24th EUROPEAN ROTORCRAFT FORUM
Marseilles, France - 15th-17th September 1998

TE 07
The Use of Modelling and Simulation in Support of First of Class Flying Trials

D Fitzjohn
G P Turner
G D Padfield
Flight Management and Control Department
Defence Evaluation and Research Agency
Bedford
United Kingdom

The process of bringing new or upgraded aircraft into operational service requires an extensive and rigorous programme of flight testing to qualify the safe flight envelope and certify the operational flight envelope. While flight-testing with operational standard hardware and within the physical constraints set by the operational environment will remain the essential core of this test and evaluation activity, simulation can help make these tests more effective and efficient. The extent to which simulation can provide support to this process depends critically on the fidelity level of the component models. Modelling and Simulation has been used in various forms in this application for several decades but in recent years the fidelity level has been increasing to the point where a significant expansion of their application can be envisaged. Coupled with the growing capability is the increased need for a more cost effective and productive certification methodology to meet the military needs over the next decade. In this context, the Royal Navy (RN) will be bringing three new ships into operational service within the next decade and there is a requirement to define ship to helicopter operating limits (SHOLs) for at least five aircraft types on these ships. The RN sponsor for the certification of SHOLs has funded a programme of work at DERA into the application of Modelling and Simulation to support this process. This paper introduces the philosophy of the Military Aircraft Release and the role of First of Class Flying Trials in this process. In addition, the paper describes the modelling, test procedures and results for trials conducted on the Advanced Flight Simulator (AFS) at DERA Bedford. The trials form a series of assessments to determine the feasibility of using Modelling and Simulation in the proposed environment. The objective of the trials was to demonstrate a capability to determine SHOLs using the AFS by attempting to recreate the real-world result for a Lynx HAS Mk3 operating to the Type 23 Frigate.

1. INTRODUCTION

1.1 Military Aircraft Release

The Military Aircraft (MA) Release is the statement on behalf of the Chief of Defence Procurement (CDP) to the relevant Service Chief of Staff defining the aircraft's operating envelope, conditions, limitations, minimum build standard, minimum standard of operational software. Additionally, it covers the procedures within which the airworthiness of the design has been established. It is also the declaration to which the aircraft may be flown in Service-Regulated flying with the support of the CDP. However, MA Release is not a condition of contract and aircraft will have to be accepted if the contractual specification is met.

The terms of the MA Release are drafted by the MoD Project Director based on the aircraft Certificate of Design, on recommendations from DERA Boscombe Down and from structural advice from DERA Farnborough. The foundation for the advice to MoD comes from trials carried out by these organisations and from joint trials with the contractor. The interpretation of the MA Release for inclusion in the aircrew manuals and flight reference cards is the responsibility of the RAF Handling Squadron. This process is shown in Figure 1.

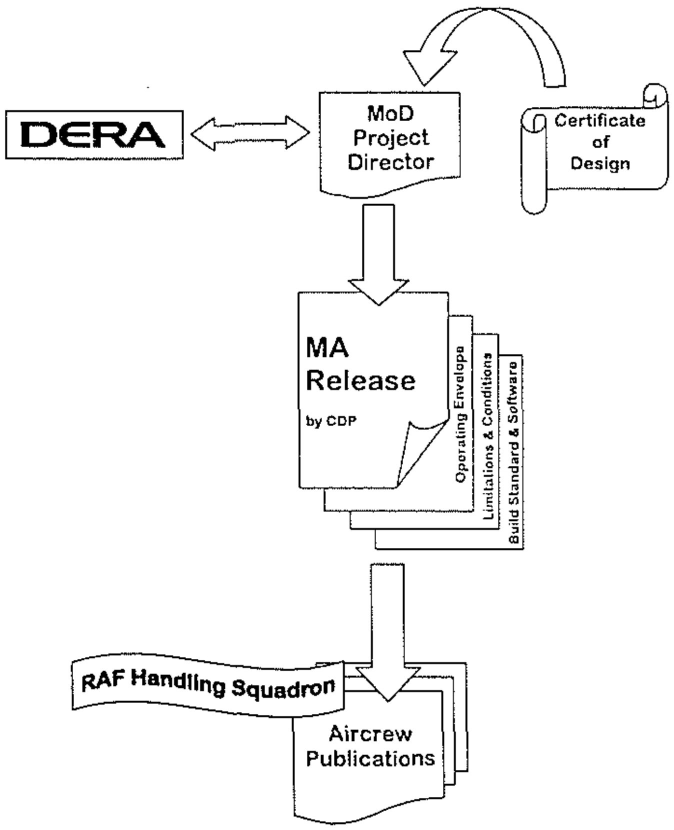

Figure 1; Military Aircraft Release Process Diagram

Currently, the process of producing the MA Release is based solely on flight testing with perhaps read across from civil certification and release data that already exists from external bodies. Modelling & Simulation (M&S) has no significant input and there is certainly no piloted simulation. It has been proposed by many agencies, that the potential for M&S to support the MA Release process is great.

Much work has been carried out in the area of handling-qualities research using simulation. The requirements for handling-qualities assessment and the derivation of the MA Release are broadly similar and current methodologies could be exploited. Additionally, it is envisaged that simulation and flight test could be used as complementary tools. Simulation would allow the safe exploration of the flight envelope in a controlled repeatable environment with the confirmation and final certification being underwritten from flight trials. There are many levels of simulation that could be exploited, both off-line and piloted. These would range from the desktop non-real time applications to the real time models driving large motion systems. Areas where it has been identified that M&S could be integrated and effective are:

- Definition of more effective trials
- Interpolation between flight assessments
- Expansion of the Operational Flight Envelope safely
- Explore where flight trials would be unsafe (tail-rotor failures)
- Explore and resolve problem areas.

