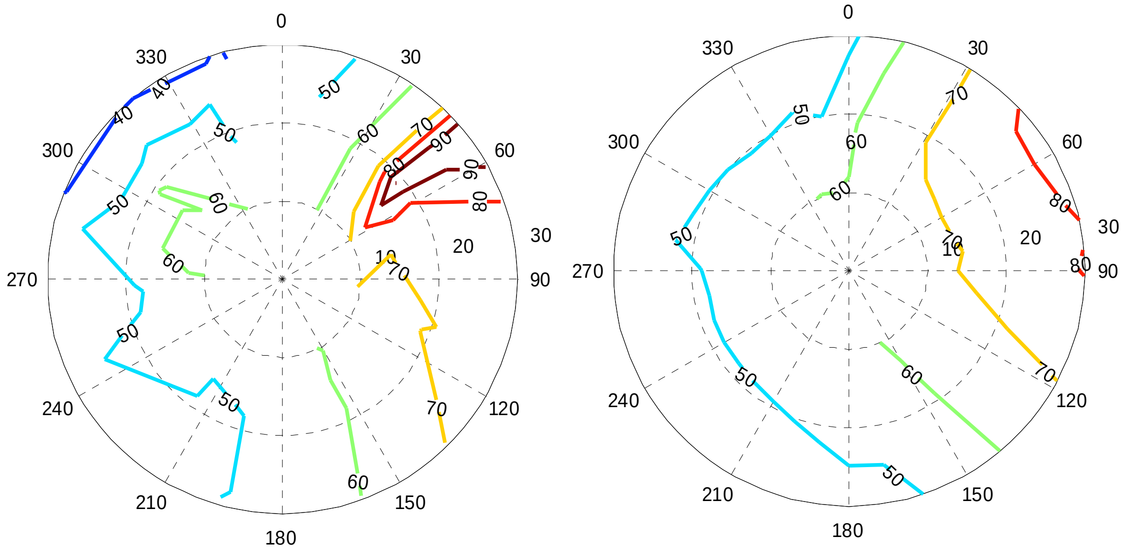


Figure 6: Pedal deflection flight test data (left) and simulation data (disk TR)

For a complete dynamic validation single axis inputs for all 4 control axes are preferred, at several speeds but at least for hover and cruise flight. However these data were not available. Instead, one of the approaches of the flight trials was simulated. The stick positions were fed into the Flightlab Lynx model, to see if the model would follow the same trajectory as during the test flight (Figure 7). It should be remarked that in this particular simulation run the ship wake was not present, which had an influence at the end of the manoeuvre as shown when the helicopter is near the ship. The flight test results are plotted using a thin black line. Around this black line a grey area is shown, which represents the Level D requirements from the FAA AC120-63 helicopter simulator qualification standard [2]. These are the most stringent civil requirements for flight mechanics modelling for training simulator applications. The simulation results are shown with a blue line. Level D requirements allow a +/- 10% adjustment of the stick positions that are fed into the model to obtain a match with flight test data within prescribed tolerances.

Although the initial torque value is very close to flight test, larger errors occur when close to the ship, up to as much as 20%. During most part of the approach torque is reasonably close to flight test and at least shows the same trend.
For the entire manoeuvre, the altitude match is within the level D limits. The drop in flight test radar altitude at time = 44 sec is due to the deck edge.
During almost the entire manoeuvre pitch and roll attitudes are within level D limits.
In the approach the heading is almost within level D limits. When the helicopter decelerates below about 40 knots, some larger heading errors occur.
In the first part of the approach the simulated ground speed is close to the flight test value. For the rest of the manoeuvre, the airspeed stays about 10 knots too high. The drop in flight test ground speed at time = 44 sec. is again due to the deck: the Doppler equipment sees zero ground speed above the deck.

