Challenges and opportunities for the real-time simulation of ship/helicopter operations

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ABSTRACT

The challenges of accurately simulating naval helicopter launch and recovery operations have been actively researched over many years, both in industry and academia. However, the same problem remains – how accurate does the whole simulation package and its various components need to be, such that the simulation data can be reliably used to support the generation of Ship/Helicopter Operating Limits (SHOLs).

The UK the Ministry of Defence Chinook helicopter Delivery Team identified a need to utilize simulation for the first time as part of an integrated, safe and progressive approach to the development of SHOLs for the Chinook aircraft. If sufficient evidence can be generated on the validity of the simulation, then the opportunity exists to more widely utilize simulation data as a cost effective ally to data generated during flight trials at sea.

The Ship/Air Interface Framework (SAIF) simulation architecture was initially developed over 15 years ago, and has recently been updated to provide a more open and flexible flight simulator interface. This has allowed high fidelity models of ship motion and air wake effects to be integrated with an engineering flight simulator of the Chinook helicopter, providing the pilot with a more realistic simulation of the dynamic operating environment. Initial simulation trials of the Chinook operating from the new Tide Class tanker vessel were conducted in 2017, prior to sea trials to be conducted in 2018.

This paper will describe the driving factors for the increased use of simulation to support the Ship/Air Integration clearance process and the latest design evolution of the SAIF architecture. Several areas for fidelity improvements in different functional areas of the simulation are also highlighted, including visual fidelity and rotor wake interaction. An evidence based methodology for the verification and validation of the simulation is also required to enable greater acceptance of simulation-based data.

ABOUT THE AUTHORS

Ian Cox is the Simulation and Training Portfolio Manager at SEA. Ian has over 20 years' experience working in the modelling and simulation industry, including working on a variety of projects such as man-in the-loop air combat simulation and the modelling of aircraft sortie rates for aircraft carriers. Ian joined SEA in 2003 where he led the initial development of the SAIF simulation architecture, including multiple trials of the SAIF system integrated with a Merlin helicopter flight simulator. More recently, Ian is the industry programme manager for the four year UK Architectures, Interoperability and Management of Simulations (AIMS) research programme, sponsored by the Defence Science and Technology Laboratory. He now oversees all of the simulation and training project delivery within SEA, which includes physics-based simulation projects such as SAIF, research activities and training systems development.

Dr Gary Henry holds the position of Senior Principal Consultant at SEA. He is responsible for specifying and developing frameworks for simulating complex, physically coupled systems. His previous experience includes the design and implementation of the UK Replenishment at Sea (RAS) and NATO Submarine Rescue System (NSRS) simulations. Dr Henry recently migrated the design of the SAIF architecture to support the NATO simulation standard known as Virtual Ships, for which he is a UK lead author.

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The launch and recovery of a helicopter to the flight deck of a moving ship is a highly dynamic operation, involving many complex interactions between the environment, the air vehicle and the helicopter crew. The accurate simulation of these operations is therefore a significant challenge. The paper provides an initial summary of the drivers that are influencing the need for Ship/Air Integration simulation and potential benefits and challenges with the adoption of simulation. A brief summary of previous multi-national activities in this domain is also provided, together with further technical details on the UK Ship/Air Interface Framework (SAIF) programme and how the SAIF flight simulator interface has recently adapted the existing Common Image Generation Interface (CIGI) standard to provide a new synchronous interface, which has been successfully integrated with the Chinook engineering flight simulator provided by Boeing Inc. The UK Chinook programme is the first to include simulation as part of an integrated approach to developing Ship/Helicopter Operating Limits (SHOLs) alongside traditional flight test activities, and the paper describes the phased approach being adopted to build up Verification and Validation (V&V) evidence, such that simulation-derived data can be trusted and accepted as part of the aircraft/ship clearance processes.

SHIP/AIR INTERFACE SIMULATION BACKGROUND

Generation of Ship/Helicopter Operating Limits

The generation of evidence to produce SHOLs for a new combination of ship/helicopter type has traditionally been conducted in the UK via First of Class Flight Trials (FOCFT) for new ships, or First of Type Flight Trials (FOTFT) for new aircraft. These trials typically involve hundreds of helicopter take-offs and landings from the ships flight deck in order to establish the boundary conditions for safe operation of the aircraft. The flight trials may require several days, if not weeks at sea, utilizing instrumented aircraft and ship and subsequent analysis of the data provides the evidence that supports the release to service of the particular ship and aircraft combination.

SHOLs may be described by a series of polar plots, showing the limiting relative Wind Over Deck (WOD), i.e. the combination of wind speed, deck motion (pitch and roll) and ship speed, for the boundary between acceptable and unacceptable pilot workload and aircraft control levels, as shown in Figure 1. A SHOL diagram may cover a range of different aircraft operating weights and operating conditions (e.g. day or night (unaided/Night Vision Devices (NVD)) operations, using a particular approach path to the flight deck). The SHOL boundary points are determined by assessing the pilot workload and aircraft handling control and power margins for an aircraft recovery and take-off at specific

