

AN OVERVIEW OF SHOL TESTING WITHIN THE ROYAL NETHERLANDS NAVY

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This is a critical overview of the Ship Helicopter Operational Limitation (SHOL) qualification program currently used by the Royal Netherlands Navy. The qualification program, in which first separately the environment and helicopter characteristics are determined, has proved to be useful for the Westland Lynx SH-14D. Unfortunately the test philosophy requires independent testing of each helicopter-ship combination during dedicated sea trials. The test campaigns at sea are time consuming and require a long planning process, while usually allowing only one chance within a small window in which everything must come together. Therefore, research is conducted for optimizing test efficiency and reduce time and cost of the qualification process without concessions in safety for the introduction of the NH-90. Three alternatives are described to replace sea trials namely: flight simulation, read-across with other helicopter types and an analytical network. All three methods have potential to partly replace sea trials and should be investigated and cross-checked with each other. If it proves to be difficult to completely replace sea trials, it should be possible to certify at least the areas where enough confidence is established in the envelope predictions and the SHOL envelope should be adjusted accordingly.



Figure 1: NH-90 NFH

1 Introduction

At present the only method to qualify a SHOL for a helicopter-ship combination is by actual flight tests at sea. During the sea trials there are usually independent tests for each ship class/aircraft, landing spot, approach type, day/night conditions, and ship motion at each relative wind condition. The sea trials are time consuming, expensive and

dependent on the environmental conditions encountered, where usually low winds result in a small envelope, even though the actual envelope may be much wider. Especially the tail and cross wind sectors are entirely dependent on the natural prevailing winds, as the ship can only sail forward instead of rearward or sideward to create the relative wind vectors. The test campaign at sea also requires flexibility with regard to aircraft/ship unserviceability and operational commitments of the ship. Therefore, once planned it usually allows only one chance to conduct the sea trials

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within a small window in which everything must come together. Because lack of testing, or benign testing conditions, the actual SHOL envelope may never be known, and the full operational potential of the helicopter-ship combination may not be realized.

2 Qualification process

Due to the innumerable helicopter-ship combinations possible it is understandable that usually no (extensive) testing has been carried out by the helicopter manufacturer for all combinations that may be of interest. To determine SHOL limitations for ships operated by the Royal Netherlands Navy a dedicated helicopter-ship qualification programme is conducted by the National Aerospace Laboratory (NLR) [1], [2]. The qualification program used for certification of the Lynx helicopter is explained, including the most recent improvements made for optimizing test efficiency for the introduction of the NH-90. 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 characteristics during shore-based hover trials as shown in Figure 2.

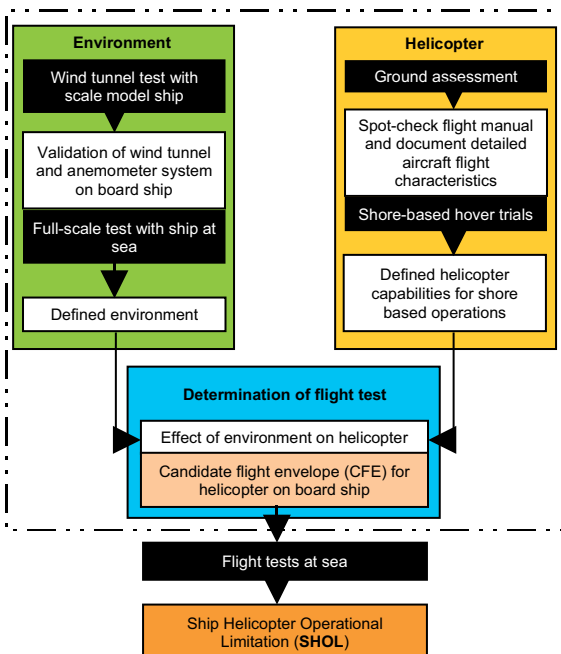


Figure 2; Flow chart current approach with ground assessment [1]

2.1 Environment

The environment near the ship deck is determined as follows. Wind tunnel tests on ship models are carried out to determine the airflow characteristics and exhaust plume paths above the flight deck and in the possible approach path of the helicopter to the ship as a function of the relative wind. The same is done for the optimal position of the ship's anemometers. The aim of the full scale wind climate test on board the ship afterwards is to establish the magnitude of errors in the ship's anemometer system, verify wind tunnel test results and determine ship motion characteristics. With the information obtained, an unambiguous relation between the anemometers readings, the undisturbed relative wind conditions, the air flow conditions above the flight deck and in the helicopter approach paths is determined as shown for a frigate type ship in Figure 3. Relative wind conditions above 50 knots are not documented. As the ship's maximum speed is around 25 knots, the natural windspeed should be at least 25 knots. These winds would result in high sea states, and thus deck motion, which would make helicopter-ship operations impossible.

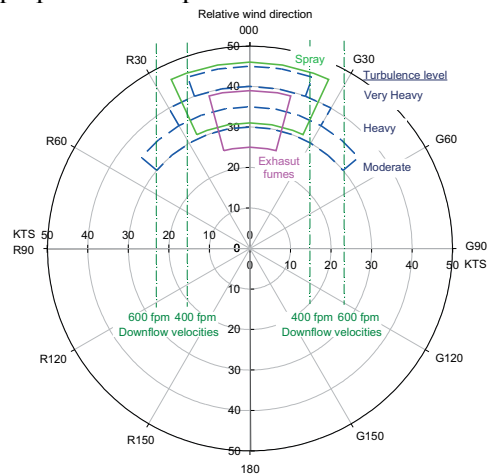


Figure 3; Example environmental conditions frigate constructed with existing data [1]

The airflow near the ship can generally be characterized by the existence of at least three flow recirculation regions as shown in Figure 4 [3]. One recirculation region, occurs upstream of the body. When seen in side view, as the ambient wind encounters the body the airflow splits in two directions; some airflow flows down toward the ground surface, and the other moves up and over the body. The flow from the first recirculation region forms a three dimensional horseshoe like ring vortex that extends outward and downstream around the sides of the body. This vortex is also

known as a necklace vortex, because it encircles the body. The second recirculation region occurs just downstream of the separated flow that occurs along the upstream top edge of the body. In general, the second recirculation region extends along the top, and often the side edges of the body. The last recirculation region is largest of the three, and corresponds to the separated flow one to three body lengths downstream of the body. Fluid mechanically, this region is called the near wake. All three recirculation zones could restrict the SHOL envelope and should be documented during determination of the environment near the ship deck.