In order to explain the relationship between First of Class Flying Trials (FOCFT) and the Military Aircraft Release (MA Release) it is necessary to clarify some terminology. Although the term FOCFT has been coined in the UK for the process of producing Ship Helicopter Operating Limits (SHOLs) for aircraft and ship combinations, it is strictly the clearing of an in-service aircraft to a new class of ship. In this case, the aircraft already has a release to service clearance or MA Release. For the scenario where a new aircraft type is being considered and the MA Release has not been published the evaluation is more correctly called, First of Type Flying Trials and it is included in the MA Release programme. In the context of this paper, there is no significant difference in the two processes; the acronym FOCFT will relate to the production of SHOLs.

1.2 Motivation

The current method of SHOL testing has been developed since the late 1960s during which time the techniques have been refined. Even with this development, the same basic ideas have remained the same for 25 years [1].

The motivation for exploring the possibility of using M&S in FOCFT stems from an international collaboration initiative in 1991 to develop high-fidelity simulation of the helicopter-ship dynamic interface. The momentum of this initiative continued as the Defence Evaluation and Research Agency (DERA), formerly DRA, developed the initial capability to simulate the dynamic interface problem driven primarily by the needs of various applied research programmes. In 1994, various briefings and demonstrations were given to representatives from the Royal Navy aviation community and the Boscombe Down, Test and Evaluation (T&E) department. At these briefings, the capabilities and potential of M&S were described.

The Royal Navy authority for the issue of SHOLs - Director General Aircraft (Navy), DGA(N) – has traditionally arranged the FOCFT with DERA Boscombe Down using RN ships and aircraft for dedicated sea trials. This tasking is obviously very expensive and diverts the assets from duties that in times of fewer ships and aircraft can have an operational impact. Therefore, any method which has the potential to develop SHOLs more quickly and cost effectively whilst maintaining safety levels is of interest to DGA(N).

Additionally, over the next ten years there is a significant increase in the requirement for FOCFT with the introduction into service of five new aircraft types or variants and three new ship classes. Even with this 'bulge' in procurement there will be pressure on DGA(N) to continue cost effectively producing SHOLs with the widest operational envelopes.

Internally, within the DERA organisation there is the opportunity to transfer the methodologies developed within the research field for helicopter handling qualities to the T&E sector. With this exchange comes the additional benefits of closer alignment of working practices and understanding across organisations with similar aims and objectives.

1.3 Benefits of Simulation

The use of simulation will ease the burden of resource management by creating a more flexible approach to FOCFT. The timing of current trials is dictated by the availability of suitable ships, aircraft and personnel. Additionally, to ensure the greatest probability of experiencing the widest possible wind and sea conditions the trial is programmed for the autumn and winter months. Normally ships are dedicated for a 2-week period to the exercise after which there is some post analysis but essentially the SHOL is derived from the data gathered at the time. By using simulation in future trial programmes, it will be possible to build flexibility into the schedule. It may be necessary due to operational constraints to split the sea trial into units around which simulation could be integrated and the work continued when the ship is no longer available. In addition, it is possible that appropriate environmental conditions could not be generated and the derived SHOL would be unnecessarily constrained. Simulation (with experience and validation) could add the benefit of at least exploring the unknown regions. Extending this logically, it should be possible to programme the ship trial outside the traditional seasons, again improving the scheduling options.

As a starting point, it is not assumed that simulating FOCFT will reduce the amount of time it takes to produce a SHOL. What is being proposed are the more efficient and productive use of limited flight test hours, through planning and the focusing of effort. There is the possibility that over the period of the trial the expensive ship time will be compensated by time on the simulator.

The helicopter and indeed the air group of the fleet are seen as the major weapon systems available to the amphibious warfare planners as well as a valuable logistic asset. Therefore, any improvement in the capability of the fleet air arm will contribute significantly to the overall effectiveness of the Royal Navy. The refinement or even broadening of the SHOL through simulation gives the command organisation a greater tactical freedom in ship manoeuvres and hence better fleet disposition.

As with all flight testing, the safety of the personnel involved is of paramount importance and should be a major driver for using M&S. Simulation will identify (and explore safely) the possible problem areas that can be noted for use in planning the sea trial. The safety benefit of this anticipation will be to minimise the risk associated with the safe expansion of the release envelope.

Other perceived operational and development benefits are:

- to create SHOLs for non-RN aircraft to operate to RN and RFA flight decks.
- to provide the answers to urgent "what if" questions that arise in time of tension.
- to provide an enhanced adaptability for current and future flight simulators and for training purposes.
- to assist in the development of the specific landing and approach aids to overcome limitations.

1.4 Introduction to the Dynamic Interface Problem

In essence, FOCFT are designed to explore the wind-over-deck envelope for the particular ship and helicopter combination. The limitations set on the operating envelope will be determined by the interactions between the ship and helicopter. With extremes of weather and a very mobile small ship's deck, together with the limitations of large helicopters, the dynamic interface (as the interaction is normally referenced) can be a very demanding operational environment. The task in question is to carryout the approach, landing, take-off and transition-away under the widest possible environmental conditions within the bounds of safe operation. FOCFT, by their very nature, cover the extremes of the flight and interface envelope.

More specifically, a number of factors and the relative impact of these changes throughout the envelope will determine the SHOL. Obviously one of the factors that set the limitation is the pilot workload. The pilots' performance will be significantly influenced by the available visual references. These can be set by natural ambient conditions, the topography of the situation and visual enhancements such as deck markings, electro-luminescent panels or night vision goggles. The piloting effort required during the manoeuvre will be a combination of positional inputs and station keeping. With the station keeping, high gain task, there will be disturbances introduced due to the motion of the landing spot or relative hover position and inputs from the airwake and turbulence. At the extremes of the flight envelope, the aircraft will be approaching its physical limitations where the pilot will have to for example manage the demanded engine torque through awareness of control inputs.