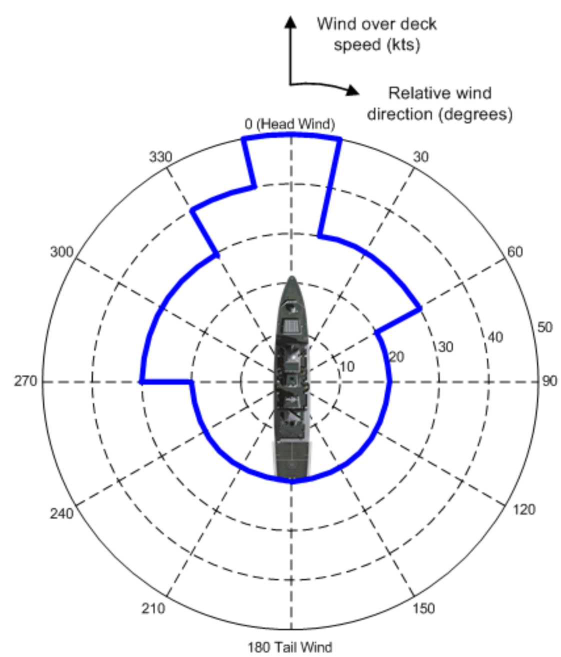

Figure 1. An example SHOL plot showing the boundary WOD conditions (blue line) for acceptable pilot workload and aircraft control

test points, defined by the WOD speed and direction. Additional limitations may be placed upon the SHOL by ship pitch and roll angle limitations, within which the aircraft may safely conduct launch/recovery and operations on the flight deck.

The Need for Simulation

There are now several driving factors that are promoting the need for cost effective and accurate simulation of the ship/air interface to complement traditional flight test activities. These factors include:

- The increasing operating costs of ships and aircraft and the crews that operate them. It has been estimated that it costs £8000 ($10,000) to operate a Chinook helicopter for 4 hours of flight during one day of a sea trial, with Royal Fleet Auxiliary (RFA) single spot ship embarked cost of £12,000 ($15,500);
- For larger ships such as an aircraft carrier with multiple helicopter operating spots, there is a need to generate SHOL clearances for each of the operating spots, which may not be achievable within the limited sea trials window of opportunity;
- For a new ship or aircraft type, there is the potential need to clear multiple ship/helicopter combinations within a short time period to support its introduction into service;
- The sea trials time may be impacted by adverse weather conditions, either too calm or too severe, which may limit the range of conditions for which evidence can be gathered and restrict the resulting SHOL clearance. The ship or aircraft may also be susceptible to availability or reliability issues that during the sea trials period that may further restrict the amount of evidence that can be gathered.

The UK Ministry of Defence (MoD) Defence Equipment and Support (DE&S) organization has issued guidance on the potential use of 'computer analysis techniques' within its Defence Standard for Aviation Arrangements in Surface Ships: Acceptance of Aviation Arrangements:

"*computational techniques may help DE&S plan the safe conduct and exploitation of the FOCFT / FOTFT and the same may be true of SHOL trials and the Fixed Wing air system equivalent. It might also be deduced that trial results could calibrate and validate computer models (subject to the actual conditions encountered) to give confidence in their use. Although empirical trials data is likely to remain essential, the general assertion might be made that, in practical terms, it will not be feasible or affordable to conduct trials with scarce ship and air assets to gather data on every possible operating circumstance and that the legacy techniques at best are a compromise.*
Thus, the systematic use of computer analysis techniques at each stage of ship-air-integration (i.e. characterizing the ship design, the air system design and the operation of ship and air system together) and then validated by carefully optimized trials, may offer DE&S a far more robust and defensible basis for constructing clearance recommendations" (Def-Stan 00-133 part 4, 2015).

Potential Benefits

In consideration of the above factors, simulation offers the potential to deliver significant benefits to the organizations responsible for generation and approval of SHOL clearances. The ability to configure a simulation to provide the required environmental test conditions provides a great deal of flexibility when compared against the prevailing conditions available during sea trials, potentially providing evidence for a wider range of SHOL test points. The operating costs of a simulation are also likely to be significantly lower than those for a ship and aircraft. A cost effective combination may therefore be considered, using simulation to generate an initial indicative SHOL, which is then spot-checked using a limited amount of flight test data. Early adoption of simulation techniques during the design process may also help to optimize the design for ship/helicopter operations, rather than discovering issues during first of class trials.

Potential Challenges

Given the complexity of the real life operations, providing a ship/air integration simulation of a suitable level of fidelity is a significant technical challenge. Each individual simulation component and the overall capability itself needs to be validated and the approach to using the simulation verified before any simulation derived data can be accepted. At present, there are no clear fidelity guidelines or acceptance criteria that prove a benchmark for the required quality of the simulation.

Furthermore, simulation may be seen as a threat to the traditional 'test and declare' approach based upon flight test and sea trials data. Confidence must be built within the flight test, aircrew and acceptance authorities that simulation can provide a reliable and accurate tool that can be used as part of the clearance process.

Multi-National Research and Development Activities

The required technologies and approach taken to accurately simulate the ship/air interface has been a research topic for over 20 years within many nations. Within the UK, research was conducted using a large motion flight simulator on the issues involved in simulating naval helicopter launch and recovery operations (Tate, 1995). More recently, Liverpool University has conducted an extensive research programme over many years, investigating aspects such as determining suitable fidelity criteria and guidelines for the modelling and simulation of the helicopter-ship dynamic interface environment (Hodge et al, 2012) and the use of modelling and simulation applied to the design of a ship's superstructure to improve the aerodynamic flow field in which the helicopter has to operate (Owen et al, 2016).

Within the US, the Joint Shipboard Integration Process (JSHIP) programme developed the Dynamic Interface Modelling and Simulation System (DIMSS), with the aim of using modelling and simulation to define a process for expanding the flight envelopes for any ship/helicopter combination (Advani and Wilkinson, 2001; Roscoe and Wilkinson, 2002). The Ship Airwake Analysis For Enhanced Dynamic Interface (SAFEDI) program, sponsored by the Office of Naval Research, has focused on improving Computational Fluid Dynamics (CFD) airwake modeling fidelity, verification and validation (V&V) of CFD airwake predictions, and creation of a desktop simulation tool (the SAFEDI Tool) for flight simulation-based airwake analysis (Polsky et al, 2016).

