METHODOLOGY OF ESTABLISHING THE SHIP-HELICOPTER OPERATING LIMITS

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ABSTRACT

Ship-helicopter interoperability underpins a broad naval aviation mission spectrum: anti-submarine, anti-piracy, maritime security, search-and-rescue, and humanitarian assistance and disaster relief. The mission effectiveness of shipboard helicopter operations is contingent on the speed of deployment, and the ability of the helicopter to launch and recover from a ship in the most severe operating conditions permissible. This impetus underscores the need to establish the Ship-Helicopter Operating Limits (SHOL) for ship-helicopter combinations in the RSN-RSAF inventory.

This article proposes a methodology to establish the SHOL through a rigorous ship-helicopter integration process – the preparation, conduct of qualification trials and post-trial analysis – that should be employed to maximise operational capability.

Keywords: naval aviation, ship-helicopter operating limits, helicopter qualification, Ship-Helicopter Operating Limits (SHOL)

INTRODUCTION

Challenges at the Ship-Helicopter Interface

Helicopter interoperability is a mainstay capability of the modern navy's surface fleet. Helicopter-capable ships of the Republic of Singapore Navy (RSN) include the *Endurance*-class Landing Ship Tank (LST), *Formidable*-class Frigate, Submarine Support and Rescue Vessel (MV Swift Rescue), NSmen Training Ship (MV Avatar) and *Independence*-class Littoral Mission Vessel. Helicopters are an important tactical system on modern warships, performing a variety of missions such as anti-submarine, anti-piracy, maritime security, troop/cargo transfer, vertical replenishment (VERTREP), Humanitarian Assistance and Disaster Relief, enabled by helicopters' inherent vertical take-off and landing capability which makes them suitable for the space constraints of a typical navy ship. The workhorse helicopters of the Republic of Singapore Air Force (RSAF) to accomplish these missions include the S-70B Naval Helicopter (NH), AS332 Super Puma, and CH-47 Chinook.

The pervasiveness of maritime-air operations (North Atlantic Treaty Organisation [NATO], 2017) does not trivialise the dynamic conditions at the ship-helicopter interface, where hazards coalesce to form one of the most challenging environments for helicopter pilots (Kääriä, 2012). Flight operations in close proximity to the ship's superstructure translate to a lower margin for error. Pilots' workload could be compounded by the dynamic movement of the ship's flight deck, degraded visual environment due to sea-spray and adverse weather, and turbulent airflow over the ships' flight decks, as shown in Figure 1 and Figure 2 (Kääriä, 2012). Despite these challenges, integration teams should strive to maximise ship-helicopter interoperability to provide operational flexibility in the most adverse environments possible. This article details the rigorous qualification programme required to define and operationalise envelopes for shipboard flight operations in the context of RSAF and the RSN.

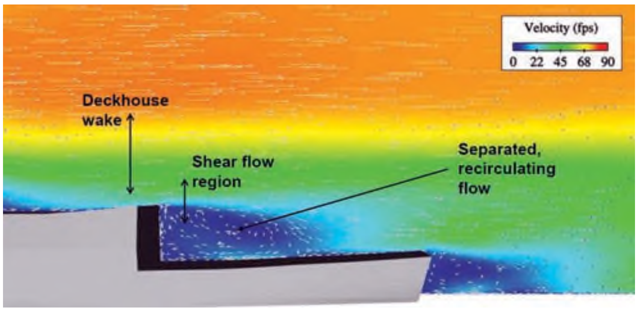


Figure 1. Characterising turbulent flow over ship superstructure and flight deck (Polsky, 2008)

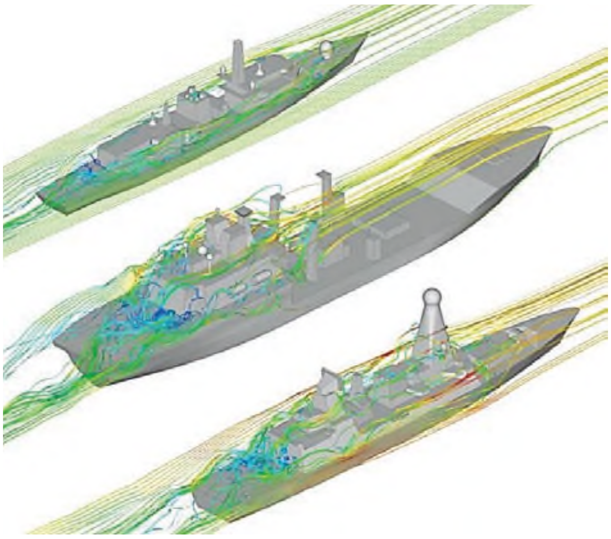


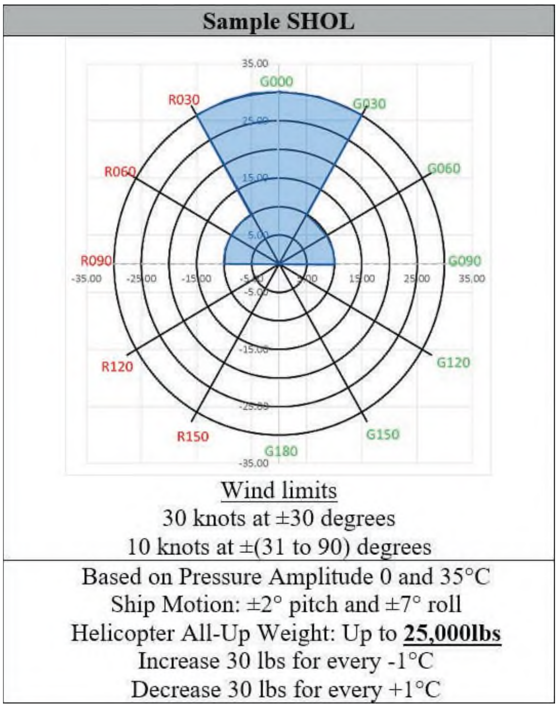
Figure 2. A Computational Fluid Dynamics (CFD) simulation of airflow over ships' topside structures (Kääriä, 2012)

Ship-Helicopter Operating Limits

The Ship-Helicopter Operating Limits (SHOL) is a polar plot of acceptable wind conditions (relative speed and direction) which is safe for the conduct of flight operations. Parameters such as the ship pitch and roll limits, and allowable maximum all-up weight (MAUW), contribute to the operational limits defined for safe flight deck handling, and helicopter launch and recovery, for each ship-helicopter combination. A sample SHOL is shown in Figure 3.