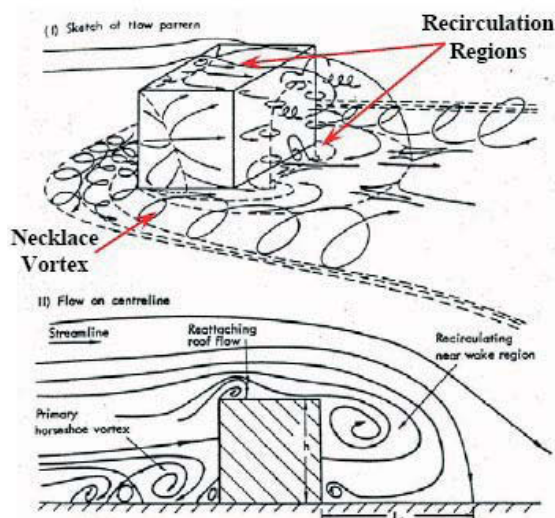


Figure 4; Three dimensional sharp edged bluff body flow [3]

The recirculation zones have the following characteristics influenced by the relative and natural wind conditions: the airwake includes high levels of turbulence (20-30%), time varying airwake with typical peak frequencies in the range 0.1 Hz – 1 Hz and shear layer bounding areas of high and low speed flow [4]. In general, the airwake near the ship deck comprises two components: a steady wind field and an unsteady component superimposed on the steady winds. The limits of the envelope are more often than not defined by pilot workload due to airwake turbulence (the unsteady component), or control limits due to the steady wind field.

There is a large amount of research into the use of Computer Fluid Dynamics (CFD) and stochastic airwake models near ships, and this research could improve the prediction of the airwake [5], [6], [7]. The use of those airwake models in the determination of the environment is currently

investigated and could replace or complement wind tunnel data. However, validation of the anemometer system on board the ship, which is one of the major issues during the qualification process, will still be required.

2.2 Helicopter

A large number of factors affect and restrict the capability of a helicopter to operate in the low speed regime. Most of the items are already identified and documented in the aircraft manual (usually not in the required detail), while other items need to be determined during shore-based trials. These items include for example [8]:

- *Handling qualities*, affected by Flight Control Mechanical Characteristics (FCMC), stability and control characteristics and cross-coupling issues;
- *Control margins*, usually 10% is used;
- *Stress limitations*, maximum rate of yaw and lateral velocity imposed by the manufacturer;
- *Performance issues*, poor vertical performance restricts the envelope;
- *Vibration levels*, for comfort of the aircrew and passengers;
- *Engine and engine control system*, could limit the rate with which collective lever movements could be made;
- *Undercarriage*, restricts vertical velocity during impact and is imposed by the manufacturer;
- *Rotor system*, restricts the degree of slope to operate from and is usually imposed by the manufacturer;
- *Center of gravity*, could restrict the low speed envelope even further for certain conditions and the worst case conditions should be tested;
- *Field Of View (FOV)*, restricts the maximum pitch and roll attitudes to maintain visual contact with the landing zone.

The determination of the helicopter characteristics starts with a ground assessment where FCMC and FOV are determined. The handling qualities, control margins, performance issues, vibration levels and aircraft attitudes due to a steady wind field are determined by static stability testing conducted during shore-based hover trials. These

shore-based static stability hover trials are conducted Outside Ground Effect (OGE), as the contribution of ground effect is considered minimal in the dynamic environment near the ship deck. The established performance margin, pitch and bank angles, controllability limits and other issues in the low speed envelope for the Lynx helicopter are than documented as shown in Figure 5.

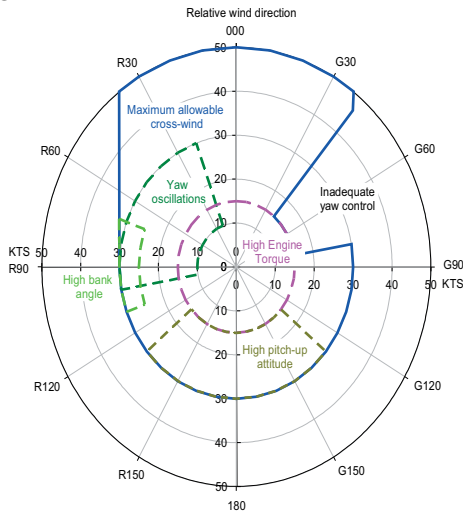


Figure 5; Example Lynx results shore-based hover trials constructed with existing data [1]

As indicated the conditions with cross-winds from starboard are the most critical, for the Lynx helicopter with its counter-clockwise main rotor and bottom-aft rotating pusher tail rotor mounted on the port side for several reasons. First, the tail rotor thrust should not only compensate for the reaction moment of the drive system of the fuselage, but also an aerodynamic weather-cocking moment of the cross-wind on the rear fuselage and fin. Secondly, the large tail rotor thrust is required in the propeller working state wherein the thrust vector is opposite to the direction of the cross-wind, which decreases the blade angle of attack. Finally, the bottom-aft rotating tail rotor is not considered as efficient as the bottom-forward rotating tail rotor [9]. In the newer version of the Lynx helicopter operated in the United Kingdom the tail rotor rotates bottom-forward and the area on starboard with inadequate yaw control does not exist anymore.

With a relative wind from port, the tail could be in the vortex ring state, wherein the thrust vector has the same direction as the cross-wind vector. Furthermore, certain combinations of cross-wind speed and flow through the main rotor in this state are forming a so-called region of unsteadiness

with yaw oscillations. The region of unsteadiness is influenced by main rotor-tail rotor wake interference and has implications for helicopter directional control. This effect is stronger for bottom-aft rotating tail rotors [9].

The helicopter attitudes and torque requirements can be explained as follows. The high pitch-up attitudes for tail wind conditions are due to the lift vector which has to be tilted slightly backwards to maintain the ground position. The high bank angles for winds from the left side are the result of the tail rotor pushing on the port side of the helicopter. To stop the resulting sideward drift to the right, the helicopter banks to port in the hover condition. When the wind comes from port there is more drift to the right to compensate and thus more bank angle required. Finally, the high engine torque requirements for low speeds are related to the power required curve, which indicate that the highest torque levels are required to hover and show a decrease in power required with increasing airspeed.

The pilot workload and vibration levels determined during the static stability testing for hover at wind speeds from all direction relative to the helicopter can be plotted as shown for pilot workload in Figure 6. The workload is expressed by the Deck Interface Pilot Effort Scale (DIPES) which is further explained in the next chapter. The data obtained indicates where, within the land-based envelope, regions exist where pilot workload is too excessive for ship-board operations and indicate the importance of the issues found during static stability testing.