The final presentation of the SHOLs to the operators is in the form of a wind over deck envelope (Figure 2) together with advice concerning turbulence and aircraft deficiencies.

The modelling of the dynamic interface problem is a particularly demanding exercise, requiring integration of the various elements that make up the scenario. Helicopter aerodynamic models have to be combined with the dynamic and visual ship descriptions to operate in a specified environment. Environmental modelling primarily consists of presenting a time-dependent and spatial distribution of the ship's "airwake". This airwake, which is described in more detail in section 4, has to model both the steady and turbulent flow. As this is a unique area of research, there is little experience available upon which to draw, either in-house or from external sources. In addition to this model integration, the collection of models has to operate in the simulation shell with the appropriate cockpit visual and ergonomic fidelity.

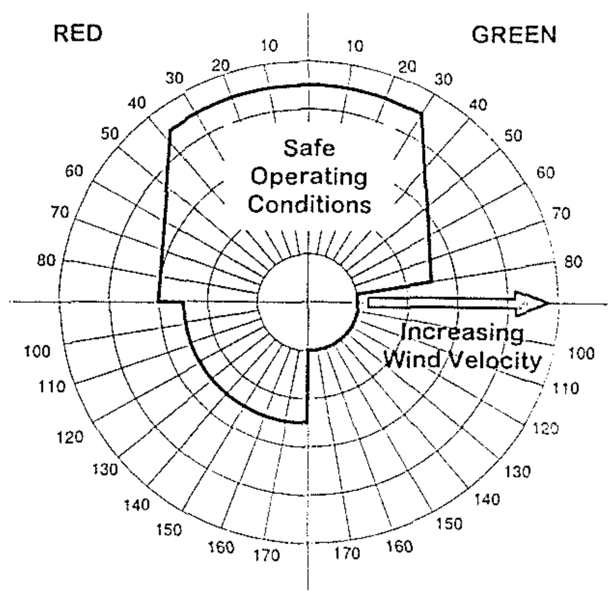

Figure 2; Example SHOL Plot

1.5 Scope of the Paper

As has already been identified the concept of FOCFT and the production of SHOLs are part of a much wider subject of aircraft clearances and in particular the MA Release. These introductory paragraphs have included a brief description of the MA Release ideas.

The remainder of this paper will be devoted to the description of the work being carried out specifically to develop the use of modelling and simulation in FOCFT. The development will be outlined in the context of a recent simulation trial and the results obtained from it.

Section 2 of this paper gives some background to the dynamic interface testing with section 3 outlining the aims and objectives of the DERA research programme. The modelling of the dynamic interface is covered in detail in section 4 and the April 1998 simulation exercise is covered in section 5.

2. BACKGROUND TO DYNAMIC INTERFACE TESTING

2.1 Dynamic Interface (DI) Testing General

As stated by Finlay [1], the aim of the DERA T&E group is to provide the widest possible envelope in terms of wind speed and direction relative to the ship and maximum deck motion limits. Ideally, the maximum possible SHOL will be the same as the land-based low-speed operating limitations. However, this maximum is not obtainable due to the operating conditions with visual cueing, ship motion, and the effects of the ship's airwake and ship motion all contributing to the degradation.

The envelopes produced by the DI Testing are for visual operations and do not account for automatic or assisted approach and landing. Conditions such as visibility are not assessed; it is assumed that a visual approach from the last ¼ mile of a typical 3°-glide slope is possible, with the chief requirement being a good horizon, or alternatively a steady ship. Envelopes are produced for the 3 landing techniques currently used by the Royal Navy.

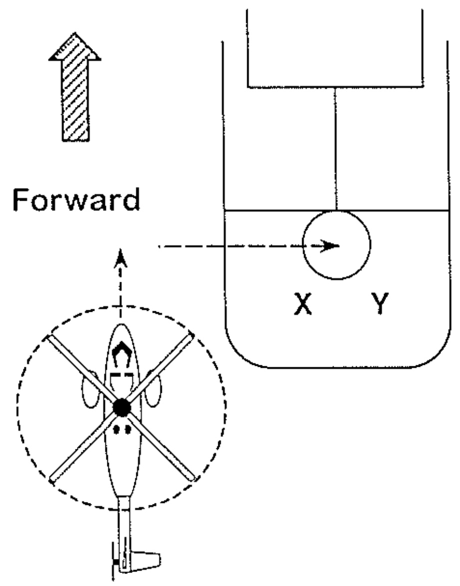

Figure 3; Port Forward Facing (pff) Landing

In the first and by far the most practised (Figure 3), the helicopter approaches to arrive at the hover alongside the port side of the ship's flight deck with the helicopter facing forward and aligned along the fore and aft axis of the ship. The aircraft is then transitioned across the deck maintaining the fore and aft position to establish a hover (5m to 7m) above the landing spot. This "port-forward-facing" (pff) manoeuvre is completed with a vertical descent to the deck.

The "starboard-forward-facing" (sff) approach is similar to the pff but the aircraft arrives alongside the starboard side of the ship's flight deck. It is usual to favour the pff approach due to the superior visibility of the deck provided to the flying pilot, who will normally be in the right-hand seat.