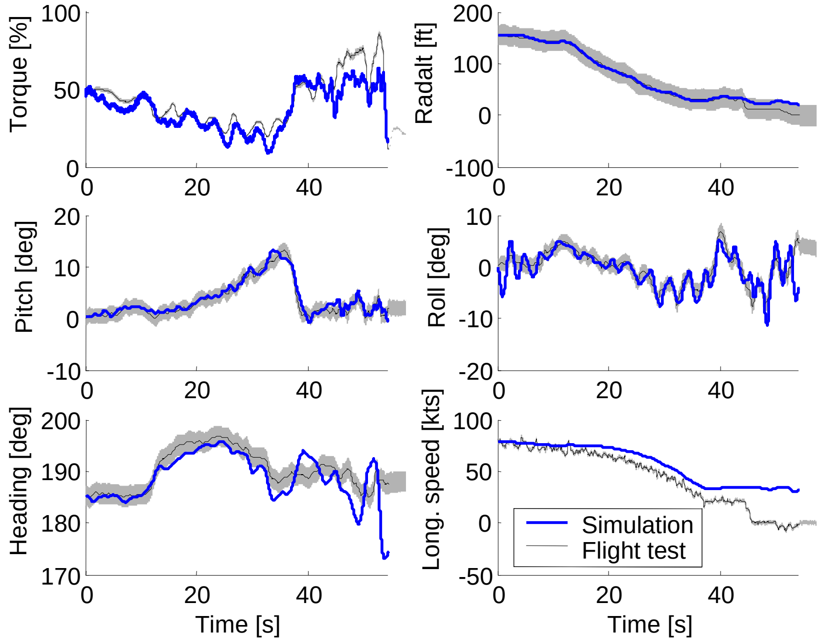


Figure 7: Match of off-line simulation with flight test for a FAP approach.

Subjective tuning is performed based on feedback provided by RNLN pilots on the helicopter responses, handling qualities and control feel relating to the FCS modelling and control loading.

6. HELICOPTER PILOT STATION

The Helicopter Pilot Station (HPS) is NLR's fixed-base reconfigurable rotorcraft simulator for real-time, pilot-in-the-loop simulation purposes.

6.1 Instrument displays

Since the main focus of the simulation is on approach/landing and therefore on 'heads up' flying, only generic instrument displays are used. The left MFD (Multi Function Display) provides generic engine instruments with rotor speed, power turbine speeds and torques. The right MFD showed a Flight and Navigation Display with the Attitude Director Indicator (ADI) on top and a Horizontal Situation Indicator (HSI) below.

6.2 Control loading

The HPS is supported by a high fidelity four-axis digital electric control loading system. In generating the control forces on the pedals, collective and cyclic controls a generic set-up was used with the following characteristics:

- A (software) adjustable friction for the collective and pedals.
- Spring force around a trim point for the cyclic. The trim point can be moved with the 4-way switch on the cyclic or can be set by depressing the ‘force trim release’ switch on the cyclic.
- To ensure a realistic operation of the heading hold function, pedal switches were manufactured for detecting feet-on and feet-off. The switches were modelled based on the dimensions and switching force in the actual Lynx helicopter.

6.3 Visual system

The outside world is displayed by three projectors on three screens providing a total field of view of 135.0° horizontally by 33.5° vertically.

Figure 8: *RNLN test pilot performing a fore-aft approach over port*

To improve the view on the ship for fore-aft approaches over port, the console was rotated to the left such that the left screen represented the view ahead. This implies however that when above deck, no view to the left was available, so the pilot had less peripheral view and thus less cues on the ship motion relative to the helicopter motion.

Down view is limited, especially in the hover wait position alongside the ship with port winds when the ship lists to starboard and the helicopter has to bank to port for lateral station keeping. Also when performing the side-step sight on the ‘bum-line’ for correct fore-aft alignment was lost too soon. In hover above deck the horizon bar provides a good cue for the height above deck but when actually landing too little deck area is visible to ensure a smooth landing.