The North Atlantic Treaty Organization (NATO) Air Vehicle Technology (AVT) Task Group 148 (NATO RTO-TR-AVT-148, 2012) has also conducted research intended to improve the safety of air operations from ships at sea, by improving aircraft launch and recovery in a ship airwake environment through the following:

a) Modelling representative ship and aircraft combinations in a wind tunnel to assess the effects of airwake on launch and recovery;
b) Modelling representative ship and aircraft combinations using Computational Fluid Dynamics (CFD) code(s) for comparisons with experimental data;
c) Assessing representative flow control devices via experiments and analyses for improvement in ship and aircraft performance; and
d) Conducting flight simulations to verify and optimize flow control solutions for improved aircraft launch and recovery.

The UK Ship/Air Interface Framework (SAIF)

Background

The SAIF programme commenced in 2003, with the aim of developing a flexible networked simulation capability based upon the High Level Architecture (HLA), for the purpose of generating SHOL evidence for any combination of ship and aircraft types. The project initially coincided with the introduction into service of the Royal Navy (RN) Daring-class Type 45 destroyer, and a key aim of the original SAIF project was to develop a simulation capable of accurately predicting the SHOLs for the Merlin Mk1 helicopter operating from the Type 45, ahead of the FOCFT. With this aim in mind, the SAIF project developed a networked version of the Merlin Mk.1 helicopter Cockpit Dynamic Simulator (CDS), based at the Royal Naval Air Station (RNAS) Culdrose.

Initial Simulation Design and Development

The original SAIF architecture provided an HLA federation design compatible with the NATO Standardization Agreement (STANAG) 4684 Standards for Virtual Ships, with the following key areas of functionality provided by separate HLA federate applications:

- *Environment Federate*: Published data on the wind speed and direction, sea state, wave spectra, time of day and visibility levels to the federation;
- *Ship Motion Federate*: Calculated in real-time the six Degrees-Of-Freedom (DOF) motion of the ship, either by using a pre-recorded time history file or by calculating the response to the individual wave sinusoids published by the Environment Federate;
- *Ship Airwake Federate*: Calculated the three-dimensional airflow velocity vector at various sample points around the air vehicle. A grid of normalized airwake flow velocities around the ship was calculated offline using CFD methods. The position of the air vehicle relative to the ship was then used to access the flow data, and calculate the airflow velocity vectors at the sample points, which were scaled by the WOD

velocity. The airflow data was then fed back to the air vehicle model for use within its internal flight dynamics calculations;

- *Landing Aids Federate*: Controlled the functionality of the various ship-borne Visual Landing Aid (VLA) systems used to support aircraft operations;
- *Visualisation Federate*: Provided a dynamic visualization of the simulation from multiple user-selected viewpoints;
- *Air Vehicle Federate*: Provided a simulation of the flight dynamics of the air vehicle. In the case of the Merlin Mk1, this functionality was provided by the Merlin CDS integrated with a SAIF-compatible interface.

Initial development of the SAIF system highlighted the need to increase the fidelity of the ship airwake federate. The original 'time-averaged' CFD data was replaced by 'time-accurate' CFD within the airwake federate, which provided a much more realistic level of ship generated turbulence cues to the pilot (Cox, Duncan, 2009). Verification and Validation (V&V) of the SAIF system concentrated upon comparing simulated SHOL test points against flight test data for the Merlin helicopter operating from the Type 23 frigate and Wave Class Auxiliary Oiler. Results using the improved time-accurate airwake federate proved to be encouraging, with the time-accurate airwake offering improvement over the previous time-averaged model for the Type 23, and in the key head-wind cases for the Wave Class, where ship-generated airwake turbulence is a key factor. Other research studies have also confirmed the benefits of using time-accurate CFD data for ship air wake simulation (Hodge et al, 2009).

In 2009, two months before the Merlin/Type 45 FOCFT, the SAIF system at Culdrose was used to generate a predicted SHOL envelope via simulation, using the same flight test crew and test procedures that were used during the sea trials. A total of 144 test points were flown in the simulator, compared to the 466 test points flown in the FOCFT. Unfortunately, only 27 of the simulated test points were directly comparable with flight test point conditions, i.e. they had the same WOD, aircraft weight, approach path and day/night conditions. This gave an insufficient numerical basis to reach a firm conclusion on the outcome of the comparison, but for the 27 comparable points, 67% were well matched in terms of pilot workload rating, 74% were well matched in terms of rotor torque rating (i.e. how much power the helicopter is using to maintain height control) and 96% were well matched in terms of tail rotor pitch rating (i.e. how much yaw/pedal is being used to maintain heading control). The definition of 'well matched' is described later in the paper at the section entitled "*Comparing Simulation vs. Flight Test Data*".

SAIF SIMULATION – RECENT TECHNOLOGY DEVELOPMENTS

The SAIF to Flight Simulator Interface

In the early versions of SAIF, the flight simulator joined the SAIF HLA federation as another HLA federate. The SAIF federation used wall clock synchronization to ensure the clocks on the computers hosting the SAIF federates did not out-run or under-run the clock used in the flight simulator. This was achieved by employing a Network Time Protocol (NTP) server, which could synchronize the computer clocks to within a few milliseconds. The interface to the flight simulator was therefore asynchronous and subject to random transport latencies. As a result, all HLA updates were required to carry time stamps, which were used to extrapolate or interpolate received data. A consequence of this was that a small but observable jitter was present in the updated data, which could be seen in the visuals. To remove the jitter, a smoothing algorithm was needed, both complicating and reducing the accuracy of the simulation.