Establishing the SHOL begins with defining the operational requirements set by the RSAF and the RSN. The operational requirements influence the naval and air platform endurance, payload, configuration, and expected area of operations. On the helicopter's end, the operational requirements define the type of helicopters to interoperate with the ship. On the ship's end, the operational requirements implicitly define the ship's flight deck sizing, hangar space and support systems for shipboard helicopter operations.

The preparation phase is key to minimising the resources required to achieve the maximum SHOL possible. The process for developing the SHOL is summarised in Figure 4. The preparation phase for each ship and helicopter may start as an asynchronous effort, with parallel paths of safety assessments, build-up trials, and performance verification for the ship and helicopter eventually converging into a single track to define the candidate flight envelope.



Wind limits
30 knots at ±30 degrees
10 knots at ±(31 to 90) degrees

Based on Pressure Amplitude 0 and 35°C
Ship Motion: ±2° pitch and ±7° roll
Helicopter All-Up Weight: Up to **25,000lbs**
Increase 30 lbs for every -1°C
Decrease 30 lbs for every +1°C

Figure 3. A sample SHOL showing wind-over-deck limitations, presented as a polar diagram; the radius representing the wind speed, the azimuth and the wind direction as measured by the ship's system (parameters in figure are arbitrary)

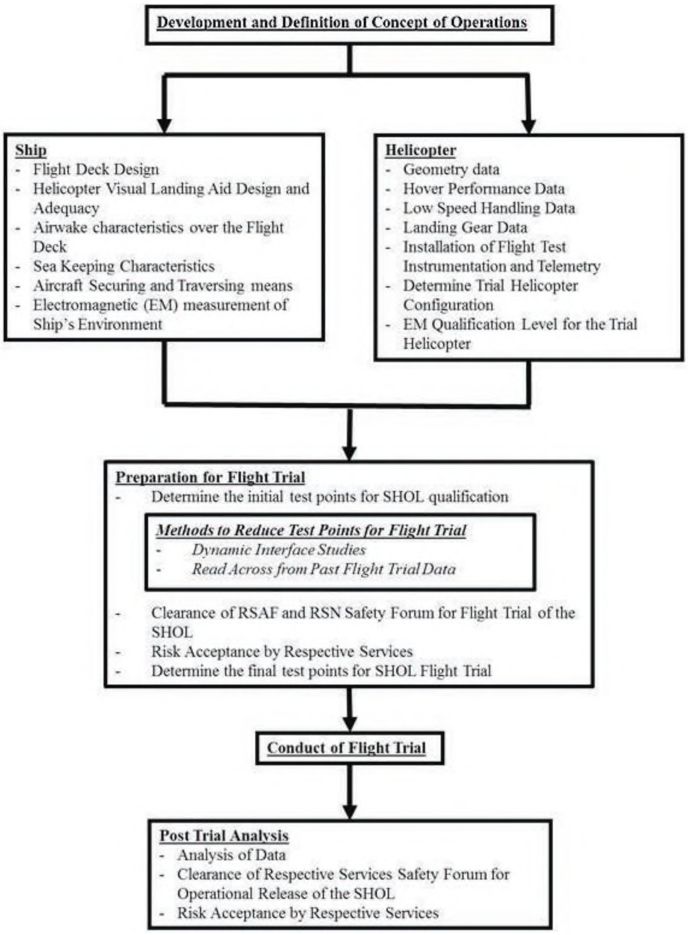


Figure 4. SHOL establishment and qualification process

PREPARATION

Naval Platform Preparatory Assessments

Naval platform preparations involve the safety assessment, performance verification, and operationalisation of ship systems that support its aviation capability. Naval platform systems essential for ship-helicopter operations are fire-fighting systems, lights, the electrical system, the aviation fuel system, helicopter visual landing aids (HVLA) systems, and communications systems. At sea trials, the ship's seakeeping performance validates the accuracy of scaled model tests conducted during the design phase. The following factors are considered during the safety assessment of the ship for helicopter operations (Wong, Liu, & Ham, 2018):

- Flight deck design
- Adequacy of HVLA
- Ship airwake characteristics
- Ship seakeeping characteristics
- Helicopter securing and traversing means, and
- Electromagnetic (EM) compatibility with the helicopters

Flight Deck Design

The flight deck design is verified via inspections and calculations during naval platform acceptance tests. The ship's flight deck has to be designed to withstand[1] an emergency-landing load of at least 2.5 times the maximum take-off weight (MTOW) of the heaviest helicopter type it is expected to operate with (PAFA Consulting Engineers, 2001). To ensure visibility of deck markings from afar, the helicopter landing circle shall be demarcated with a white line with a width of 0.3 metres. 45° night-vision goggle (NVG) lines shall be painted for each landing spot to facilitate helicopter approach over the flight deck at night under NVG conditions, as shown in Figure 5. A minimum of 1/3 rotor diameter clearance is required between the helicopter main rotor blade tip and the ship superstructure, as illustrated in Figure 6 (Wong, Liu, & Ham, 2018). This criterion has been used on all RSN ships consistently, except for the LST which has 2/3 rotor diameter clearance. Additionally, the flight deck should be sized to ensure that the helicopter will remain safely on deck with a minimum of one wheel within the landing circle (Wong, Liu, & Ham, 2018).