The final approach pattern used is the "into-wind" (Figure 4). A progression is made along the

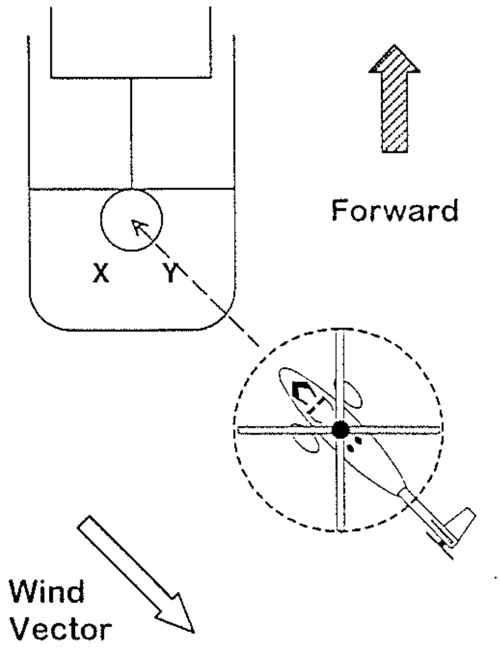

Figure 4; Into Wind Approach

relative wind vector to establish a hover alongside the ship facing into wind. The transition is made across the deck keeping the aircraft "into wind" before a vertical descent is made to the deck. If the physical layout of the deck permits, this type of landing can be executed in any direction through 360°.

2.2 Operational use of SHOLs

The idea of First of Class and First of Type trials was introduced above and the relationship to the MA Release. In either case, the result of the trial is an operating envelope for the particular aircraft and ship combination. The process of producing the SHOL is very much the responsibility of the aviation departments obviously with the assistance of their naval colleagues. However, operationally the responsibility for the safe operation of the embarked naval air assets rests with the ship's warfare department and in particular the commanding officer.

For this reason the SHOLs are published in the naval reference books held on board the ships and not as part of the aircraft publications. When the ship is conducting flying operations, the safe wind-over-deck conditions are established by the Officer of the Watch (OOW) on the bridge (with reference to the SHOL) by steaming an appropriate course and speed. When selecting a particular operating point within the SHOL the OOW's considerations include navigation hazards, other shipping and possibly weapon firing arcs.

3. DERA'S FIRST OF CLASS SIMULATION PROGRAMME

3.1 Aims and objectives

The aim of the programme was to identify a new FOCFT methodology which integrates and uses existing DERA assets and other research packages. The assets identified for possible use were the Rolling Platform at DERA Boscombe Down and the Advanced Flight Simulator at DERA Bedford. It was proposed that these facilities could be used to relieve the financial, operational and flight safety burden associated with the FOCFT by using them as an integral part of the clearance procedure.

During the course of the programme other DERA research programmes have been developing vital ship motion, airwake, turbulence, visual databases of ships and validation elements. Alongside this research, there has been aircraft modelling activity that has been directly used in simulation of the trials. The main programme elements are shown in Figure 5.

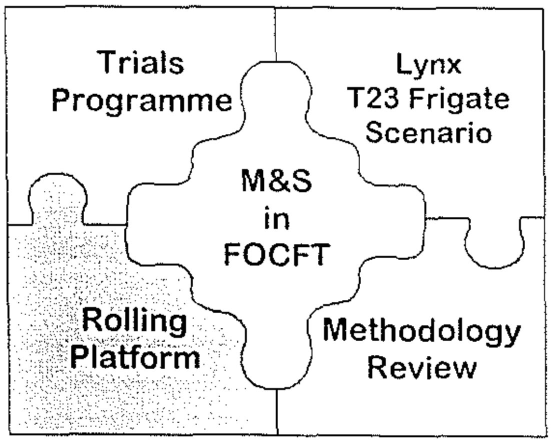

Figure 5: DERA M&S in FOCFT Programme

3.2 DERA Programme

Following the motivation described above, DERA, in conjunction with the Ministry of Defence (MoD) customer DGA(N), decided to instigate a programme of investigation and development based on the stated aims and objectives. The early phase of the programme was a study into the alternative techniques that could be exploited to assist in the FOCFT. Subsequent tasks in the project have been concerned with the development of the simulation aspects and the integration of the various models.

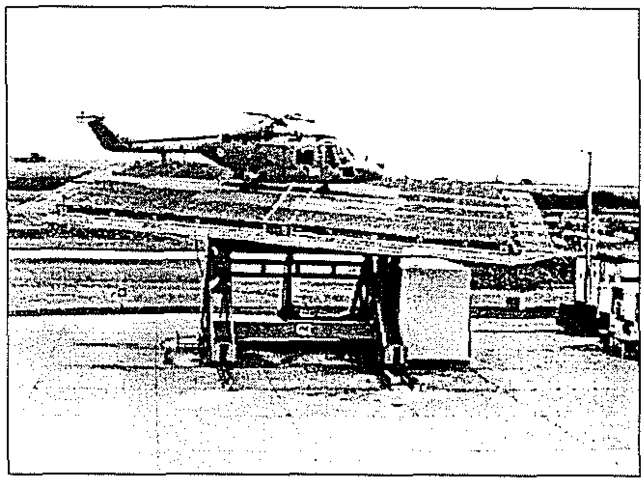

Figure 6; Rolling Platform at DERA Boscombe Down

In searching for alternatives to the First of Class sea trials, the Rolling Platform (Figure 6) was identified for its potential to simulate the motion of the flight deck of a frigate or destroyer size deck. Unique in the world the Rolling Platform has been developed for Merlin/EH101 deck handling system trials. The platform consists of an elevated metal mesh deck that can roll in a single axis and is driven by a single hydraulic ram under computer control.

The profile of the deck motion can either be a straight sinusoidal or recorded ship motion.

A Rolling Platform trial took place at Boscombe Down late 1996 comprised of a progressive programme of landings. Initially the platform was stationary and landings were carried out to an inclined deck. Next the platform was rolled using the sinusoidal input and finally the rolling input was taken from recorded ship motion. In all cases, the maximum roll angle did not exceed 10°.

It was noted from the trial that the lack of an illustrative ship's superstructure was the most significant shortfall and because of this, it was concluded that there would be little benefit from using the Rolling Platform in FOCFT.