The static stability testing during the shore-based hover trials could be complemented by control response testing and relevant role maneuvers. There is research into the use of ADS-33 in a maritime environment, and that research could improve the prediction of low speed helicopter characteristics for the CFE [10]. Furthermore, the dynamic testing could be used to test the helicopter with different aggressiveness levels and document the characteristics before conducting the sea trials. This information should be required as it would be very likely that operational pilots do not always fly as accurate as the pilots which conducted the sea trials.

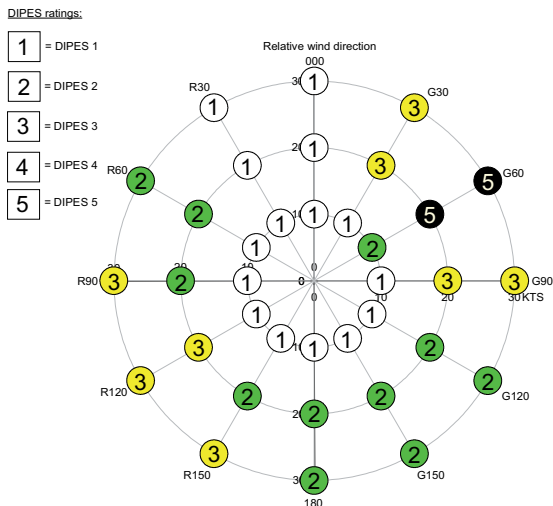


Figure 6; Example presentation pilot workload in hover (not based on flight test data)

2.3 Candidate Flight Envelope

Knowing the environment near the ship deck and the relevant characteristics of the helicopter in the low speed regime, the effects on helicopter operations near ships are estimated in a CFE, which is to be confirmed or adapted on the basis of flight test at sea as shown in Figure 7. The CFE is based on the land-based relative wind diagram of the helicopter in which the predicted hazardous environmental conditions near the ship deck are left out. Thus, more flight envelope restrictions for maritime operations are imposed than during land-based operations. The CFE is then the starting point for the construction of a flight test plan. If the determination of the amount of testing at sea would not be possible quantitatively, then it could be done at least qualitatively.

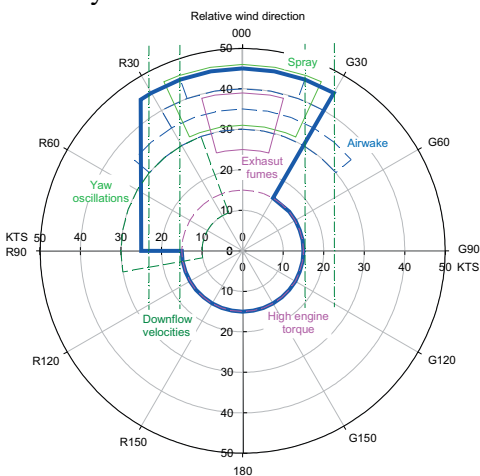


Figure 7; Resultant CFE constructed with existing data [1]

It should be noted that a CFE envelope results from measurements of the ship’s environment, helicopter performance measurements and analyses. Whether or not this envelope could be used operationally still has to be determined by means of dedicated flight tests at sea. The operational wind envelopes are then drawn up around the acceptable test points attained during the sea trials and are established as SHOL. The acceptable data points for the SHOLs should then be connected, where bold lines indicate boundaries dictated by workload or aircraft limits; thin lines should show where boundaries were established because no further data could be recorded. This will allow easy planning for additional SHOL trials for envelope expansion. The SHOLs are expressed in relative wind speed, relative wind direction, deck motion and All-Up Mass (AUM).

3 Qualitative test technique

In spite of all the research into stability and control flight test techniques it is still impossible to guarantee good handling qualities by designing aircraft so that all the aeroderivatives fall within certain limits. Therefore, handling qualities investigations of aircraft are conducted to determine if the pilot-aircraft combination can safely and precisely perform the role for which it is intended. In general terms the task as a test team will be to define the usable flight envelope of an aircraft based on the role the aircraft is intended to perform. The correct choice and use of a handling quality rating scale and amount of test pilots required will be particularly important.

The performance associated with a particular task, defined by a set of tolerances, is the standard to which the task should be accomplished. The performance achieved is an expression of the amount of pilot workload and compensation, be it physical and/or mental required to achieve a particular standard, or level of performance. Adequate performance will allow the task to be achieved, while desired performance is what you would like to achieve related to the role. In making an assessment, the test pilot should concentrate on own judgment or reactions, and should not attempt to explain or analyze the reasons for the aircraft’s behaviors during flight.

The handling quality rating is not necessarily prescribed by the task tolerance required to

achieve. A rating in isolation does not tell the whole story; it must be associated with a verbal description of the extent and nature of the associated pilot compensation. This information must, therefore, be recorded coincidentally with the allocation of the rating itself. The rating should be awarded as soon after the task has been flown as feasible, otherwise it becomes less and less valid as memories and impressions fade. There needs to be a very good reason to change the ratings initially assigned. Furthermore, it is unreasonable to expect a test pilot to give an accurate handling quality rating to a task the first attempt. Some allowance will have to be made for the learning skills and adaptability of the individual by the conduct of a certain amount of practice. The amount of practice required for the test pilot can vary depending on experience level. However, care must be taken that the test pilot does not become too familiar with a task.

Pilot compensation during SHOL qualification is mainly a measure of the additional pilot workload necessary to achieve a given level of performance in the environmental conditions near a ship deck. In other words, compensation is effort over and above that which would be required if the vehicle was perfectly adapted for the task. For sustained period, the pilot can only provide a small degree of compensation for those environmental conditions. The degree of pilot compensation and hence workload, necessary to overcome the environmental conditions near the ship would be used as a measure of boundary's for the SHOL envelope.

The DIPES workload scale is a 5-point scale also in use by both the Naval Air Systems Command (NAVAIR) in the United States and QinetiQ in the United Kingdom for SHOL testing as shown in Figure 9 [11], [12]. The evaluator is led through a number of two possible decisions to one of the categories. The advantages of this scale are that it is only a 5-point scale, which could be used for multiple task evolutions for multiple axis tasks. There are not too many specific tolerances required and its supports binary decisions. The ratings are coupled to different colors based on a traffic light, which is easier to use during data analysis. An example from a SHOL trial conducted in the United Kingdom is shown in Figure 8, beware there are different colors used for each rating.

To allow comparison of the ratings assigned with the DIPES rating scale, ADS-33 criteria and acceptable and unacceptable conclusions these items are combined as shown in Table 1. The DIPES rating includes suffixes indicating the reason for the deficiencies enabling a better understanding of the rating and direct comparison with issues encountered during shore-based hover trials. Furthermore, the handling quality ratings assigned by the pilot are compared to quantitative data as shown in Table 2. The highest rating of the quantitative data and qualitative data is used as the correct rating for the tested condition.