A better solution is to use time managed or synchronous communication. While the HLA does support time management services, these are tricky to use and carry their own overhead. The use of time managed services also prevents the HLA from using the faster UDP communications protocol. The Virtual Ships simulation standard implements its own time management services just using the basic HLA services, and carries little overhead. The new design of SAIF now uses the Virtual Ships time management scheme, and can potentially connect to other Virtual Ships simulations using the same scheme. However it transpires that many flight simulators do not support HLA connectivity, let alone the special version used by Virtual Ships. Part of the reason is the steep learning curve to implement HLA. Because all flight simulators need to drive a high resolution display system, many flight simulators support a generic interface for connecting to image generators, known as the Common Image Generation Interface (CIGI).

The CIGI interface is a synchronous interface and defines the coordinate systems and data conventions for the exchange of data between the flight simulator and its image generator. Because the flight simulator engineers are more likely to be familiar with CIGI than HLA, the SAIF system was designed to implement a simple version that contains only three message types (two of which carry no data) and seven data type packets.

This approach has the benefits of providing a quick implementation path for the flight simulator engineers, and a synchronous interface, therefore eliminating the need for NTP, jitter and smoothing algorithms. The interface does, however, require that the SAIF system responds to flight simulator air wake queries within the agreed time step of the simulation (typically at 40 to 50Hz). This is quite a constraint when one realizes that the SAIF system has to find up to 100 air flow velocities stored in 120GB of air wake data!

A further improvement has been the combining of the three desktop computers of the early SAIF system into a single hardware rack-mount system containing high end Xeon CPUs, 128GB of RAM and a solid state disc (SSD) Redundant Array of Independent Disks (RAID) for the air wake data. We can now say that SAIF is truly a system in a box. A further usability improvement is that SAIF does not require it to have a human operator. Instead, the SAIF interface has been designed so that the flight simulator is able to control the complete SAIF scenario, from start-up to restart or shutdown. Once the flight simulator has implemented the CIGI-like SAIF interface, using SAIF is little more than plugging in an Ethernet cable and powering it up.

Integration of SAIF with the Boeing Chinook Engineering Flight Simulator

In preparation for this activity, SEA provided Boeing with a software installer for SAIF that could be installed and run on a basic PC. This allowed Boeing to develop and test their end of the SAIF communications link, with support from SEA. With the link running successfully, the SAIF hardware rack system was delivered to Boeing and connected to the flight simulator. The initial tests were very successful; and the minor issues found were easily fixed on site. The initial integration of the SAIF rack with the Chinook simulator took less than one week, and subsequent updates of the system taking less than one day.

Computing the Ship Air Wake

Frazer-Nash Consultancy (FNC) was tasked to compute the ship air wake data using CFD. The first step was to run steady state simulations, using ANSYS Fluent 17.1 with the Reynolds Average Navier-Stokes (RANS) method, and the k-ε subgrid-scale turbulence model. This informed the appropriate sizing of the mesh to use for the transient simulations and provide an initial flow field. The steady state simulations were run with zero ship speed and a wind speed of 25kts at a fixed reference point above sea level. The mesh resolution for the CFD model was set so that 80% of the turbulent kinetic energy is resolved explicitly, with the remaining 20% covered by a subgrid model.

The transient simulations were solved in ANSYS Fluent using the Large Eddy Simulation (LES) method, and the Dynamic Smagorinsky subgrid-scale turbulence model. A time step of 0.0125s (80Hz) was used in the transient simulations. This was twice the 40Hz frequency required for the SAIF simulator, to ensure sufficient temporal resolution. It was important to check that the unsteady flow field washes through the whole domain before starting to capture a transient dataset before starting to capture the simulator data. Thirty seconds of transient data were simulated.

The generated air wake data was converted to the standard SAIF format, which comprises three nested rectangular domains placed around the ship at spatial resolutions of 1m, 2m and 4m. This data was further processed by SEA into a format suitable for real-time access, and at the same time the air wake time histories were adjusted so that there was a smooth join of the beginning and end of each time history, to allow the air wake data to be seamlessly cycled during a simulation. The implementation of the air wake data into SAIF was verified by arranging SAIF to replay the air wake time history at specified locations and comparing the resulting time history with that from the original FNC computed air wake data.

UK CHINOOK SHIP/AIR INTERFACE SIMULATION PROJECT

Customer Vision

The UK MoD Chinook helicopter Delivery Team (DT) has a requirement to clear four different versions of the Chinook (Mks 4, 5, 6 and 6A) to seven different UK ships by 2023. The DT has recognized that this would be unaffordable to achieve using traditional flight test methods alone, so has looked to the SAIF simulation capability to provide an alternative source of data to support the generation of SHOL clearances.

The Chinook DT are working closely with Boeing Inc. in the US, who are the Design Organization (DO) and Original Equipment Manufacturer (OEM) for the Chinook, such that the DO is fully involved in and endorses the approach taken to provide safe operational clearances for the aircraft. Boeing also has access to a high fidelity full motion engineering flight simulator for the Chinook at its site in Philadelphia, which can be reconfigured to represent the UK versions of the aircraft. An initial feasibility study conducted between Boeing and SEA concluded that the Chinook flight simulator could be integrated with the SAIF architecture in order to provide high fidelity ship air wake and ship motion representations of the UK ships.