Considerable effort has been put into the development of the modelling and simulation capability of the dynamic interface at DERA Bedford. This has come directly because of the requirements of this programme and other applied research packages.

As a starting point, it was decided to attempt to model the scenario of the Lynx and the Type 23 Frigate combination. The outputs from the DERA applied research had been concentrating on this point especially on the Type 23 Frigate as it is the main target operating platform for the Merlin. Within the Rotorcraft Group at DERA Bedford the Lynx helicopter has been extensively modelled. In addition, data from recent sea trials was available which, with the published SHOL, would allow a degree of validation.

A series of AFS trials has taken place, which have progressed from proving the model integration aspects to comparison of the SHOL data and analysis of the methodology used. The first such trial took place in February 1997 and this was the first occasion when the modelling of aircraft, ship and the environment was brought together. A second exercise in April 1997 was taken as an opportunity to fly test points that would enable a SHOL to be produced. The aims of this trial were to:

- Demonstrate a capability to determine SHOLs using the AFS.
- Validate the AFS models by comparison with actual ship trial data
- Demonstrate the advantages of using simulation in support of ship-borne trials.

The objective to quantitatively validate the AFS models was not achieved during this trial but is programmed for future sessions. However, what was now clear was that it was feasible to use M&S in this scenario and produce operating envelopes. As with all simulation exercises the test points can be carried out in fully repeatable conditions this is not an option during sea trials. Also in comparison with the sea trials a much higher sortie rate can be generated without the need to reposition the ship between test points or for refuelling opportunities to maintain the test mass.

The latest in the series of Lynx/Type 23 simulations was carried out in April 1998 as a repeat exercise but with all the experience and corrections from previous attempts. This trial has been discussed in more detail below.

4. SIMULATION OF THE DYNAMIC INTERFACE

4.1 Overview

The accuracy of any simulator will depend on the provision of realistic motion and visual cues to the pilot and on convincing models of both the subject aircraft and its environment. For the simulation of the helicopter / ship dynamic interface the requirements of cueing are particularly important due to the high gain nature of the deck landing task and the need to accurately reproduce the control strategy used by the pilot in the real world. Likewise the intention to predict the vehicle limits with sufficient accuracy to provide valuable guidance to the tests at sea requires a high level of fidelity in the models of the vehicle and its environment. This section provides descriptions of both the cueing and the models that make up the dynamic interface simulation at DERA Bedford.

4.2 Environmental Models

One of the major components of the DI simulation was the development of a model to predict the characteristics of the disturbed flow-field in the lee of the ship's superstructure. The model has been developed by Woodfield Aviation Research (WAR) under contract from DERA as described by Woodfield and Tomlinson [2]. It can produce estimates of the airwake around a ship of any shape for which it has been configured. Configurations currently exist for the Type 23 Frigate and the

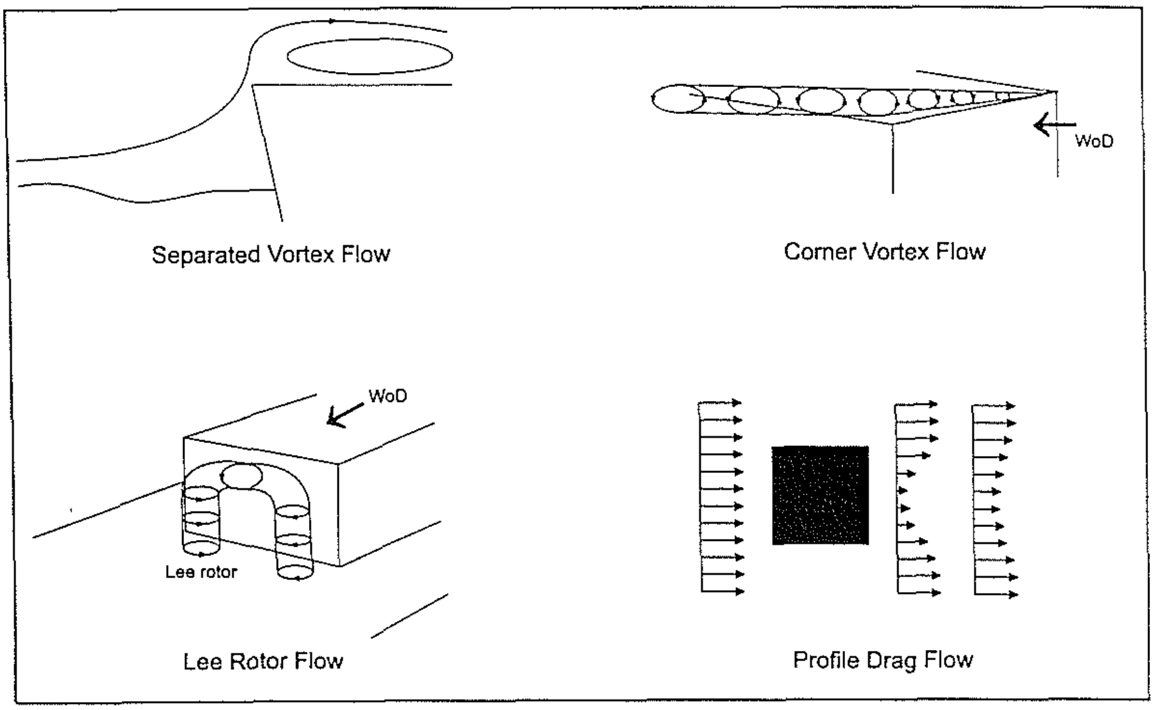

Figure 7; Basic Flow Elements

Landing Platform Helicopter (LPH). For the purposes of this paper, the airwake behind a bluff body will be considered as a combination of steady wind components, that vary spatially but are independent of time, and unsteady, or turbulent components that vary in space and time.