For SHOL qualification usually only one pilot flies each test condition twice. Although the opinion of the pilot is formed in collaboration with the observations of the co-pilot and the Flight Test Engineer (FTE), there are only two ratings upon which to define the final shape of the envelope. Since the development of SHOLs is highly dependent upon the subjective ratings of the experimental test pilots, those ratings must be supported with quantitative data and instrumented aircraft should be used. Particularly since the test conditions encountered during SHOL qualification can not be accurately reproduced at-sea as they can in any simulation.

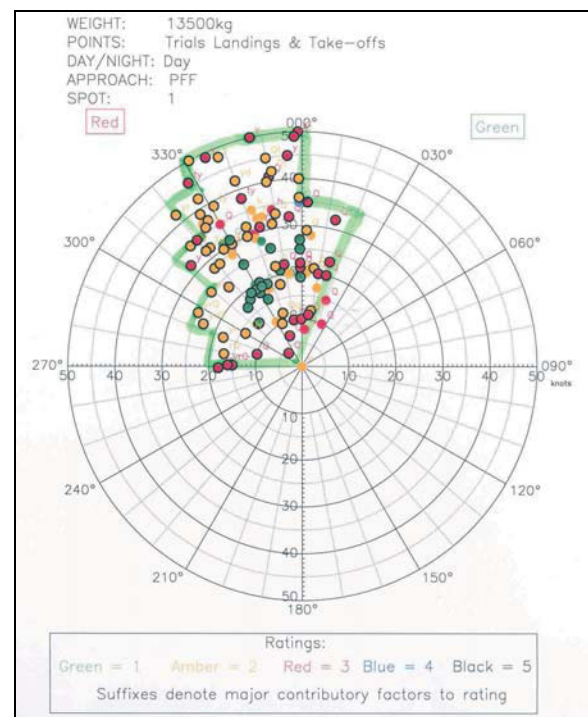


Figure 8; Example DIPES ratings [12]

Table 1; Relationship between DIPES and other assessment criteria

Achieved performance	DIPES	ADS-33 level	Conclusion
Desirable	1 2	1	Acceptable
Adequate	3	2	
Inadequate	4	3	Unacceptable
Loss of control	5		

Table 2; Objective data [12]

Torque (%)		Tail rotor pitch (%) (100% = full tail power)		Rating
Mean	Peak	Mean	Peak	
<90	<100	<85	<90	1
90 – 95	100 – 106	85 – 88	90 – 93	2
95 – 99	106 – 111	88 – 91	93 – 95	3
99 – 106	111 – 117	91 – 95	>95	4
>106	>117	>95	Yaw	5

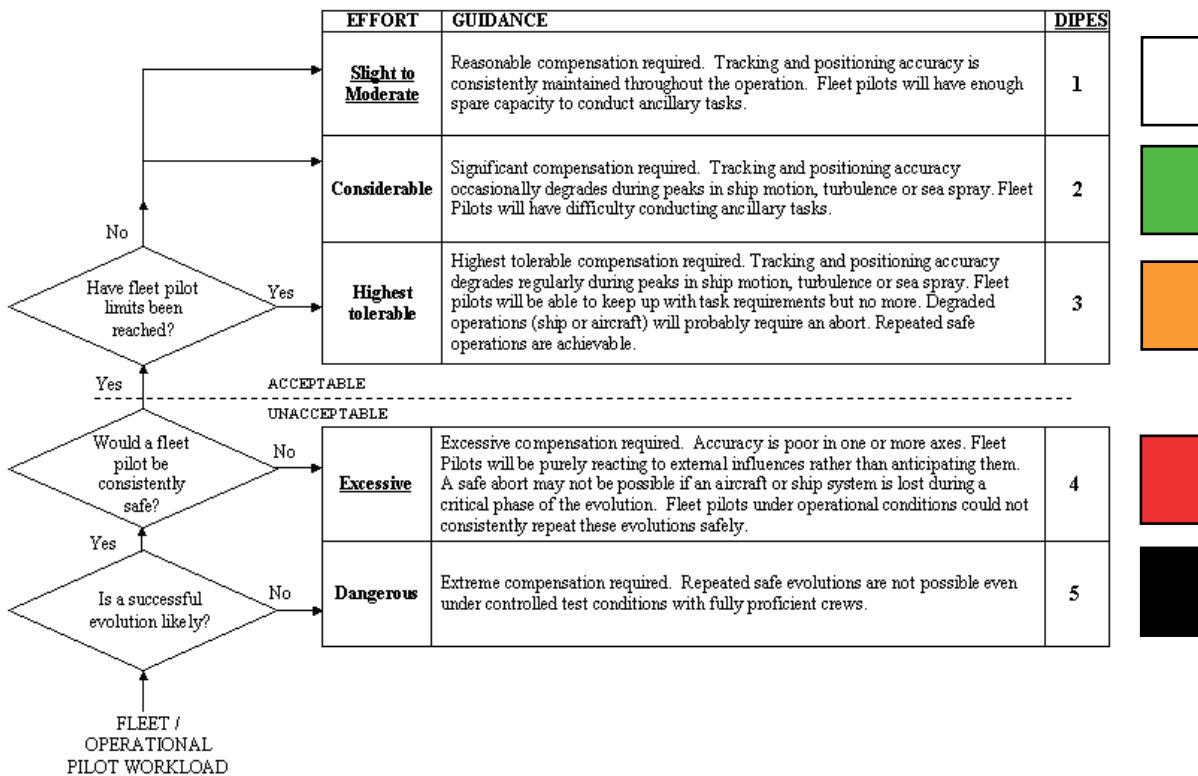


Figure 9; DIPES rating scale [12]

There is an assumed relationship between assigned ratings for pilot workload and difficulty of the task as shown in Figure 10. It shows that pilot workload increases with increasing difficulty of the task, but it also shows that the scatter in the assigned pilot workload (error bars) varies with increasing difficulty. This could result in a pilot which rates the test points usually somewhat higher as the average pilot and is on the safe side. Although it could also be possible that the pilot rates somewhat lower as average and test points could be included in the SHOL envelope, which would be more difficult to fly by the average pilot. Some clarity on this situation can be achieved by recognition of the fact that poor handling qualities can be compensated by training. In other words after enough training it is likely that every pilot can fly each other SHOLs, but only after enough training and thus costs.