In order to provide a safe and progressive approach to the introduction and V&V of simulation to support the generation of Chinook SHOL clearances, the DT has planned an incremental set of three phases of work (Crawl-Walk-Run), in order to build up confidence in simulation and build up V&V evidence. The DT is also appointing an Independent Technical Expert (ITE) to evaluate simulation approach and V&V evidence.

Phase 1 "Crawl": Chinook/Tide Class

During phase 1, the initial integration activity of the SAIF system with the Chinook flight simulator was conducted, in order to prove the hardware and software interface between the two systems. Models of the new Royal Fleet Auxiliary (RFA) Tide Class ship covering ship motion, ship air wake and a 3D visual model of the ship were integrated within the SAIF system, and a 3D visual model of the ship was also integrated within the Chinook flight simulator Image Generator (IG) system. An initial piloted assessment was conducted in 2017 on the SAIF configured Chinook simulator, the results of which are discussed below. The FOCFT for Chinook/Tide Class is due to take place later in 2018, and will provide a good opportunity to compare simulated and flight test data. Unlike the previous Merlin/Type 45 FOCFT, replication of specific simulation test points within the flight trials programme will be a key objective to support the V&V process of the simulation. At this stage, the initial SHOL clearance for the Chinook/Tide Class is likely to still be purely based upon FOCFT trials data, but once a level of confidence has been demonstrated in the simulation there is potential to expand the this clearance. Initial V&V of the SAIF components and Chinook flight simulator has already been conducted prior to Phase 1.

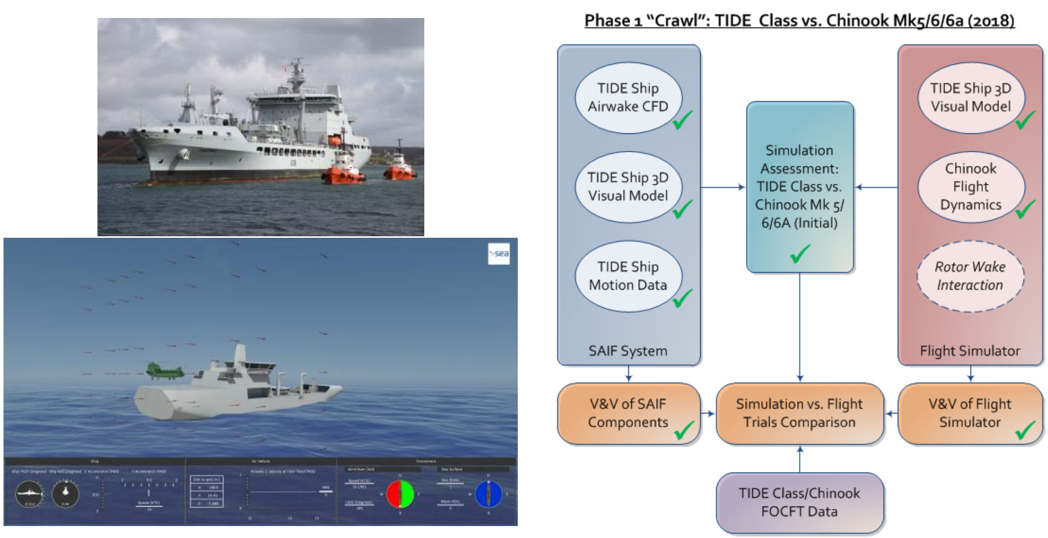

Figure 2. Phase 1 provides the first opportunity to simulate Chinook operations from the Tide Class (top left) using the SAIF environment (bottom left taken from SAIF visualization)

Phase 2 "Walk": Chinook/QE Class

Given a positive outcome from phase 1, i.e. the simulation appears to at least provide a credible representation of the Chinook operations from the Tide Class, phase 2 provides a further opportunity to build up more simulation V&V evidence for the simulation for a different ship type, the QE Class aircraft carrier, which has very different ship motion and airwake characteristics and multiple helicopter operating spots. The FOCFT for Chinook/QE Class were originally scheduled to take place after the Chinook/Tide Class, but were in fact conducted in early 2018. Models of the QE Class covering ship motion, ship air wake and a 3D visual model of the ship have also now been integrated within the SAIF system and Chinook flight simulator in early 2018, with a plan to conduct a simulation assessment of FOCFT test points later in the year to feed into the simulation vs. flight trials comparison. At the end of phase 2, sufficient V&V evidence should be available on the quality of the simulation to inform how simulation data may be used to expand the current Chinook/QEC SHOL clearance and could play a larger role in generating the SHOL clearances for the Chinook for the remaining five ships in phase 3.