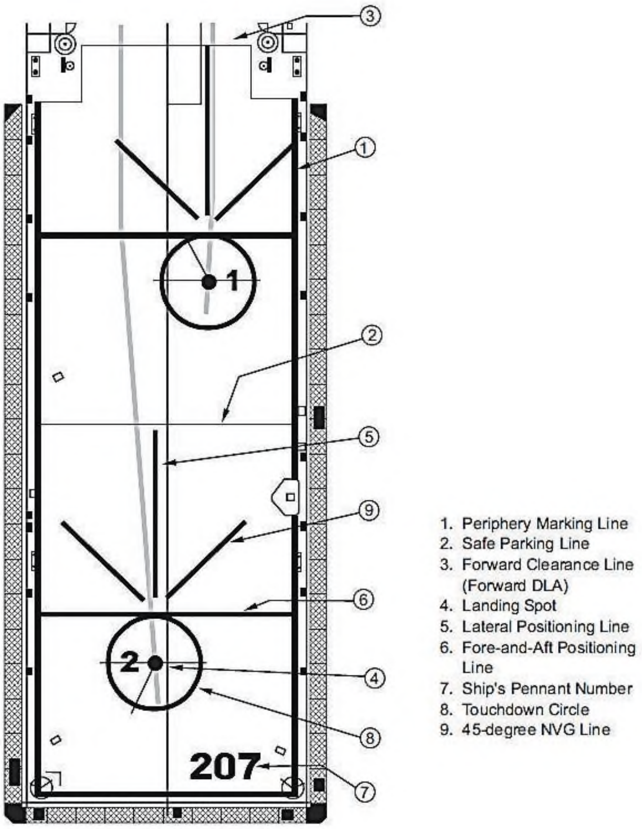


Figure 5. An example of flight deck markings (NATO, 2017)

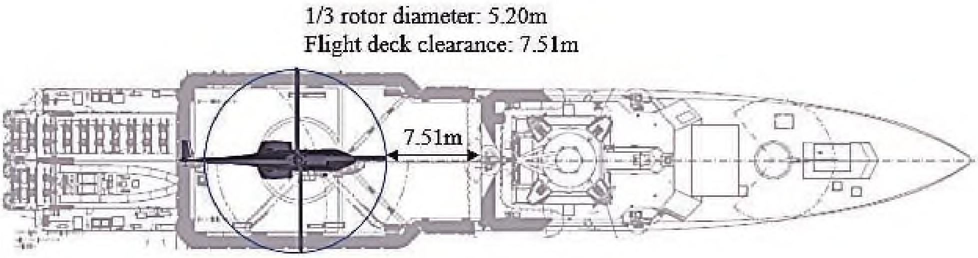


Figure 6. An illustration of 1/3 rotor diameter clearance requirement

To prevent the helicopter from sliding off the flight deck in adverse weather and sea conditions, flight decks and areas where helicopters are likely to be traversed or parked are coated with a non-skid surface having a minimum dry-deck coefficient of friction of 0.6 (NATO, 2017).

For ships that are capable of supporting helicopter in-flight refuelling (HIFR), the block letter “H” is painted on the deck to designate the spot over which the helicopter must lower its hoist hook to pick up the refuelling hose as shown in Figure 7. At least two grounding points should be provided on the port and starboard sides of the flight deck to ground static electricity generated during flight. These grounding points must also be usable during VERTREP and HIFR operations.

Figure 7. Deck markings for HIFR-capable ships (Ministry of Defence [MINDEF], 2018)

Adequacy of Helicopter Visual Landing Aids (HVLA)

The ship's HVLA provide the necessary visual references in supporting pilots to land and take off the helicopter from the ships across a range of meteorological, day and night conditions. The typical HVLA are shown in Figure 8. HVLA must be NVG Class A-compatible and remain operationally adequate even in light-polluted littoral environments (Liu, Wong, & Ham, 2018). Applicable standards for HVLA compliance are MIL-STD-3009, CAP 437 and CAP 168. Verification of HVLA adequacy at flight trials involves ascertaining the effectiveness and performance (detection range) by pilots in both day and night (unaided and NVG-aided) conditions.

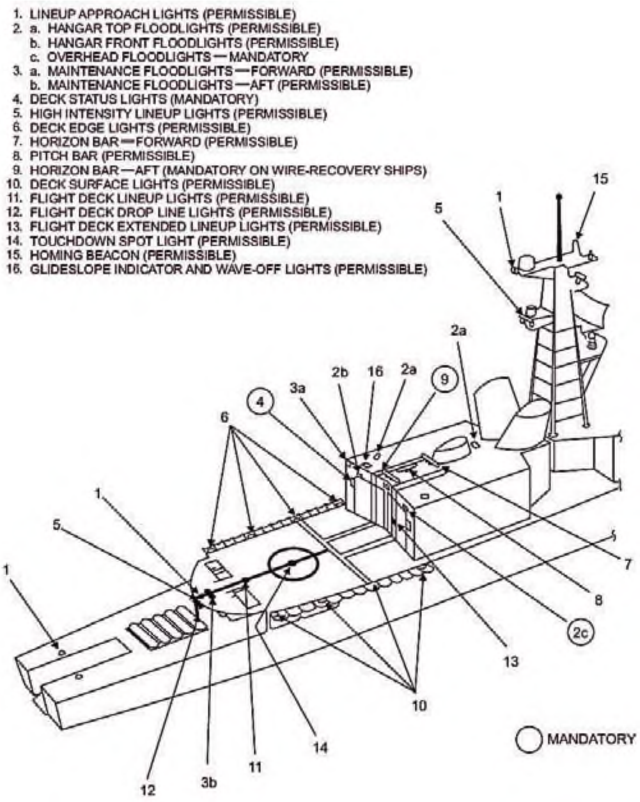


Figure 8. Typical HVLA on a navy ship (NATO, 2017)

Ship Airwake Characteristics

Pilots need to maintain helicopter stability through a complex flow field that arises from the forward motion of the ship and the interactions of the atmospheric boundary layer with the ship's superstructure. The ship's airwake contains spatial gradients in flow speed and direction arising from the free shear layers, a zone of recirculation, large wakes and vortex structures. For flight decks located aft of the ships, the helicopter is required to traverse free shear layers which separate from the superstructure. Beneath these shear layers is a recirculation zone closer to the rear face of the superstructure which could affect the stability of the helicopter as it enters into hover in ground-effect. This unsteadiness in the flow field has significant energy over the frequency bandwidth to affect helicopter stability and handling qualities, therefore increasing the pilot workload (Lee & Zan, 2003). The Appendix details the requirements of wind tunnel tests. Adherence to pre-determined measurement points above and around the flight deck supported the relative assessment of airwake effects on available helicopter power and control margins.