The open space in which the simulator is situated does not provide a confined cockpit feeling which made one pilot remark it felt like being in two worlds at the same time, as if one is detached from the helicopter. A closed cockpit or window styles cannot be modelled since these would interfere with the beams of the projectors above the pilot. This will be implemented later, since window styles provide much-used cues for correctly lining up with the ship.

7. PILOTED SESSIONS IN HPS

Through piloted sessions in the HPS, the status of the modelling was regularly evaluated and further improvements were defined. Over the course of the project 5 sessions were held for several helicopter ship combinations, focussing on the most recently qualified helicopter-ship combination in the last two sessions. Two current (active-duty) RNLN pilots participated in the last session including the test pilot who performed the flight trials at sea. Landings and take-offs were performed for the same environmental conditions as were present during the flight trials for the RNLN.

7.1 Test program

The standard RNLN Fore-Aft procedure over port side was flown. The approach was a GPI approach along the 3-degree glide slope which is normally only done at night. This compensated for some lacking visual cues but hampered comparison with day-time flight test data (without GPI). Starting point was at 200ft with a groundspeed of 60 knots at a distance of 1 nm to the ship on a heading of 30 degrees relative to the ship. Take-offs were also performed over port. The procedures for fore-aft landing and take-off are as follows:

Landing:

1. Deceleration and descent up to the hover wait position abeam of the landing spot. The hover wait position is approximately 0.75 rotor diameter next to the ship (either starboard or port) with the horizon bar at eye level. The helicopter's longitudinal axis is parallel to the ship's centreline;
2. Side ward transition from hover wait position, horizon bar at eye level:
3. Hover over the landing spot, horizon bar at eye level;
4. Vertical descent to land-on.

Take-off:

1. Vertical take-off;
2. Hover position over the landing spot, horizon bar at eye level;
3. Side ward transition with simultaneous slow climb, to the windward side, until approximately 1.5 main rotor diameter next to the ship, abeam the landing spot;
4. Yaw approximately 30 degree and climb away from the ship.

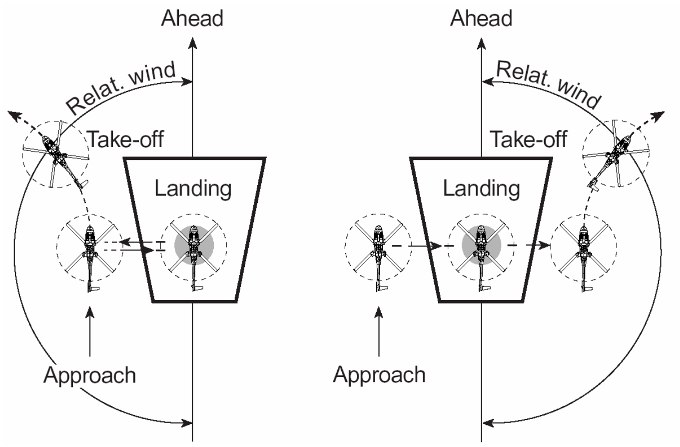


Figure 9 : Fore-aft port approach and take-off [1]

By using the wake rake wind tunnel measurements to model the ship air wake the available wind directions were limited from R90 to G90 with steps of 30 degrees. Relative wind conditions were chosen on the outer edges of the SHOL as determined in flight test and also one condition that fell outside of the SHOL.

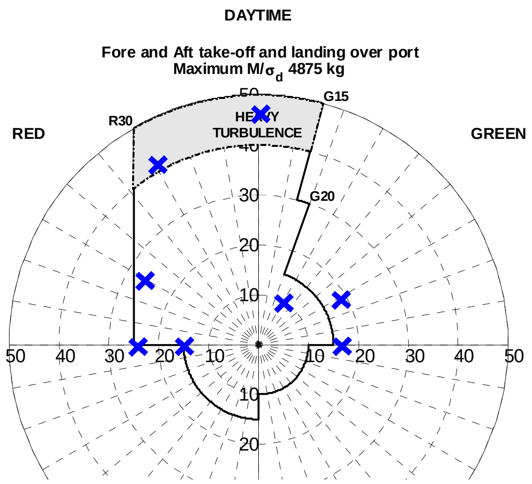


Figure 10: Test points piloted simulation session [1]