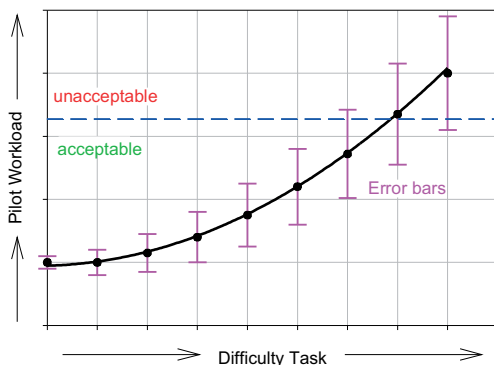


Figure 10; Assumed relation for pilot scatter with task difficulty (not based on flight test data)

The importance of multiple pilots and objective data gathering was demonstrated during the final evaluation of the Dynamic Interface Modelling and Simulation System (DIMSS) project in the United States [13]. During the evaluation multiple pilots flew the same test condition in a simulator. The result was three different envelopes, with some significant differences that cannot be ignored, indicating the large subjective contribution of the pilots for the final shape of the SHOLs. Therefore, quantitative data should be used to establish a correlation with the qualitative assessment of workload given by the pilot. This is required to compensate for the difference in qualitative opinion of the test pilots used and to cross-check the assigned ratings. This also highlights the shortcoming of most SHOL qualification programs where usually only one pilot is used.

Those differences in pilot opinion are not a surprise and experience has shown that one of the following items is usually responsible [14]:

- The pilot is using a different technique than the other pilot;
- The pilot is flying the task differently, usually with a different level of aggressiveness;
- The disturbance environment is not the same, usually as a result of using a random turbulence model, or flying on days with differing wind conditions;
- The level of training is not consistent. Additional training may be necessary to get some pilots up on the learning curve. It is also possible that some of the evaluation pilots may be over trained which can have a dominant effect on the ratings;
- The high level of concentration required, and the repetitions nature of handling qualities experiments leads to rapid pilot fatigue. Experience has shown that pilot rating scatter can often be traced to a fatigued (and hence unmotivated) evaluator. The effect is subtle in that the pilot himself may not recognize the symptoms, and is often anxious to “press on”;
- There is vested interest to include certain parts in the SHOL. Some pilots do not want to come back to the operational squadron after a test campaign and show a very small SHOL, which the coming years all pilots are restricted to use.

4 Comparison Lynx SHOLs

The Westland Lynx SH-14D helicopter used by the Royal Netherlands Navy is in service since 1976 and is still qualified to operate from six different ship classes. The Lynx helicopter will be replaced within the near future by the NH-90 and therefore near the end of service within the Royal Netherlands Navy it is time to learn the lessons from the past and use them for the future.

4.1 “Common Lynx SHOL”

A simple comparison was made between indicated wind conditions, without anemometer corrections, for the most recent SHOLs presently in use for three completely different ship types (see Figure 11 to Figure 13): an auxiliary ship “Hr.Ms.

Amsterdam”, a Landing Platform Dock (LPD) “Hr.Ms. Rotterdam” and the air defence and command frigate “Hr.Ms. de Ruyter”. The previous SHOLs were not taken into account as it showed that the size steadily increased during each helicopter-ship qualification process based on the experience. The SHOLs for the last three ships are very similar and were considered representative towards the maximum achievable envelope for those ship types. This indicates the importance of confidence in the CFE, reducing the required safety steps for an incremental approach during sea trials, resulting in a wider envelope.

The three different SHOLs, for a daytime fore-aft approach, were plotted and the area enclosed within all these SHOLs was studied as shown in Figure 14. It shows the green and red sector on a polar plot where the azimuth and wind speeds of the relative wind conditions are shown. This “Common Lynx SHOL” became an average of 24% smaller than the SHOLs for the three different ship types individually. The differences were mainly in the tail wind conditions and some for the maximum wind speed in the forward sector and the cross-wind component from starboard.

The differences between the envelopes for each ship were affected by: the different environmental conditions encountered, time constraints, different pilots flying the tests and the accuracy of the anemometer systems. This had some impact for the boundaries of the SHOL and care should be taken without a proper understanding of the test campaign to consider the envelope as the full representation of the helicopter-ship combination. For this example, the differences in the forward sector could be explained by the physical parameters of the superstructure, as the lower hangar of the “Hr.Ms. de Ruyter” produced less airwake recirculation for higher wind speeds allowing a larger SHOL in that area. The differences in tail wind conditions were due to time constraints. Finally, the anemometer error for one of the ships restricts the indicated relative wind in the green sector towards 15-20°. When those corrections would be applied the “Common Lynx SHOL” could be increased towards green 30. Although it is a simple comparison, it shows that the SHOLs for the Lynx helicopter were mainly dependent at the own shore-based relative wind envelope. Most effects from the environment near the ship deck were predicted as shown in Figure 7.



Figure 11: Auxiliary ship “Hr.Ms. Amsterdam”



Figure 12: LPD “Hr.Ms. Rotterdam”



Figure 13: Frigate “Hr.Ms. de Ruyter”

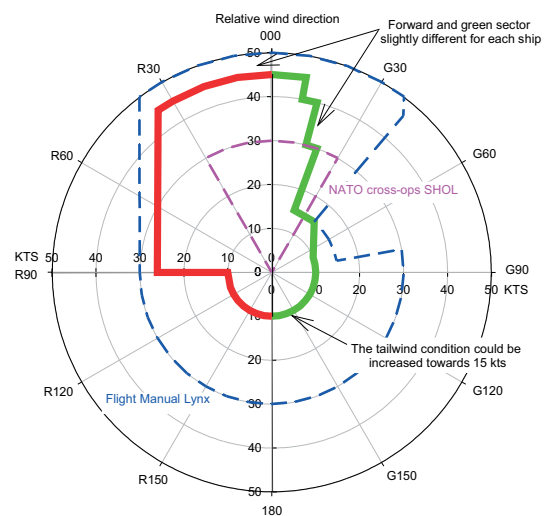


Figure 14: Constructed “Common Lynx SHOL” with flight manual comparison [15]

The differences with the flight manual are due to the tail wind conditions which are usually 15 knots maximum near the ship deck to avoid high pitch-up attitudes and high closure rates with the superstructure. For green winds the pedal limits and margins for control activity in the airwake near the ship deck mainly contribute to the reduction in size. Furthermore, there needs to be a safety margin with the maximum lateral velocity limits to avoid exceeding those limits during lateral re-positioning above the flight deck. Important to note is that the NATO cross-ops SHOL is not included for all these ship types and care should be taken to use the NATO cross-ops SHOL without proper understanding of the limits for each particular helicopter type and ship characteristics.