Ship Seakeeping Characteristics

The ship's seakeeping characteristics are verified during sea trials against the predicted ship attitude when model tank tests are carried out during the naval platform's design phase. A *dynamic interface study* is carried out to define the launch and recovery envelopes for each ship-helicopter pair, identify the probability for periods of quiescence, and evaluate the flight deck motions in various sea-states for conditions unsafe for ship-helicopter operations. Unsafe conditions arise if any of the following occurs:

- Ship motion causes helicopter to slide on the flight deck,
- Securing system, such as lashing chains, exceeds the design load,
- Landing gear lifts off the flight deck, or
- Helicopter undercarriage or landing gear experience forces that exceed design load limits.

Helicopter Securing and Traversing System

The helicopter should be secured on the flight deck within the shortest time possible upon landing to mitigate the risk of the helicopter sliding or experiencing dynamic rollover. One possible means of securing is the manual tie-down of the helicopter by the flight deck crew with lashing chains secured from lashing pots (tie-down points) to the mooring points on the helicopter. The distribution of tie-down points should follow the prescribed layout in US Navy's Bulletin 1L. The lashing pots are assessed for adequate reinforcement to withstand the expected loads during operations. In one case study, a calculation of the foundation strength was carried out by Femap software to calculate the maximum Shell Von Mises Stress and deformation of the flight deck for zones requiring local reinforcement with welded brackets to be identified, as shown in Figure 9.

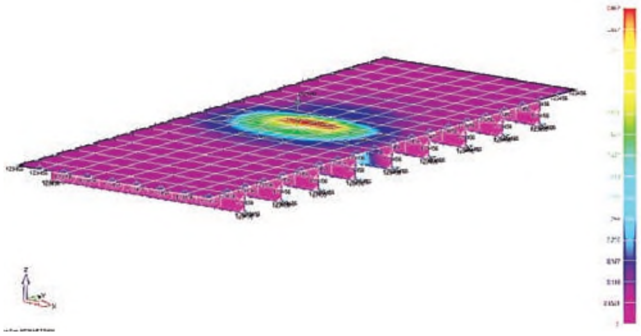


Figure 9. Finite Element Analysis of a navy ship flight deck

Manual securing could be time consuming. To mitigate this, automatic securing systems such as the Aircraft Ship Integrated Secure and Traverse (ASIST) System can be used to secure the helicopter, as shown in Figure 10. These systems provide automatic tracking of the helicopter and present visual cues to the pilot to land the helicopter in the designated landing area. Upon landing, the Rapid Securing Device (RSD) will automatically secure the helicopter on the flight deck in a matter of seconds.

Figure 10. S-70B NH recovery with ASIST system on a navy ship (MINDEF, 2018)

Electromagnetic Compatibility

EM Compatibility for ship-helicopter operations is determined through a study of the radiation hazards (RADHAZ) and High Intensity Radiated Fields (HIRF) from each platform separately prior to a combined safety assessment for operationalisation. RADHAZ analysis covers Hazards of Electromagnetic Radiation to Ordnance (HERO), Hazards of Electromagnetic Radiation to Personnel (HERP), Hazards of Electromagnetic Radiation to Fuel (HERF) and High Intensity Radiated Fields (HIRF). The HERO assessment calculates the safety distance for ordnance to ensure that no unintended ignition would be caused by EM energy generated by the ship and helicopter transmitters. HERP assessments calculate safety distances for personnel to ensure that the radiation levels do not become hazardous to the crew on the ship and helicopter. A 6dB safety margin is added onto the measured average EM field of each ship and helicopter emitter, as required by MIL-STD-464 to account for uncertainties in measurement, before being compared against the qualified HIRF, HERO, HERP and HERF limits of the helicopter and ship. Details of these assessments are found in the Appendix.

Helicopter Preparatory Assessments

The complex maritime environment motivates a preparatory assessment on the helicopter's compatibility for shipboard operations. This assessment is supported by data provided earlier by the helicopter manufacturer, comprising helicopter geometry and dimensions, inertial properties, landing gear configuration and design load limits, and electromagnetic vulnerability qualification limits, as elaborated in the Appendix.

FLIGHT TRIALS

The completion of preparatory analyses for the ship and helicopter is followed by the conduct of flight trials to qualify the SHOL. Flight trials may span a few days to a few weeks. Resource commitments are compounded by the months of work-up training for the aircrew and ship crew, helicopter-support equipment certification, post-trial recovery, and opportunity cost of the trial assets; hence, there is a strong impetus to streamline the existing ship-helicopter qualification process.

The design of the flight trials is led by the RSAF's Test and Evaluation Centre. For each specific test objective defined for the flight trial, the measures of performance, pass/fail criteria, test methodology, data collection requirements and expected results are clearly articulated during the test plan reviews to ensure that the trial scope encompass all test points needed to define the SHOL.

A standardised test progression approach ensures that a safe incremental build-up is employed to qualify potentially high workload test points (NATO, 2003). Each test sortie comprises an approach-recovery-landing-launch-departure cycle, conducted by the same test pilot with consistent wind-over-deck conditions. The parameters acquired are both quantitative and qualitative in nature, including pilot workload, adequacy of HVLA, helicopter power and control margins, helicopter stability, ship motion, helicopter landing gear loads, and helicopter landing dispersion, as listed in Tables A2 and A3 (In Appendix). These parameters cannot be evaluated in isolation during these flight trials. Therefore, a comprehensive rating in the form of a five-point Deck Interface Pilot Effort Scale (DIPES) is assigned by the test pilot to evaluate the operational pilot workload and indication of parameters that contributed to the elevated difficulty of that event, as detailed in Table A4. Flight trials that are designed to include measures of effectiveness of HVLA are recommended to use the Visual Landing Aids Rating Scale shown in Table A5. These rating systems and scales were developed to enhance sharing of flight test results by different countries (NATO, 2003).

POST-TRIAL ANALYSIS

The post-trial analysis compares flight test data and pilots' DIPES input for all the test points defining the candidate SHOL envelope. Figure 11 shows an example of the DIPES rating provided by a test pilot. For this particular trial, the highest DIPES rating was 2 for the range of test points, which implies that considerable effort was required to land and take off the helicopter at these relative wind conditions. The pilots' power and control inputs would be checked to ensure that there will be sufficient power and control margins throughout all phases of ship-helicopter operations to handle contingencies, or to compensate against external disturbances, such as wind gusts, to the helicopter. Any encroachment of power and control inputs into safety margins would render that test point *unsatisfactory*, hence reducing the operating envelope represented by that test point on grounds of unsafe helicopter operation. Power correction factors (obtained from helicopter hover performance charts) are applied to account for ambient temperature and weight differences as a result of variation in the test environment and fuel consumption respectively. Figure 12 shows a sample summary of control inputs at various test points. In this example, the minimum and maximum longitudinal Control Position Input (CPI) percentages were collected and tabulated for various relative wind conditions throughout the entire flight trials.