7.2 Test data

Figure 11 shows results for a relative G60/19 wind condition. Since radar altitude is plotted, the crossing of the deck edge is clearly visible as a sharp drop in altitude. Flight test for this condition was done during the day without GPI. Establishing a steady hover wait position took about 10 seconds more than in flight test which might be due to following the GPI. Finding the right position above the spot took over 10 seconds more.
Flight test ground speed is provided by Doppler speed which drops to zero when above the flight deck. The ground speed in simulation stays equal to the ship speed when above deck. During the approach the increase at 10s in torque in simulation leads to a deviation of the glide path. In the hover wait position the average torque matches well but variations in simulation are larger. When hovering above deck torque varies much more than in flight test with maximum levels over 120% (flight test 100%). One of the difficulties was that the pilots found it hard to find the correct collective setting, which is normally a task that does not require any special attention. However the lack of a vertical motion cue in the fixed base HPS is thought to have a large effect. To this end, a dynamic seat could provide the pilot direct heave cues and a 'seat of the pants' flying sensation which would likely yield more realistic collective handling.

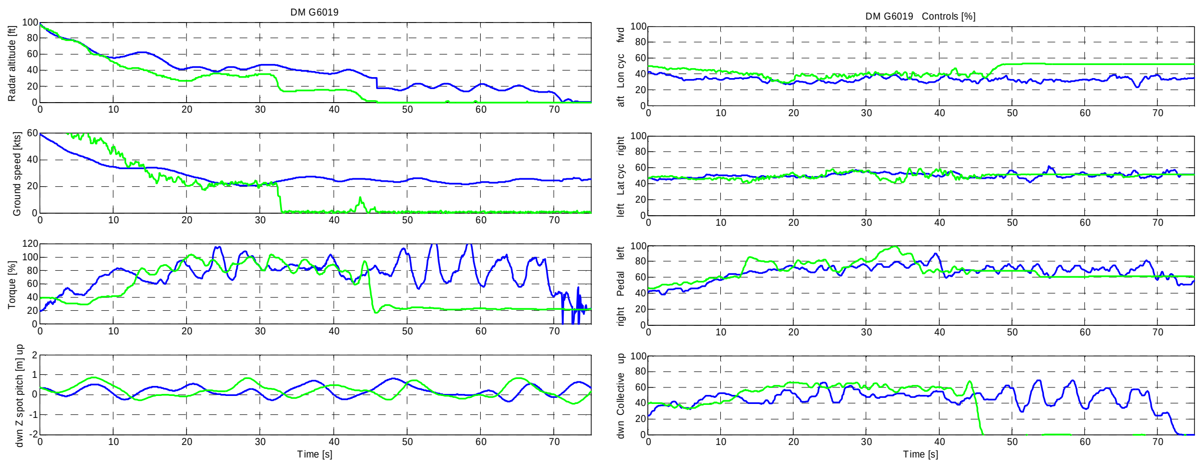


Figure 11: Landing over port, HPS session (blue) and flight test (green) for G60/19.

Longitudinal cyclic matches well. Variations in lateral cyclic are largest during sidestep In flight test the pedal stop was reached during the sidestep and therefore this test point did not make it into the SHOL. In simulation the maximum pedal was 90% and this occurred in the hover wait position port of the ship. Trim validation for shore-based hover results (without ship wake) showed that for the G60/19 relative wind condition pedal was under predicted.