4.2 Drawbacks current approach

A cursory analysis of the current approach to developing a helicopter-ship system reveals that SHOL envelopes are never specified in advance of the ship or helicopter design. Instead, the ship and helicopter are designed and built independently and only then is the SHOL envelope tested. There is no specification of the envelope prior to the design process; the envelope that results from the combination of the independent designs is what is accepted. The process contrasts sharply with a typical procurement procedure in which a system is designed and built to an agreed set of requirements. Thus the envelope development process suffers from two inherent problems: First failure to specify performance requirements for the helicopter-ship system and secondly failure to fully test the performance of the system. Furthermore, there is no worldwide recognized regulation for the conduction of the SHOL qualification process.

The improvements in accuracy of the models and methods to determine the environment near the ship deck and implementation into flight simulations could be used during the development phase of both the helicopter and ship for this purpose. These improvements in simulation capability in contrary do not automatically result in a reduction in the required sea trials during the qualification phase. They are beneficial for the determination of the CFE and could increase safety and time during the sea trials, but it is presently hard to replace actual flight tests with the current test philosophy. Those sea trials are dependent on the encountered environmental

conditions and subjective ratings of the test pilots. As a result the question remains if the certified SHOL is a full test of the performance of the system. When applying all the new developments in the qualification program it would be required to find a balance between costs for prediction of the CFE and the use of dedicated sea trials as shown in Figure 15. It shows that there will be a situation in which the additional costs used for the determination of the CFE will only increase the total costs and no benefit comes from all the improvements in simulation. Furthermore, it shows that the largest cost reduction could be made in reduction or complete replacement of the required sea trials.

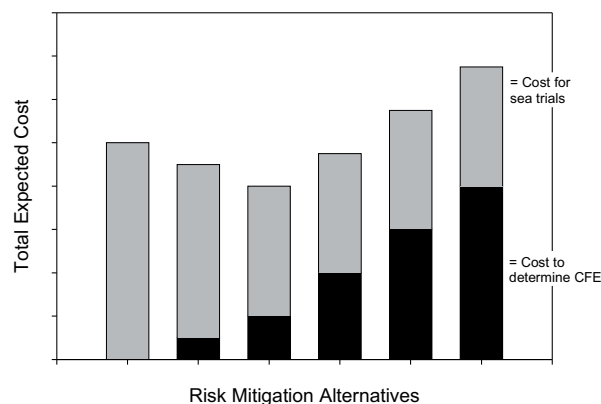


Figure 15; Estimated cost for SHOL qualification with sea trials included

Good, practically applicable alternatives should be developed to reduce or replace sea trials at minimal cost for the CFE predictions according to the principle “as simple as possible, as complex as necessary”. For these alternatives the goals should be properly set during the development phase. The development of such alternatives is complicated by a lack of quantitative knowledge of the involved uncertainties near the ship deck. Therefore, further research should not only aim for more prediction methods, but should also aim at quantification of the related uncertainties. This process requires analysis and understanding of the real system and the involved phenomena that drive the SHOL boundaries.

A task of the modeler afterwards is to “qualify” the model, where qualification is the determination of adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application. Thereafter, validation is the process of determining the degree to which a model is an

accurate representation of the real world from the perspective of the intended uses of the model. The better the overlap between the validated domain and the application domain, and the better the understanding of the underlying physical (and mathematical) principles, the stronger the inferences with respect to accuracy could be. The effect of validation and application domain on the strength of inference is shown in Figure 16. Clearly the inference in a non-overlap case as shown could be less firm, than for the full-overlap case in which the application domain falls within the validation domain.

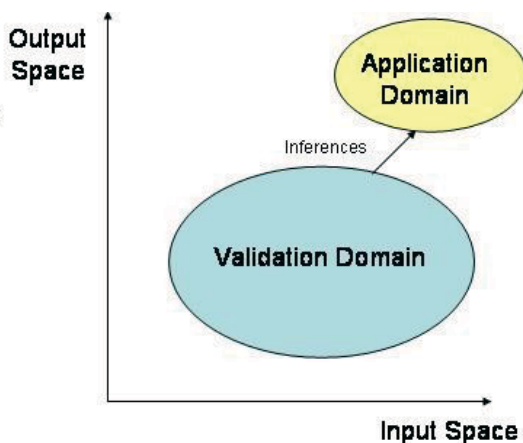


Figure 16; Difference in justified confidence level for validation and application domain [16]

A SHOL simulation tool could thus only be used to make predictions with a sufficient certainty, after it has successfully passed the validation phase. As a result an optimized SHOL simulation tool for a new ship or new helicopter can only be developed after the first sea trials are conducted. This requires that for the first SHOL trials, the simulation tool analysis and actual sea trials should be conducted in parallel. Once it passed these phases it could be used for other helicopter-ship combinations. The simulation tools should then indicate which areas could be certified with predictions only, which areas need to be tested anyway and which areas are dangerous taken out of the envelope before even conducting the sea trials. This process is actually already used to determine the CFE, however there is still not enough confidence to replace actual sea trials, which with the current simulation developments should be just a matter of time. Especially, as there will be similarity in every helicopter-ship combination tested, as this is mainly based on the helicopter characteristics.

5 Alternatives

The main questions that must be answered are: 1) How much at sea testing is required to reduce time and cost of the qualification process without concessions in safety? 2) How much data is then required before enough confidence could be placed in a flight envelope predicted through analysis, simulation and/or previous experience with the helicopter and ship type? The answer is necessarily based on fidelity of the alternative test method.

The Simulation Interoperability Standards Organization (SISO) [17] defines fidelity as: *'The degree to which a model or simulation reproduces the state and behavior of a real world object or the perception of a real world object, feature, condition, or chosen standard in a measurable or perceivable manner; a measure of the realism of a model or simulation; faithfulness. Fidelity should generally be described with respect to the measures, standards or perceptions used in assessing or stating it.'*

5.1 Flight simulation

Flight simulations provide an attractive contribution to the current helicopter-ship developmental and testing scenario allowing controlled testing of the system. It should be noted that there is a strong emphasis on the word "estimate". The simulation could only estimate flight envelope, with accuracy depending on the fidelity of the simulation. Less confidence can be placed in an envelope estimated by a low fidelity simulation opposed to an envelope predicted by a high fidelity simulation. Indeed, there are a number of current operational training simulators with a shipboard scenario but none have been used to predict flight envelopes because the fidelity is considered insufficient for the task. Even for training, simulators are only used to introduce the pilot to the shipboard environment, and do not provide a substitute for at sea shipboard landings because existing fidelity falls short of that required.