4.3 Steady winds

The name of the model, Woodfield Aviation Modular Airwake for Simulation (WAMAS), reflects the underlying assumption on which the model is built. That is, the main features of the flow-field in the lee of a ship can be predicted by adding together the effects of basic flow elements or modules located at, and associated with, various parts of the ships' geometry. The complete set of basic flow elements comprises the following (see also Figure 7):

- separated vortex – occurs when the flow approaches a corner at an angle near to the perpendicular and forms a separation bubble just downstream of the corner over which the main flow moves with increased velocity.
- corner vortex – formed when the flow hits a corner at a shallow angle and rolls up into a vortex which is swept along in the direction of the mean local flow.
- lee rotor – a flow in the shape of a horseshoe vortex which forms behind a bluff body where the width is large or of similar dimension to the height.
- profile drag – used to represent the loss in dynamic head in the lee of a solid structure due to the blockage effect.
- inflow / outflow – used to create appropriate boundary conditions at solid boundaries through which flow can not pass.

Before being added together, the relative magnitude of each basic flow element is calculated according to the dimensions of the geometric feature to which it is attached. The relationships between the magnitudes of the flows and the dimensions of the geometry have been derived from empirical data.

The model prediction of the flow for a wind coming over the deck of a Type 23 Frigate at 30 knots from an azimuth 30 degrees to the starboard is shown in Figure 8. The flow illustrated here was calculated in a horizontal plane at a height above the deck that would be typical for the main rotor of a helicopter traversing the deck during a standard Royal Navy approach. The figure shows the contours of vertical airwake velocity in ft/s where the approximate outline of the deck has been added together with the position of the landing spot indicated by the cross hairs. The face of the hangar door would be located at the y=0 line. The flow shows a large region of downwash just off the port edge caused by the flow coming off the hangar roof and the downwards flow over the port edge of the deck. In addition, there is a region of upwash along most of the starboard half of the deck caused by a combination of:

- the downwash hitting the deck and being re-circulated due to the presence of the hangar face
- flow up over the edge of the deck due to the starboard wind
- a vortex being shed from the starboard vertical edge of the hangar that is being convected with the airflow at approximately a 30° angle.

4.4 Turbulent winds

The WAMAS model also predicts the pattern of turbulence intensities (magnitude of the time varying component) in the airwake. These magnitudes are predicted as a function of the position in space that is multiplied by an appropriate random time history that possesses the same statistics as the expected turbulent wind. The Statistical Discrete Gust Model, described by Jones [3], is used for this purpose.

Time dependent turbulence is generated in the strong shear layers that exist between the flow past the superstructure and the low velocity regions immediately downstream of the structure. Initially the turbulence is in small eddies and these then

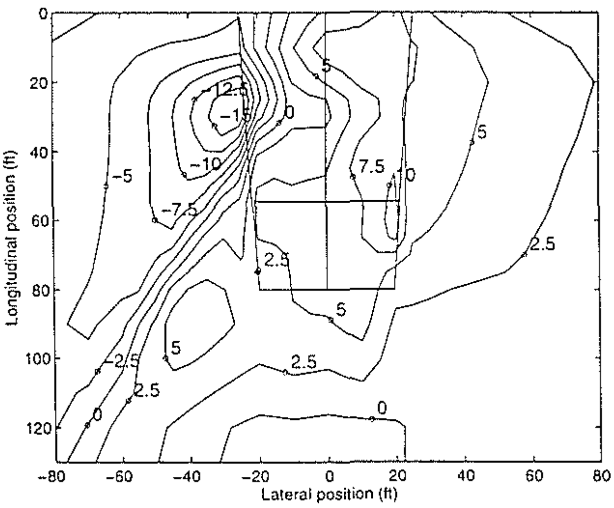

Figure 8; Steady winds for Frigate, wind 30kts/30° starboard

amalgamate to form larger eddies up to sizes around that of the structures. As the shear regions dissipate further downstream then fewer new turbulent eddies are formed and the larger eddies decay into smaller ones. It should be noted that the turbulence is usually not so large downstream of the centre of a bluff body as it is downstream of the edge of a bluff body. Turbulence intensities are calculated independently for the vertical, longitudinal and lateral axes, as these values are typically uncorrelated. In addition, they are related to turbulence in the frequency range 0.2 Hz to 2 Hz that is expected to have an effect on pilot control strategy. This is opposed to merely creating additional vibrations without affecting the flight path of the aircraft. Also modelled is the attenuation of the vertical component of turbulence near to a horizontal surface (such as the deck of the ship) owing to the boundary condition which will not let any flow penetrate the deck and hence at this point the intensity must be zero.

The turbulence intensities in a horizontal plane over the deck of a Type 23 Frigate are shown in Figure 9 for the same wind case as was used to illustrate the steady winds in Figure 8. The plot shows contours of the turbulence intensity in ft/s

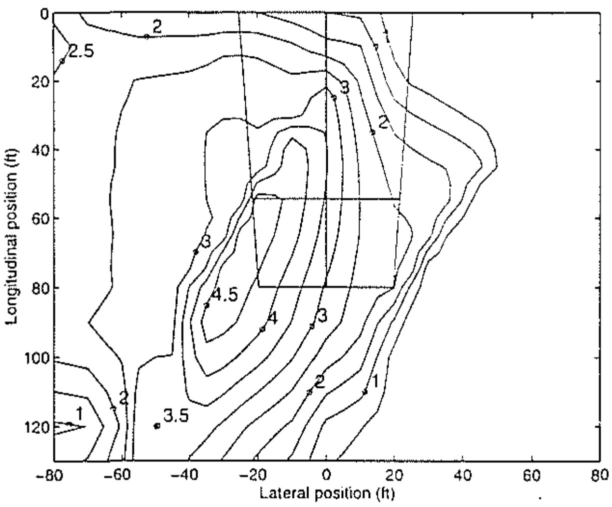

Figure 9; Turbulent winds for Frigate, wind 30kts/30° starboard

(equivalent to the root-mean-square of the expected turbulence time history). It is seen that there is a large region of relatively intense turbulence on the port edge that has been generated owing to the shear layers at the starboard edge of the hangar. Eddies formed here are convected along a path at approximately 30° to the corner and amalgamate to reach a maximum intensity just aft of the deck location marking ("bum-line") and over the port deck edge.