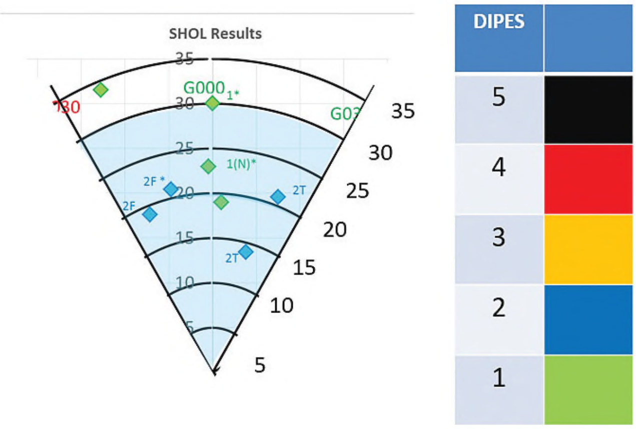


Figure 11. A sample of DIPES Rating for each test point

Performance Rejection

The flight trials seek to determine parameters that will limit the helicopter's performance under atmospheric conditions specified for the mission. Atmospheric conditions that are hot and high (altitude) typically limit engine performance. Therefore, it is important to determine the precise limiting factor for the atmospheric conditions specified to enable objective comparison of data points flown during the test campaign. Applying weight corrections for any day with temperatures higher than the International Standard Atmosphere is restrictive to the RSAF, given that typical flying conditions are warmer. Once the precise limiting factors (e.g. torque, power) are known, referred parameters are used. The referred weight (i.e. helicopter weight as a function of air density) technique is employed to enable a set of tests conducted during prevailing atmospheric conditions at the SHOL definition trials to be directly comparable with another set of tests conducted under different atmospheric conditions (Cooke & Fitzpatrick, 2010).

Error Analysis

Errors in flight test measurements are an inevitable characteristic of all measurements. Ideally, a measurement should be repeated several times. However, in reality, flight trials are unable to replicate similar conditions exactly for repeated measurements, therefore error bars are introduced to support analysis of the test points required to define the SHOL. Error bars are determined by the summation of instrumentation errors and fractional errors in quadrature (Taylor, 1997). In the example shown in Figure 12, an upper and lower error bar of 1% was applied to digital Flight Test Instrumentation (FTI) results, while a higher error bar of 5% was applied for test points that employed manual FTI (e.g. when the digital FTI was faulty or was not used for that test point). This approach provides a check on the significance of error sources. If the reduction of raw data involves parameters raised to high powers, these parameters need to be measured with a higher degree of precision if the calculated results are not to be degraded in probable error. This analysis of measured errors and required computation may affect the choice of instrumentation for a flight trial. In Figure 12, all CPIs did not encroach into the pre-determined 10% forward or aft control safety margins. Should any of the error bars encroach into the pre-determined 10% safety margin, the test team would have to highlight this at the post-trial review. This analysis is repeated for helicopter cyclic, pedals and collective controls.

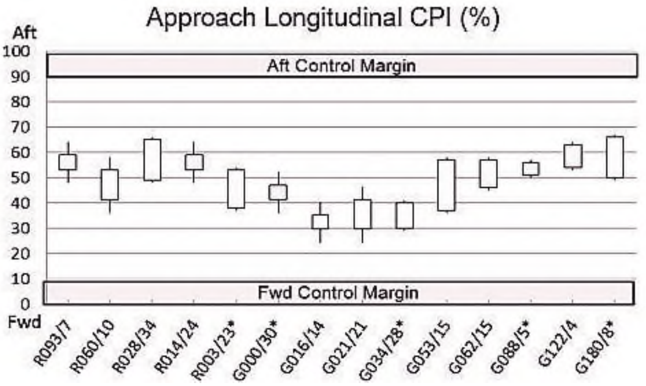


Figure 12. A sample control position input chart indicating the range of CPI at different relative wind conditions

Defining the SHOL

Once flight trial data on helicopter power and control margins, and pilot workload and effectiveness are collated, the operating envelope of the SHOL can be defined. Other verifications for ship-helicopter interoperability may also include the following:

- HVLA effectiveness and performance
- Effectiveness of helicopter tie-down
- Effectiveness of munitions tie-down
- EM compatibility assessment
- Helicopter maintenance and armament operations

Any unsatisfactory element of verification trials from the list above warrants a review of the candidate SHOL envelope and proposed risk mitigating measures to ensure that ship-helicopter operations are safe. The presence of new hazards unearthed during the flight trials should be promulgated to the RSN and the RSAF safety forums for review and acceptance of mitigation measures and residual risk levels, as part of the process to operationalise the SHOL.

DISCUSSION

Shortcomings of the Traditional SHOL Qualification Process

The shortcoming of the traditional SHOL qualification process which culminates in full-scale ship-helicopter trials lies in its resource-intensiveness. Several navies have experimented with alternate means to unlock efficiencies through piloted flight simulations and CFD simulations (NATO, 2003; Forrest, Owen, & Padfield, 2012). At present, simulation techniques still rely on the ship-helicopter test and evaluation community to generate the evidence underpinning prediction model development for future SHOL establishment by simulation (NATO, 2003).

The traditional SHOL qualification process establishes a specific pairwise operating envelope for each ship-helicopter combination, implying the need to conduct separate ship-helicopter trials between each helicopter type in the RSAF and each RSN ship it is expected to operate with. SHOL developments are limited by the relative wind and sea state conditions encountered during full scale trials for each ship-helicopter pair, often requiring test teams to pursue desired test conditions as the helicopter commences its approach for each test sortie. Prevailing relative wind and sea state conditions may also result in the inability to verify the extreme test points required to establish the edge of the candidate SHOL envelope, hence necessitating a follow-up trial which incurs additional cost. Another shortcoming of the traditional SHOL qualification process is the reliance on the opinion of one or a few test pilots who have been instructed to interpolate cognitively to account for the capabilities and skill of the 'worst qualified pilot' who operates in the SHOL. Roscoe and Wilkinson (2002) found that the pilot(s) used to qualify the candidate SHOL could have an impact on the envelope released for operational use, despite trial pilots being briefed to take into account cognitively the skill of the worst qualified pilot. In their simulator test, four test pilots were assigned to develop a SHOL for a specific ship-helicopter combination, which resulted in four unique SHOLs. However, Roscoe and Wilkinson (2002)'s recommendation to avoid reliance on a single pilot may be challenging to adhere to in light of resource constraints.