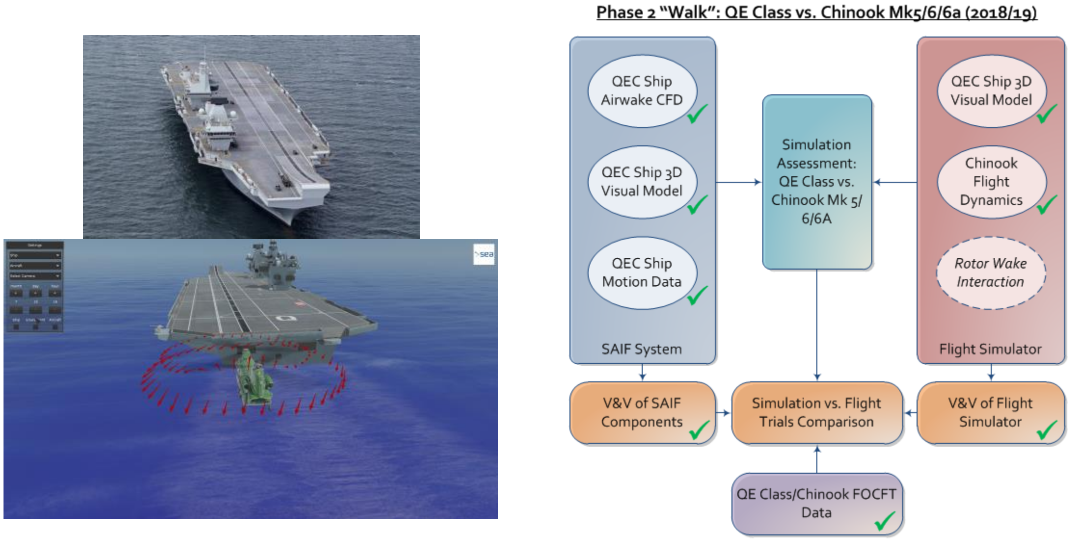

Figure 3. Phase 2 will assess Chinook operations from the QEC Class (top left) within the SAIF environment

Phase 3 "Run": Chinook/In-service ships

Progression to phase 3, backed up by a positive set of V&V evidence will enable the Chinook DT to consider increasing levels of simulation to clear the aircraft from the remaining five in-service ships. This would not be done exclusively using simulation, and 'ship mini-trials' utilizing an instrumented aircraft/ship are also planned to spot check any simulation data to confirm that any assumptions or SHOL clearances derived using simulation are still valid. Integration of the ship motion, air wake and 3D visual models for the ship platforms will still need to be conducted prior to any simulation assessments.

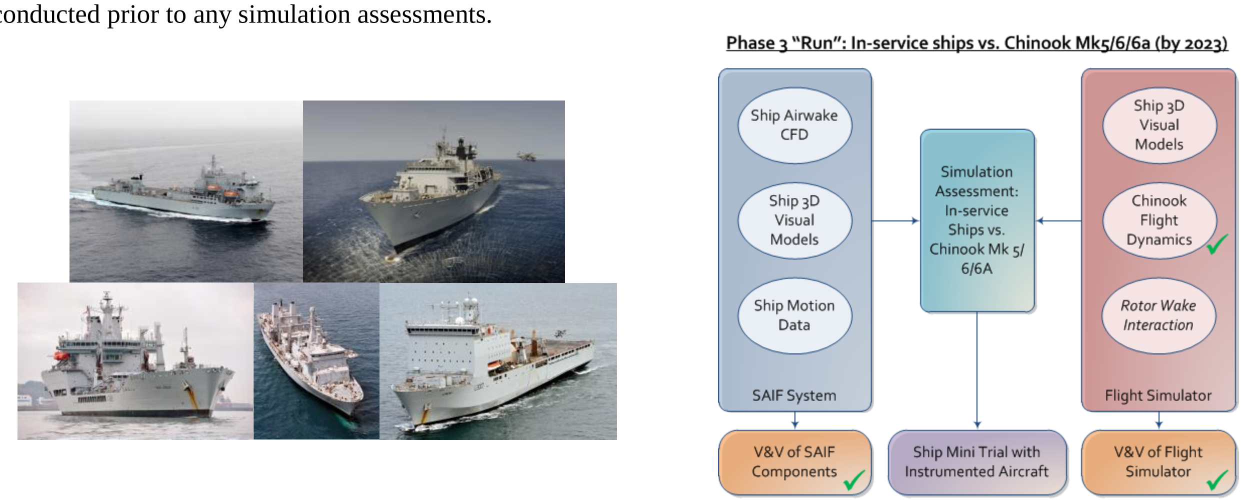

Figure 4. Phase 3 may use simulation to clear Chinook operations from the five in-service ships (clockwise from top left: RFA Argus, Albion Class, Bay Class, RFA Fort Victoria and Wave Class)

Only once a sufficient level of simulation comparison and V&V activity has taken place, backed up by Boeing as the DO for the aircraft, and independently assessed by the ITE, can the data derived from simulation be considered as the primary source of data to support the SHOL clearances.

LATEST RESULTS AND FINDINGS

Integration Results

Initial testing of the Chinook flight simulator integrated with the SAIF system configured with data for the Tide Class ship conducted in 2017 proved that the interface between the two systems operated reliably, providing a consistent 40Hz data transfer rate between the two systems. This is the same frequency as the frequency of CFD air wake data used by the SAIF air wake model and provided a sufficiently high update rate for integration with the Chinook flight dynamics model.

One potential issue is the amount of time it takes to load the large quantities of air wake data into memory before that start of the SAIF simulation. For the Tide Class, this took approximately 40 seconds to load 55GB of data for one WOD direction, which is a manageable delay at the start of the simulation. However, for the QE Class aircraft carrier, the 120Gb of data for one WOD direction took up to 150 seconds to load. Alternative ways of loading and reading the air wake data, such that the 40Hz data transfer rate between the SAIF system and flight simulator is achieved, are now under investigation.