Also take-offs over port side were performed. The trend was that torque variation during the hover above deck was larger than in flight test, with higher maxima.
In Figure 12 it can be seen that comparable results for the duration of the phases and the steepness of the climb-out were obtained. As seen in the landing, the hover above deck resulted in larger torque variations than in flight test with a maximum of 120% (flight test 100%). Longitudinal cyclic was under predicted up to 20%. Lateral cyclic shows a good match. Pedal is more under predicted than during the landing, up to 20%.

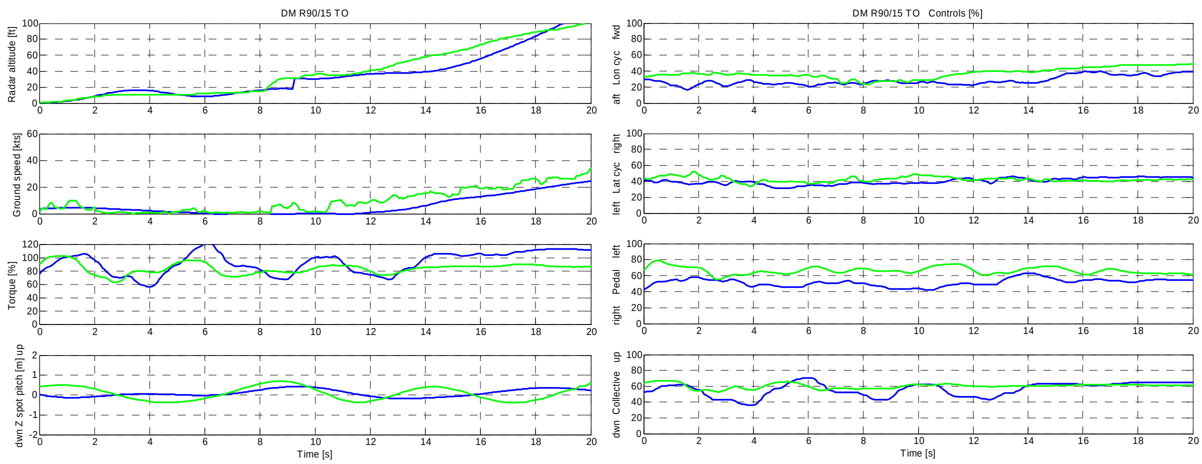


Figure 12: Take-off over port, HPS session (blue) and flight test (green) for R90/15.

In the final phase of the project this session will be elaborately repeated with the same RNLN pilots participating. This allows for a comparison with NLR flight test data for validation of the dynamic interface simulation. The Lynx model will then be further validated and improvements based on the pilot's feedback will have been made. Fredyn calculations will be performed for all test conditions to include the effect of heave in the vertical spot motion and its effect on collective and torque.

7.3 Pilot rating

Torque and tail rotor considerations alone are not adequate to cover all factors influencing the limitations, and it is necessary for the pilot to assess the workload associated with a take-off and landing. For the pilot's assessment of the flight trials, rating forms are filled out for each test condition. Ratings are given on the NLR 4 point rating scale. The pilot rating is given for the 4 separate phases of the take-off and landing. Only the highest ratings are taken into account as these represent the critical conditions.

Rating	Pilot workload
1	minimal
2	moderate
3	considerable
4	not acceptable

Although the test pilot involved in the sea trials gave ratings in the HPS comparable to those he gave in flight test, the HPS ratings are not considered very trustworthy yet for deciding whether the specific relative wind condition should be in the SHOL, since it is unclear yet what discrepancies in the rating say about the fidelity of the simulation. One pilot noted for example that because of missing cues he was flying more cautious than normally. When trying to fly as in normal flight this resulted in worse performance and higher pilot workload rating.

Another pilot gave better ratings but performed less well requiring more time and hovering further away from the ship. This pilot does not have any experience with helicopter operations on the subject ship. This pilot had not been working with the NLR rating scale before and considered it too limited for assigning a workload rating. In the sea trials regularly half points were given, suggesting larger scale might be useful for flight testing too. In the last session (planned in September) the Cooper Harper workload rating scale will be used as a comparison with the 4 point NLR rating scale.