One Helicopter-Many Ships Approach

Engineering analysis underpins the *one helicopter-many ships* approach via a read-across of ship wind tunnel studies against data on helicopter performance characteristics and precedent flight trials. Flight trial results from one ship-helicopter pair could be used to support analysis for another on the basis of *similarity*. This would result in a reduction of the trial resources needed to qualify the SHOL for each pair of helicopter and ship. Table 1 outlines the data required to support engineering analysis.

	Data required	Analysis supported
1.	Wind tunnel studies for all ship classes expected to operate with the helicopter	Ship airwake assessment and its impact to helicopter operations – (see Figure A3 for recommended measurement grid dimensions)
2.	Helicopter hover performance characteristics	Assessment of helicopter power and control margin assessment in the ship environment
3.	Helicopter low speed characteristics	Assessment of helicopter power and control margin assessment in the ship environment
4.	Dynamic Interface Analysis for ship-helicopter pair	Investigate dynamic behaviour of the helicopter embarked on each ship under secured and free-deck conditions
5.	Helicopter pilot vision plot	Assessment of pilot's ability to see HVLA and shipboard visual cues
6.	Past flight trial data of helicopter with other ships	Assessment of helicopter power and control margin assessment in the ship environment; Review of hazards, adequacy, applicability of risk mitigation measures for future flight trials
7.	EM compatibility assessment of ship and helicopter, or if absent, EM levels of ship and helicopter, and respective platforms' EM limits	RADHAZ study and recommendations

Table 1. Data required to support engineering analysis

Test points could be designed to verify the worst case scenarios under which the helicopter would experience the highest disturbance. For example, a relative wind from the left bearing 270 (Red[2]-30 wind) would result in a higher disturbance for a helicopter departing from starboard, as compared to a relative wind from bearing 030 (Green 30 wind), and vice versa for a helicopter departing from port, as shown in Figure 13. Scaling up this principle in the context of SHOL development for a new helicopter, the approach entails conducting flight trials only on the ship that presents the most adverse conditions for helicopter operations. This is a more resource-efficient approach for ship-helicopter integration.

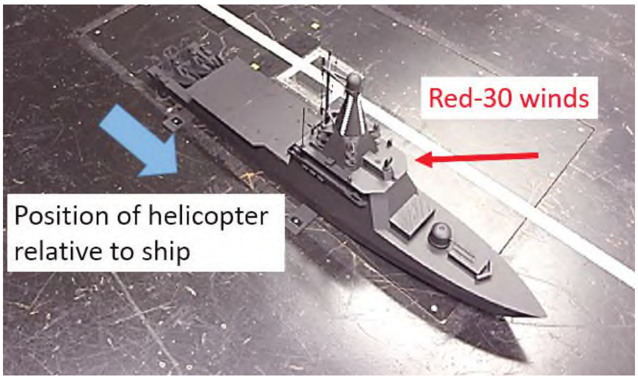


Figure 13. Worst-case relative wind conditions caused by Red-30 winds for a helicopter's starboard departure

It is also possible to read across the pilot vision plot from one ship-helicopter configuration to subsequent ship-helicopter combinations. There are pilot vision requirements set forth in MIL-STD-850B, which outline the minimum angles of unimpaired vision (See Figure 14 for the pilot visibility requirements for helicopters designed with side-by-side cockpit layout). By studying the helicopter vision plot, it is possible to assess if the HVLA are visible to the pilots, and if the placement of the HVLA on one ship is comparable with previous ships.

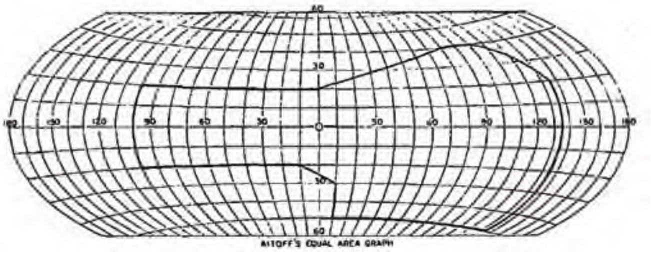


Figure 14. Requirements for pilot visibility for helicopters designed with side-by-side cockpit layouts (NATO, 1970)

CONCLUSION

Integration teams should strive to maximise ship-helicopter interoperability in the most adverse environments possible for operational flexibility. The resource-intensiveness of the traditional SHOL qualification process underscores the early acquisition of technical data and completion of supporting studies to achieve safe and efficient operationalisation of ship-helicopter interoperability.

APPENDIX

Ship Wind Tunnel Tests

Wind tunnel tests are conducted on a scaled model (see Figure A1) during naval platform design reviews to determine optimal anemometer positions, airwake characteristics above the flight deck and aft of the ship, and air flow deviations at various predefined positions above and around the ship. A typical wind tunnel is equipped with reference instrumentation to measure total temperature, differential tunnel contraction pressures, and two total pressures in the settling chamber. Smoke was used to visualise flow patterns (see Figure A2). The size of the recirculation region was determined with coloured oil on the flight deck – helicopter operations within this region should be minimised as it may result in helicopter over-torque or insufficient helicopter control margins to counter the unsteady flow.

The recommended measurement grid positions relative to the landing spot are detailed in Figure A3. Wind tunnel data and anemometer placement enable naval platform engineers to chart the air flow conditions above the flight deck and in the helicopter approach/departure paths as shown in Figure A4.