To make an accurate prediction of the SHOL envelope, high fidelity levels are necessary for the airwake and aerodynamic models, in addition to the interaction between them. Thereafter intensive tuning is required to match with the actual test data [18]. The additional amount of work required to tune the simulation model after the

SHOL trial is not cost beneficial for qualification purposes, but could be beneficial for training. This was demonstrated after extensive research for the Dynamic Interface Modeling and Simulation System (DIMSS) project in the United States [13]. The goal of DIMSS was to define a process for expanding SHOLs for any helicopter-ship combination using modeling and simulation. The man in the loop simulation included several high fidelity models of the ship and ocean environment, aircraft cockpit, flight controls and flight characteristics. The project was supported by an extensive verification, validation and accreditation process, where data was collected during two sea trials. Despite two dedicated sea trials, the test conditions were not favorable for achieving the necessary test results for validation. Ironically, one of the reasons why modeling and simulation could be used for SHOL qualification, the ability to test any condition, is the reason why the simulation could not be accredited. While the lack of validation data from flight test caused the project to fail short of achieving full accreditation, the achievements of the program were used to the advancement of shipboard training.

The improvements in the current flight simulations have much potential to replace actual training hours for deck landings, and could replace certain areas of the SHOL qualification process in the near future. This could only be possible when the shortcomings of the simulation models are known in detail. Some of the present challenges are for example. The ships airwake characteristics which can only be pre-computed for a limited number of ship motion profiles while the physical ship motion is a random and statistical process. An erroneous phase error could occur between the ship airwake that has been generated from a pre-defined ship motion profile and the on-line computed real time ship motion due to the limited length of the pre-computed ship airwake time variation. Furthermore, the interaction between the ship airwake and the airflow generated by the helicopter should be understood. This is because a rotor operating close to a superstructure develops a completely new flow field, which cannot be determined by simple vector addition/subtraction of flow fields [3].

5.2 Read-across

Read-across using existing ship and aircraft knowledge to provide a SHOL could be very promising and is already used for certain cases. It

is used for provision of limited SHOLs by desk top analyses (based on ship similarity), some expansion of flight test data and to establish certain read-across procedures between aircraft types in the United Kingdom [12]. Furthermore, in optimizing for test efficiency, a read across method was adopted by testing the predicted worst case to conservatively bracket the other cases for the same flight conditions, applied for a ship with two landing spots, one forward and one aft [18]. In forward wind conditions, landing was conducted using the forward landing spot, as turbulence was greater just aft of the ship's superstructure as compared to the aft spot. By doing so, the aft spot was not tested again for the same wind conditions as it would not be worse than the forward spot. For wind from port, a starboard approach was adopted to maximize the helicopter's exposure to turbulence and cover the worst case pedal margin. The same consideration was adopted for wind from starboard. For aft wind cases, only the aft landing spot was tested as this position experiences wind roll-up from the stern of the ship. The read-across between a port and starboard approach should not be recommended without a thorough understanding of the environment near the ship deck.

To attempt to assess all wind conditions at all masses would be a very large if not untenable task and landing at different masses could be certified by read-across [2]. In essence take-offs or landings which are rated as unacceptable at low mass are also read up to higher masses as unacceptable. Take-offs or landings which are rated as acceptable at high mass are read down to lower masses. The reasoning behind this is perhaps obvious; an easy landing at high mass is also likely to be easy (if not easier) at a lower mass. Equally a landing which is rated as unacceptable at low mass because lack of power or control margins will not be any better at a higher mass and the same is considered to be true of handling issues. This provides a rational basis for expanding the evidence available at any one mass without conducting a particular test point at that mass. Generally speaking, an aircraft will have a wider (larger) operating envelope at light All-Up Mass (AUM) than at heavy AUM due to reduced control and power margins as the helicopter mass increases.

The use of read-across between helicopter types for the same ship is not commonly used. This is

unfortunate as every ship in the modern warfare scenarios rarely operates with only one type of helicopter. There is not enough data presently available but this concept could be used during the introduction of the NH-90 which will operate from many ships where the Lynx is already certified. If it proves that the NH-90 would be wider than the Lynx for one ship, it would likely to be wider for other ships as well. In that case it would not be efficient to prove that the NH-90 has a wider envelope over and over again and at least the area covered for the Lynx SHOL could be certified for the NH-90 beforehand. Based on money and operational requirements the SHOL could then be enlarged when required.

5.3 Analytical Network

An analytical network could be developed based on shore-based hover trial data. Once the land based trials are conducted the determined relative wind envelope forms the basis for any additional trials and can only decrease in size in the environment near the ship deck. Furthermore, the helicopter characteristics are the rejection criteria for the SHOL and not the environmental conditions near the ship deck in isolation as every helicopter reacts differently. For the Lynx the most important quantitative rejection criteria are torque and pedal margin, and qualitative pilot workload [19].

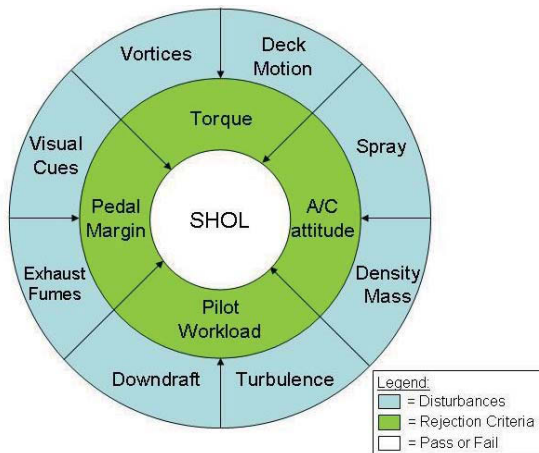


Figure 17; Example relation disturbance and rejection criteria based on pilots opinions [19]

The development of such an analytical network could be complicated by a lack of quantitative knowledge of the involved uncertainties near the ship deck. The development process requires analysis and understanding of the real system and the involved phenomena that drive the SHOL boundaries. Although there would be certain

disturbances which could be easily modeled on the shore-based hover trial data like the density mass and vertical downdraft on the leeward side of the ship. This could be explained by the shore-based hover data obtained during static stability testing for torque as shown in Figure 18. This figure shows the torque values in a 360° azimuth for different relative wind speeds.