In order to make use of the model results in a real-time simulation it was necessary to generate a look-up table of sufficient size to capture all the features of the model output without requiring prohibitive amount of computer memory for storage. This required a non-uniform calculation grid which allows a higher number of calculation points where the flow pattern was expected to vary rapidly with distance and highly spaced points where the flow was expected to be approximately constant. It was assumed that both the pattern of steady winds and the turbulence intensities were independent of wind over deck velocity and therefore a new table was required for each wind azimuth case where all the results are normalised by the wind over deck velocity. This assumption is expected to hold well for moderate and strong winds but may become increasingly inappropriate for cases where the wind is weak and the flow pattern may have significantly changed.

A large amount of data and pilot comment has now been collected from using the WAMAS model not only in this research but also in other programmes sponsored by the UK MoD. The combination of these programmes has built a level of confidence in the model allowing it to be used to investigate some of the operational problems associated with the deck-landing task. The model has also been supplied to government representatives in Australia and the USA in support of their own studies into the simulation of the helicopter/ship dynamic interface as part of continuing collaboration under the auspices of TTCP (The Technical Co-operation Program).

4.5 Helicopter Model

The helicopter model used for this work was Flightlab produced by Advanced Rotorcraft Technology, California. Flightlab is a generic helicopter model with component models of varying complexity that can be assembled by the user to generate a complete vehicle model with the required level of fidelity. For this work Flightlab was configured as a Lynx Mk3 with a blade element representation of the main rotor and a modal description of the blade elastics with three mode shapes dominated by first and second flap, and first lag modes. A three-state Peters-He dynamic inflow model was used to represent the rotor inflow. Of particular importance to this work was the inclusion of the interference effects between main and tail rotors that are known to produce holes in the tail rotor performance envelope at certain angles around the azimuth, as reported by Ellin [5]. The effects were predicted by an off-line analysis using a vortex wake model to estimate the main rotor inflow and its influence on the tail rotor. The data for numerous different flight conditions were then assembled in a rotor map model of the tail rotor for use in real time. The tail rotor performance can be illustrated using a plot of the pedal margin required to trim, over a range of flight conditions, expressed as a percentage of the overall travel where 0% is full left pedal and 100% is full right pedal. Typically a pedal margin of 10% at either end of the control travel is set as an operational limitation i.e. the required pedal must not be less than 10% or greater than 90%. Figure 10

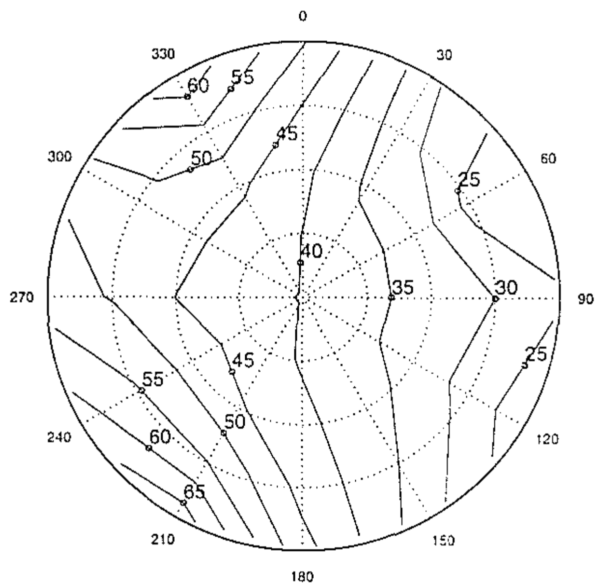

Figure 10; Pedal margin plot in clean air

shows the predictions of the Flightlab model trimmed in clear air for winds around the azimuth with increasing speed. The plot shows a region near the 60 degrees azimuth where there is evidence of the interaction between the main rotor and tail rotor.

An important part of the work conducted was the appropriate integration of the helicopter model with the models of steady airwake and turbulence. A study by Turner [6] established that it was necessary to use a blade element model with the steady airwake sampled at each individual blade element. This is in order to predict all the features of the rotor forces and moments, as opposed to using a disc rotor model with approximate sampling.

The turbulence is based on three uncorrelated random time histories, one for each of the three body axes velocities. The turbulence intensity is evaluated from the WAMAS look-up table at a single point, the rotor hub, and the scaled turbulence time histories assumed to engulf the entire rotor simultaneously. Experience with using this model has shown the perturbations to the aircraft flight path are realistic. However, a more detailed modelling of interaction of turbulence with the helicopter model is an area of future work.

4.6 Ship Motion Model

The ship motion is predicted off-line by a generic ship model described by Andrew and Loader [7]. The user is able to specify the direction and speed of the sea waves relative to the ship and the desired sea state. The predicted ship motion is then recorded in a 20-minute time history that is used in the real-time simulation to drive the visual model of the ship.