Figure A1. A ship wind tunnel model

Figure A2. Flow visualisation of airwake at leeward side of the ship

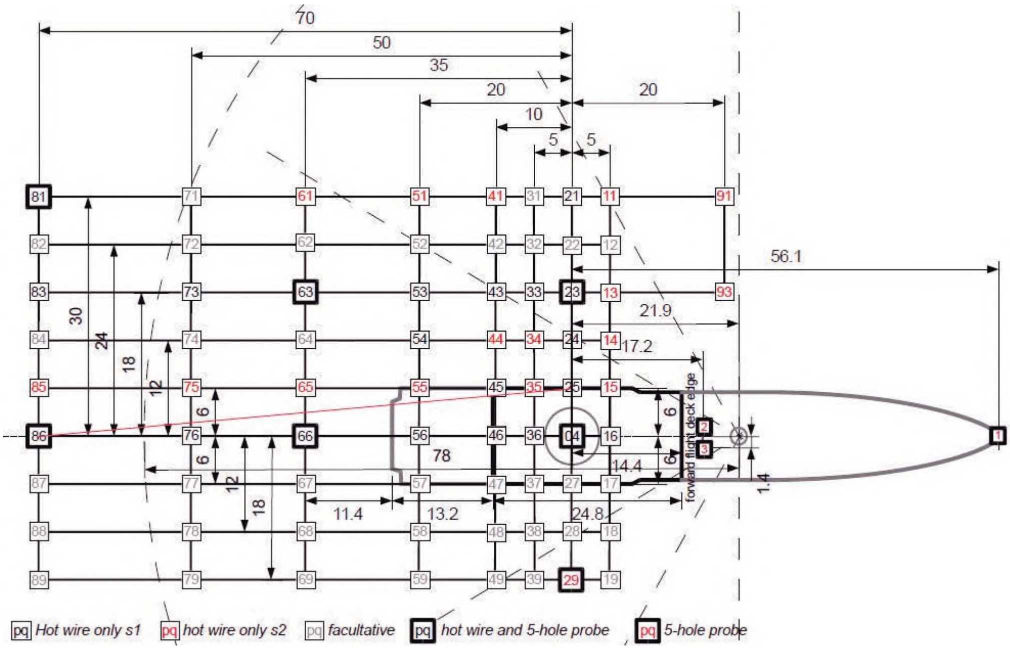


Figure A3. Recommended measurement grid positions relative to the landing spot of the ship. The stations with thick outlines were also measured with a 5-hole probe (full size dimensions in metres)

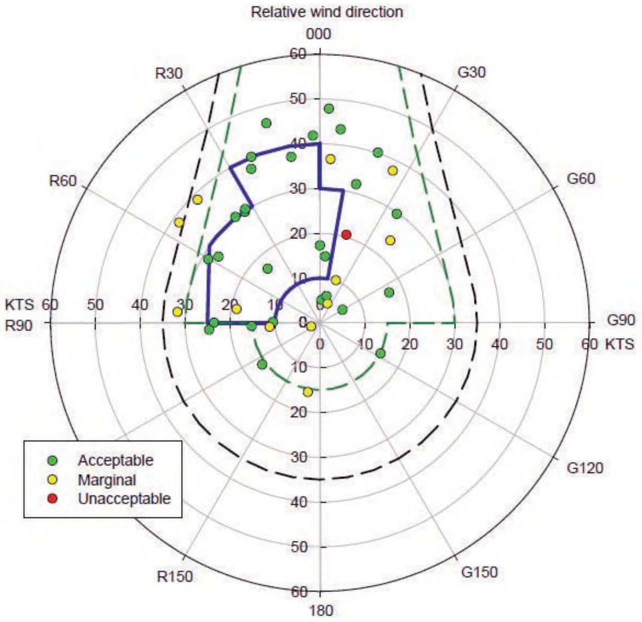


Figure A4. Sample ship environmental conditions constructed with wind tunnel data (Hoencamp, 2009)

Electromagnetic Compatibility

HERP and HERO analyses involve thermal heating effects, and use the average power for assessment of their safety limits. HERF assessments deal with hazards during refuelling operations, and uses peak power for assessment as it involves igniting fuel vapours due to induced arcing which is dependent on the fuel-air mixture, peak power level and air gap distance. The relevant standards for HERF analysis are NAVSEA OP3565 Vol 1, Rev 6 and MIL-STD-464.

The HIRF assessment calculates the safety distances of electromagnetic interference (EMI), HERO and HERP from an approaching helicopter. This involves an assessment of helicopter vulnerability against a ship's transmitters to determine the electromagnetically compatible state of the ship and helicopter. To mitigate RADHAZ in cases where the safety distances are impractical, selected sensors on both the ship and helicopter shall not be allowed to transmit at a pre-determined distance as documented in the SHOL. A sample of EM risk-mitigation recommendations is shown in Table A1.

RADHAZ		Summary of Mitigating Measures	
		Helicopter Configuration 1	**Helicopter Configuration 2**
HERP	Helicopter perspective	Distance for the transmitter to be ceased before helicopter reaches ship • Transmitter SA: 30m	
	Ship perspective	Ship crew to observe safety distance while operating next to helicopter. Helicopter transmitter • Transmitter AA: 0.2m • Transmitter AB: 0.1m	
HERO	Helicopter perspective	No ship transmitter restrictions	
	Ship perspective	No ordnance near flight deck during helicopter operations. Helicopter transmitter • Transmitter AA: 0.2m • Transmitter AB: 0.1m	
HERF	Ship and Helicopter perspective	• No transmitter restriction for aviation fuel • Prohibiting operation of handheld communications equipment within 10feet (~3m) of refuelling activities	
HIRF	Ship and Helicopter perspective	No transmission restriction	Distance for the transmitter to be ceased before helicopter reaches ship Ship transmitter • Transmitter SB: 100m

Table A1. A sample summary of RADHAZ mitigations (figures and details are arbitrary)

Helicopter Data Required

Helicopter Geometry

The geometric data of the helicopter includes the main rotor diameter, tail rotor diameter, equivalent helicopter side and frontal areas. With respect to the helicopter zero reference in 3-dimensional space, the location of the main and tail landing gear axles, main rotor hub and securing system (if any) would be required. The inertial properties of the helicopter to be determined includes the centre of mass, and the mass moment of inertia for the masses of various helicopters.

Hover Performance Analysis

Helicopter hover performance analysis examines the engine (power) and control parameters, such as pedal and torque, as a function of helicopter weight in hover in ground effect and hover out of ground effect conditions. Once these relationships are known, correction factors would be derived and used for post-flight trial analysis. These derived data can also be used as a comparison against the data presented in the helicopter flight manual.