Potential Fidelity Improvements

Short Term (1-2 years)

Several potential improvements to the fidelity of the simulation were identified during the 2017 integration:

- *Ocean visuals*: The IG system used in the Chinook flight simulator was unable to visualize the same sea spectrum data (i.e. the collection of wave sinusoids) that the SAIF ship motion software was using in its calculations. This resulted in the potential issue of the ship motion appearing to be uncorrelated with the wave motion seen by pilot in the simulator. This issue is currently under investigation and may be rectified by an upgrade to the IG system.
- *Ship motion*: The pilots questioned some of the levels of simulated ship motion for the Tide Class, especially in higher sea state conditions. Further V&V of the Tide Class ship motion model against reference information from model tank tests is being conducted in 2018.
- *Ship visual model*: Improvements to the fidelity of the Tide Class ship visual model in the simulator IG were identified by the pilots, such as more detail around the hangar and ring bolts to the ships flight deck. These features would aid the depth perception of the pilot in the simulator, allowing them to fly the helicopter more accurately and realistically.
- *Simulator motion cues*: The Chinook simulator is fitted with a 'g-seat' and vibration platform to provide additional cues to the pilot when the aircraft is encountering turbulence or demanding high levels of torque through the rotor system. It was felt that these devices may need more tuning to provide effects that are appropriate with the levels of turbulence being simulated, although it would be difficult to obtain any objective data (i.e. actual vibration levels from the aircraft under measured conditions) which could be applied to a tuning exercise.
- *Background atmospheric turbulence*: The initial CFD air wake data produced for the Tide Class did not include any data to simulate the background levels of atmospheric turbulence typically encountered close to the sea surface. Frazer-Nash Consultancy has now conducted further work to produce some additional data sets that include a level of background turbulence, but this data may only be valid for a specific WOD velocity and may not be normalized and subsequently scaled by the WOD velocity in the same way as the 'ship generated' air wake data. Further piloted simulations are planned to assess the impact of adding atmospheric turbulence effects and if they should be included for future simulations.
- *Rotor downwash effects*: The air wake does not take account of the downwash effects from the helicopter rotors and any subsequent flow re-circulation effects that may be present when the helicopter is operating close to the ship's flight deck. Boeing are currently conducting further research in this area to consider how rotor downwash and re-circulation effects may be included within the simulation.

Long Term (3 years and beyond)
There are several limitations of the current simulation that are recognized and may be addressed via improvements in technology. Many of these limitations are related to current implementation of the ship air wake model in order to allow it to function within a real time simulation. These air wake model limitations include:

- The ship air wake currently assumes a 'static' ship, i.e. the air wake does not vary as the ship pitches and rolls;
- Each CFD air wake file is calculated for one WOD velocity and direction assuming a fixed combination of ship velocity and ambient wind velocity. For the Tide Class and QE Class, this was based upon zero ship velocity and the WOD purely generated by the ambient wind. The same WOD could be achieved using multiple different ship/wind combinations, each with its own slightly different set of flow characteristics.

The possibility of using a real-time CFD flow calculation that is fully coupled with a dynamic flight simulation application has been a topic of research for over 10 years (Alpman et al, 2007; Kenny et al, 2008; Oruc et al, 2017). However, to the best of the authors' knowledge, this still appears to be some way from becoming a practical reality in the near future. Alternative faster computational techniques, such as particle-based methods, perhaps offer a more suitable means of providing real-time ship air wake flow dynamics, if they can be sufficiently proven and validated.

SHIP/AIR INTERFACE SIMULATION – REMAINING CHALLENGES

Comparing Simulation vs. Flight Test Data
The most powerful source of V&V evidence is the analysis of simulation and flight test data for a directly comparable SHOL test point, i.e. a landing/take-off flown to the same WOD, aircraft weight, approach path and day/night conditions and assessed using the same ratings. It is therefore highly desirable that the aircraft and ship involved in a FOCFT/FOTFT are instrumented, such that data regarding the platforms can be recorded and subsequently compared against simulation data. Opportunities for potential data comparisons include:

- *Pilot workload ratings*: The Dynamic Interface Pilot Effort Scale (DIPES) workload rating is used to assess the level of pilot workload associated with recovery and take-off for each SHOL test point. A DIPES rating of 1 to 5 is given by the flight test team for each test point, together with up to 3 out of 14 letter descriptors, which define the main causal factors behind the given rating (e.g. R = Roll control, Y = Yaw control, H = Height control). By comparing the ratings generated by the simulation against flight test data for the same test point, a measurement of the validity of the simulation can be obtained. A potential criterion was developed as part of the previous SAIF studies to assess the ratings, stating that the simulator ratings must be within one point of the flight test ratings with at least one identical DIPES descriptor, for it to be considered as well matched.
- *Flightpath analysis*: The simulated approach path of the helicopter to the ship can be directly compared against the actual flight path flown during the sea trials and measured using differential Global Positioning System (GPS) data, to check that the simulated aircraft is being flown in a similar way to the real aircraft.
- *Aircraft performance analysis*: In addition to the DIPES workload rating, the mean and peak values of engine torque and pedal position are analyzed using recorded aircraft Flight Test Instrumentation (FTI) data. The data is assessed to see if the aircraft exceeded performance limits relating to the power demanded from the engines and transmission system, or the amount of remaining pedal control authority. A rating of 1 to 5 is then given for 'torque' and 'pedal'. The SHOL boundary is then determined by the boundary between ratings 3 and 4 for the highest score between the DIPES workload, torque and pedal ratings.
- *Pilot control system input analysis*: The cyclic, collective and pedal control inputs made by the pilot for each SHOL test point may also be recorded during the sea trials. This may permit the analysis of the control inputs made by the pilot for the same test conditions in the simulator, to assess if the pilot is flying the aircraft in a significantly different manner in the simulator.

It should also be noted that due to the human pilot-in-the-loop, there will be a degree of variability in both simulated and real flight test data. It is therefore unreasonable to expect a simulation to provide a perfect match to flight test data, but the question to be answered remains – is the simulation sufficiently accurate to be a useful tool? The definition of 'sufficiently accurate' needs to be determined via a robust and independent V&V process.