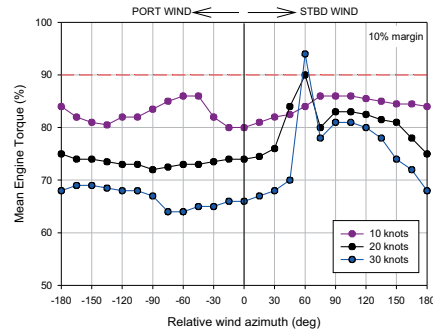


Figure 18; Torque data Lynx shore-based hover trials constructed with existing data [20]

As expected the torque will decrease with increasing relative wind speeds. The Lynx helicopter has inadequate yaw control between green 40 and green 80 as shown in Figure 5. The result is that torque exceeds the 10% safety margin and that area would fail to pass the binary decision process for certification in the SHOL. For example, when the helicopter would take-off from the ship deck with low relative wind speed with a higher density mass, and therefore an increase in power required for hover, the margin before exceeding safety limits would decrease. It would then be possible to calculate the minimal wind speed required for take-off without approaching the 10% safety margin and the SHOL being adjusted accordingly. This could be useful for certification of Hot & Heavy environments (hot means that the Outside Air Temperature is high).

For test conditions where shore-based data is far enough from any safety margins, that area should be certified accordingly. If there is any doubt sea trials should be conducted. Of course the relation between qualitative rejection criteria would be simpler to make than the relationship between pilot workload and disturbances, and further research should be conducted. On the other hand, there is a relationship between deck motion and pilot workload for example, which was demonstrated when two test pilots with experience operating on small ships both flew the shipboard recovery and super slide task for increasing

difficulty by simulating an increase in deck motion (NRC aggressive heave axis handling task). With ample torque margin, the two pilots rated the operations very similarly for both the shipboard recovery and super slide task as shown in Figure 19. When torque margin was reduced to 10% the story changed considerably and the pilot workload increased considerably for the shipboard recovery task as shown in Figure 20 [10].

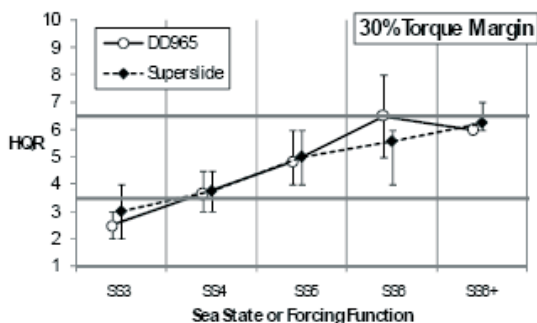


Figure 19; High torque margin [10]

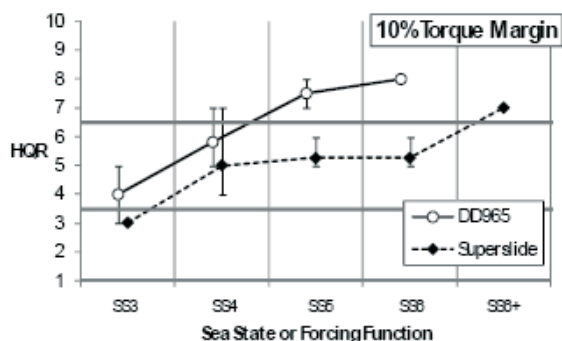


Figure 20; Low torque margin [10]

5.4 Discussion

The sea trials are the most expensive part of the qualification process and this is where most cost benefits could be achieved. There are three different alternatives described which have the potential to at least partially replace sea trials, each with their own shortcomings. Once the shortcomings are completely understood, it would be possible to use the three methods initially in parallel and use the data to cross-check the models with each other. The aim would be to use the improvements in simulation and test methods, such that the flow chart for SHOL trials could be adjusted as shown in Figure 21. The flow chart shows three options once the CFE is established: complete sea trials for new ships and helicopter types, sea trials for areas with low confidence in the CFE and/or small safety margins before

exceeding limits, and direct SHOL certification without even conducting sea trials.

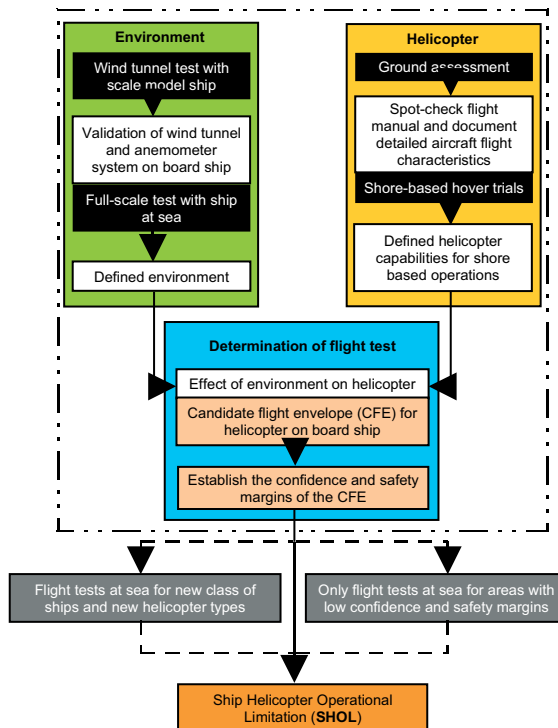


Figure 21; Flow chart with options

6 Conclusions

The current method for the determination of the SHOL envelope by the Royal Netherlands Navy is described. It has proved to be a very useful approach in which first separately the environment and helicopter characteristics are determined and thereafter combined in the CFE. The drawback of this approach is that there are sea trials required for certification of the SHOL. Once planned sea trials usually allow only one chance to get it done within a small window in which everything must come together. Because lack of testing, or benign testing conditions, the actual SHOL envelope may never be known, and the full operational potential for the helicopter-ship combination may not be realized even when the CFE predicted a much wider envelope.

The improvements in simulation techniques should be used to find alternatives to replace actual sea trials and not only to improve the CFE. Without replacing any sea trials, improvement of the CFE would probably only increase the total cost of the qualification process. Since a simulation model can never fully capture the complex physical phenomena that contribute to

the system behavior, simulation predictions are always wrong, in the sense that they never perfectly agree with reality. Nevertheless simulation models can still be used, as long as the user has some idea of how well the model-predictions agree with reality. Therefore, three alternatives are described to replace sea trials namely: flight simulation, read-across and an analytical network. All three methods have potential to partly replace sea trials and should be investigated and cross-checked with each other. If it proves to be difficult to completely replace sea trials, it should be possible to certify at least the areas where enough confidence is established in the CFE predictions and the SHOL envelope should be adjusted accordingly.

7 Future work

The influence from test pilots flying the SHOL qualification should be determined in order to set a minimum required pilots and quantitative data comparison matrix to make the process more objective. Furthermore, the potential of flight simulation, read-across and an analytical network to replace actual sea trials will be investigated during the introduction of the NH-90. The process should be accurately documented in regulations, in which the required steps and fidelity should be described.

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