8. SUPPORTING SHOL PREDICTION

8.1 Validation

Besides the validation of the helicopter flight dynamics model (discussed in 5.2), the entire simulation-chain needs to be validated through piloted sessions for its intended purpose of supporting the prediction of shipboard limits. These piloted sessions provide feedback on discrepancies and missing cues, enables comparison with helicopter parameters as measured in flight test (speed, altitude, control positions, attitudes) and pilot rating. When only a very high level of fidelity is considered 'good enough' this will be at the expense of higher cost. Also, the fidelity of the sub-models must be in balance with each other, e.g. full-motion would not be useful if the helicopter model is not considered realistic enough.

The results of the piloted HPS sessions have been compared with the flight test data to qualitatively describe the fidelity of the modelling. However, no quantitative fidelity criteria are available in the literature for validating the helicopter-ship dynamic interface simulation in a real-time piloted session in the simulator.

8.2 Implementation in SHOL method

A helicopter-ship simulation capacity is thought to be able to support the current SHOL method through safe exploration of the CFEs in an early stage without depending on the availability of personnel, materiel and the required environmental conditions. Exploring the CFEs in simulation should enable the flight test engineers to draw up a more refined test program for evaluation at sea. It is therefore thought that simulation can increase the efficiency of the current helicopter-ship flight testing at sea and save on required time and money.

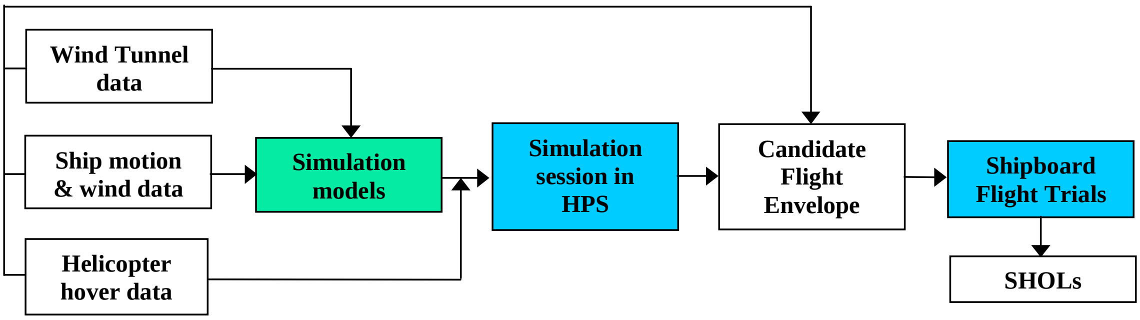


Figure 13: Contribution of simulation to SHOL determination.

The fidelity of the simulation capacity will likely be further evaluated in a follow-up project. The focus will be on the actual use of the simulation capacity by running parallel to the upcoming qualification process of the next RNLN helicopter-ship combination. So without delivering an actual input, results obtained by simulation will be compared to those of the current method. This is to define to what level the simulation can support the SHOL determination process.

8.3 Future additions

Additional wind tunnel tests should be carried out to obtain data on ship air wake turbulence through step-by-step measurements. More relative wind directions should be covered with the wake traverses, including winds from the aft sector which is now completely lacking. Also a traverse upwind of the spot should be included to be able to create a complete, realistic ship air wake field.

The use of Fredyn for ship motion calculations enables a head-start to produce first results in the simulator since no dependency on the acquisition of full-scale ship motion in the maiden trip exists. Nonetheless, inclusion of heave measurements in future full-scale ship motion and wind climate tests is considered worthwhile. This would enable simulation of the exact same ship motions as in flight testing for further validation of the helicopter-ship dynamic interface simulation.

The Helicopter Pilot Station will be upgraded at the end of 2007 with a 180 degree by 50 degree visual system. In the mean time NLR is also developing a new full mission helicopter research simulator with a larger field-of-view.

9. REFERENCES

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