Verification and Validation Approach
For the UK Chinook programme, the ITE will have the responsibility for providing an overarching V&V approach that provides the evidence on the status of individual functions within the simulation and the V&V status of the simulation as a whole.

For the key individual functions within the SAIF simulation, V&V evidence can be gathered on how well that particular function represents reality. For example, outputs from the SAIF ship motion model are compared against ship seakeeping performance data from scale model tank tests, sea trials and other reference models, to inform the V&V status of the model. The ship airwake data used in the simulation can also be compared against full scale anemometer readings measured during Air Flow/Air Pattern sea trials or scale model wind tunnel data (Snyder et al). A significant amount of V&V evidence for the Chinook flight simulator is also held by Boeing as part of their previous engineering activity.

The Simulation Interoperability and Standards Organization (SISO) provide a Guide for Generic Methodology for Verification and Validation (GM-VV) to Support Acceptance of Models, Simulations, and Data. The GM-VV provides a technical framework that focuses on modelling and simulation V&V practices and promotes the use of a structured goal-claim network methodology, as shown in Figure 5, to define the acceptance criteria and evidence solutions (the left-hand side V&V 'goal' network) and then builds up the individual items of evidence and acceptability claims (the right-hand side V&V 'claim' network). It is recommended that the ITE follows this approach in co-operation with the customer, simulation developers, aircraft DO, flight test community and Release to Service authorities such that the V&V goals and claims for the UK Chinook SAI simulation activities are clearly understood by all parties.

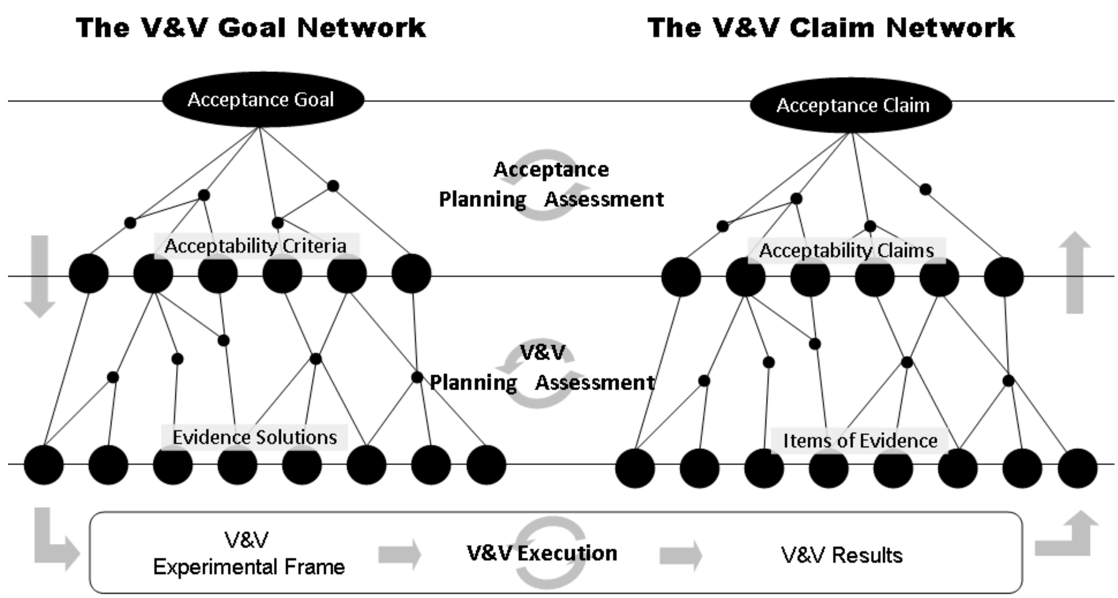

Figure 5. The SISO GM-VV Goal-Claim Network provides a structured approach to defining and presenting V&V evidence

Acceptance of Data Derived from Simulation
The UK Defence Standard 00-133 has highlighted the opportunity to increase the use of simulation as part of the ship/helicopter clearance process, which the UK Chinook DT is now adopting. However, there still needs to be a 'cultural shift' such that simulation derived data can be trusted by the relevant stakeholders. In particular, the following key activities need to happen alongside the technical developments:

- The benchmark for the SAIF simulation acceptability criteria (i.e. how good does the simulation need to be?) needs to be agreed and set as part of the V&V activity. This will clearly define the expectations of the clearance authorities, whilst not being overly optimistic about the capabilities of the simulation to represent all of the factors present in real world operations to a high level of fidelity.

- The flight test community needs to embrace simulation as a viable tool alongside traditional flight trials at sea, rather than seeing simulation as a threat to their livelihood. The inclusion of simulation derived data may help to deliver more affordable and focused flight trials activities that will also help to validate the simulation outputs. This is very much the approach being now promoted by the UK Chinook DT as opposed to the previous Merlin/Type 45 FOCFT.

SUMMARY AND CONCLUSIONS

Simulation offers the potential to provide a cost effective and flexible tool alongside traditional flight test activities, to support the generation of data to support the release to service for new ship/aircraft operations. The UK Chinook programme is the first to adopt a phased approach (i.e. Crawl-Walk-Run) to use increasing levels of simulation data to support their clearance schedule. The initial technical integration of the SAIF capability with the Chinook engineering flight simulator has been successfully achieved and a number of potential fidelity improvements identified. The focus of the work is now shifting to the V&V of the simulation, to inform the current acceptance evidence and claims to support the use of simulation data within the formal clearance process.

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