Low Speed Handling Analysis

Low speed handling analysis provides a good understanding of the control and handling characteristics of the helicopter torque, and control margins against the relative wind speed and its azimuth when operating in close proximity to the ship. This data is essential for the test team to identify any critical test points which would need to be flight tested subsequently.

Flight Test Instrumentation

FTI on the helicopter is recommended to measure and record the parameters for power and control inputs (cyclic lateral, cyclic longitudinal and pedal), and landing gear loads during the trial for the test team to perform post-trial analysis. Telemetry capability can also be implemented onto the helicopter to allow the Trial Director to constantly monitor the helicopter performance from the ship throughout the trial. On-board digital FTI also affords better resolution of data for post-trial analysis.

Trial Helicopter Configuration

The defined Concept of Operations determines the configuration of the trial helicopter. The trial helicopter may require ballast to achieve a weight as close to its intended MAUW for the development of the SHOL and for it to be qualified as practicable. Although it is expected that the helicopter's weight decreases over the duration of a trial with the consumption of fuel, the trial team should plan the test points carefully to include the intended MAUW at the most adverse wind conditions articulated by the SHOL.

Blade Sailing

Blade Sailing is an aeroelastic phenomenon typically observed during the start-up or shut-down of a helicopter. This phenomenon adversely affects helicopter main rotors rotating at low speeds in high or turbulent wind conditions. The resultant excessive flapping could cause the blade to strike the airframe or personnel in the helicopter's vicinity. Adherence to the manufacturer's prescribed rotor start-stop limits would mitigate the risk of blade sailing (Newman, 1999; NATO, 2003). Helicopters designed with rotor brakes could employ them to stop slow-rotating blades sooner.

Data Collected at Flight Trials

Parameter	Typical Range	
Pedal position	+/- 100	%
Collective position	0/100	%
Cyclic fore/aft Position	+/- 100	%
Cyclic lateral position	+/- 100	%
Heading	0/360	degrees
Roll attitude	+/- 360	degrees
Pitch attitude	+/- 360	degrees
Doppler velocities	+/- 40	knots
Longitudinal (Vx)	-30/120	knots
Lateral (Vy)	+/- 40	knots
Engine torque port & starboard	0/150	%
Engine inlet temperature	-25/100	˚C
Radio altimeter	0/1000	feet
Weight	Light - heavy	lbs

Table A2. List of helicopter data to be acquired (NATO, 2003)

Parameter	Typical Range	
Ship speed through water	0/45	knots
Pitch	+/- 10	degrees
Roll	+/- 10	degrees
Heading	0/360	degrees
Outside-air temperature	-25/60	˚C
Pitch attitude	+/- 360	degrees
Relative wind speed	+/- 40	knots
Relative wind heading	-30/120	degrees
HVLA settings	0/100	%
Helicopter fuelling pressure setting	0/10	bar
Wave swell direction	0/360	degrees

Table A3. List of ship data to be acquired (NATO, 2003)

EFFORT	GUIDANCE	DIPES
Slight to Moderate	Reasonable compensation required. Tracking and positioning accuracy is consistently maintained throughout the operation. Fleet pilots will have enough spare capacity to conduct ancillary tasks.	1
Considerable	Significant compensation required. Tracking and positioning accuracy occasionally degrades during peaks in ship motion, sea spray or turbulence. Fleet Pilots will have difficulty conducting ancillary tasks.	2
Highest Tolerable	Highest tolerable compensation required. Tracking and positioning accuracy degrades regularly during peaks in ship motion, sea spray or turbulence. Fleet pilots will be able to keep up with task requirements but no more. Degraded operations (ship or helicopter) will probably require an abort. Repeated safe operations are achievable. This point defines the recommended limit.	3
Excessive	Excessive compensation required. Accuracy is poor in one or more axes. Fleet Pilots will be purely reacting to external influences rather than anticipating them. A safe abort may not be possible if a helicopter or ship system is lost during a critical phase of the evolution. Fleet pilots under operational conditions could not consistently repeat these evolutions safely.	4
Dangerous	Extreme compensation required. Repeated safe evolutions are not possible even under controlled test conditions with fully proficient crews.	5
Acceptable **(DIPES 1-3)** Unacceptable **(DIPES 4-5)**		

Each DIPES rating may be given one or more suffixes to descript the cause(s) of increased pilot workload:

Pitch control	P	Helicopter attitude	A
Turbulence	T	Height control	H
Roll control	R	Spray	S
Deck motion	D	Forward/aft positioning	F
Yaw control	Y	Torque control	Q
Visual cues	V	Lateral positioning	L
		Funnel Exhaust	E

Table A4. The DIPES rating scale (NATO, 2003)

HVLA rating	Adequacy	Rating Description
1	Good	Configuration provides visual cues that require little or no pilot effort to interpret; recoveries are slightly more difficult than those attempted in daylight.
2	Satisfactory	Configuration provides minimum amount of visual cues necessary for routine safe fleet recovery operations.
3	Adequate	Configuration is adequate for fleet use in non-routine basis. Use when operationally necessary and with prior pilot training on the configuration.
4	Marginal	Configuration provides inadequate visual cues for consistently safe fleet recovery operations; recoveries could be conducted with significantly increased risk in critical or wartime situations.
5	Unsatisfactory	Configuration provides insufficient visual cues for safe recovery; unacceptable risks associated with recovery attempts in these conditions.

Table A5. HVLA Rating Scale (NATO, 2003)

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ENDNOTES

[1] The flight deck shall only be permitted to deform elastically under crash load.

[2] *Red winds* is naval and air force terminology for winds from the Port side of the platform; conversely, *Green winds* refer to the starboard side

BIOGRAPHY

LIU Yaowen is a Principal Engineer (Naval Systems) leading the design and integration of hull systems on board the Littoral Mission Vessel (LMV). Yaowen was the project manager and lead systems safety engineer for the operationalisation of helicopter interoperability on an RSN ship in 2017, building upon his prior experience in ship-helicopter integration trials for two helicopter types on a Training Ship. He graduated with a Master of Science and Engineering (Naval Architecture) from the University of Michigan in 2013, and Bachelor of Engineering (Mechanical) from the National University of Singapore (NUS) in 2008.

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