4.7 Motion Cueing

Motion cues were provided by the Large Motion System (LMS) and supplemented by an active G-seat that provided vibration cues at the rotor passing frequency. The amplitude of the vibrations was modulated according to the magnitude of the fluctuations in the rotor hub vertical force. The LMS has 5 degrees of freedom providing motion in roll, pitch, yaw, heave and sway (although by changing the orientation of the cockpit the sway degree of freedom can be replaced by surge). The maximum performance of the motion system in each axis is summarised by Table 1 below. It is noted these performance values can be achieved in each axis simultaneously. The motion demands on the LMS are generated from the output of the model via a set of motion drive laws which aim to accurately reproduce the onset of accelerations whilst washing out the longer term accelerations in order to stay within the limits of displacement.

Axis	Displacement	Velocity	Acceleration
Pitch	± 0.5 rad	± 0.5 rad/s	± 2.0 rad/s^2
Roll	± 0.5 rad	± 1.5 rad/s	± 3.0 rad/s^2
Yaw	± 0.5 rad	± 0.5 rad/s	± 1.5 rad/s^2
Heave	± 4 m	± 2.5 m/s	± 5 m/s^2
Sway	± 5 m	± 3 m/s	± 10 m/s^2

Table 1; LMS performance envelope

4.8 Visual Cueing

The visual cues are provided by an IMAGE 600PT system via five collimated CRT monitors mounted in such as way as to approximate the field of view from the right-hand seat of a Lynx – including a chin window but excluding the overhead canopies.

Detailed photo-textured representations of the Type 23 Frigate and LPH have been developed and provide an accurate simulation of the ship geometry and markings. Light levels can vary from broad daylight to complete darkness and there is the ability to lower visibility with fog and haze. A moving sea surface has also been modelled complete with photo-texturing to provide height cues. A representation of the sea wake is placed behind the ship to provide closure information particularly during night-time scenarios, when very few alternative cues exist. Head Down Displays are provided on two re-configurable CRT monitors which for this work were displaying airspeed, barometric altitude, radar altitude, engine torque, rotorspeed and an artificial horizon.

5. APRIL 98 TRIAL

5.1 Trial Objectives and Plan

As was described above, the AFS trial conducted in April 1998 was one of a series of simulation exercises with the aim of proving the feasibility of using M&S in FOCFT. In addition the areas highlighted from the previous trials had been addressed and corrected or improved. It was considered that the realism of the simulation was such that direct comparisons of simulated and actual test points could be made for the Lynx/Type23 combination and a critical analysis of the results carried out.

Due to constraints on the available simulation time, it was decided to target particular areas of the operating envelope, which were considered important to defining the shape of the SHOL. In sea trials, the test points are determined based on first exploring the "safe" regions and then moving into areas where there is greater uncertainty and risk. Without the concern of flight safety, the AFS test plan could explore the edges of the envelope relatively safely. Because of the limited time, only the standard pff profile was to be examined at a single aircraft mass.

5.2 Test Point Assessment

For the trial, three test pilots were used, two from the UK and one from the US Navy (through the TTCP international collaboration agreement). Test points were allocated to the pilots, some of which were duplicated for comparison.

Having flown the test manoeuvre (that involved the approach, hover alongside, the transition and the deck landing) the pilot was required to assess the whole operation. The assessment was made against the 6-point scale (Table 2) currently in use by the rotary wing squadron at DERA Boscombe Down and fully described in Reference 1.

Rating		Remarks
1	No Problem	Minimal pilot effort required resulting in an easy task
2	Satisfactory	Landing carried out with low pilot workload
3	Limit(s) Approached	Safe landings can be carried out but limits of power etc. are approached, reached, or moderate pilot workload. Situation becoming more difficult due to one or more factors.
	or	
4	Limit(s) Reached	These points define the fleet limits recommended by DERA Boscombe Down
5	Unacceptable	Test pilot able to land helicopter under controlled conditions but limits of power etc are exceeded. High pilot workload.
6	Dangerous	Test pilot attempting the landing causes aircraft limitations to be exceeded. Excessive pilot workload.

Table 2; Pilot rating scale

In addition the pilot rating, the vehicle parameters (torque and control margins) were recorded from the models and compared against a table of aircraft limitations. A typical table of vehicle limitations is given in Table 3.

The final assessment of the acceptability of a particular test point was the worst case of either the aircraft performance or pilot workload. For plotting the SHOL, any point that is rated greater that 4 is unacceptable and will be outside the eventual operational envelope.

5.3 Results

The results from the trial in April 98 have been summarised on a SHOL diagram at Figure 11. The points have been categorised as discussed above into acceptable and unacceptable based on either the pilots handling scale (Table 2) or the performance table (Table 3). Additional points are presented that, due to differences in pilot opinion could not be given a definitive rating. Also shown on the diagram is a SHOL envelope based on the published version in operational use.

Rating	Torque %		
	Mean	Peak	
1 or 2	< 95	< 105	Acceptable
3	95 to 98	105 to 110	Acceptable
4	98 to 100	110 to 115	Acceptable
5	> 100	> 115	Unacceptable
Rating	**Tail Rotor Pedal Margin %**		
	Mean	Peak	
1 or 2	> 12	> 10	Acceptable
3	12 to 10	10 to 7.5	Acceptable
4	10 to 8	7.5 to 5	Acceptable
5	< 8	5 to 0	Unacceptable

Table 3; Typical Torque and Pedal Rating Scales

Due to the security classification of the information resulting from this work Figure 11 has been de-sensitised in order to be published in this paper.

Insufficient test points were flown to be able to draw the SHOL envelope from basic principles. [Incidentally, when a FOCFT is being planned a "target" SHOL is produced from previous experience with similar aircraft types and knowledge of ship operations. Therefore, the envelopes are never produced solely based on the sea trial.] The actual

SHOL in this case has been used to validate the results from the simulator. Certain parts of the envelope have not been examined in this study but the critical points have been included for comparison.

There are three distinct areas of interest to be studied from the results presented here. Firstly, in the ahead wind case there was complete agreement between the pilots with the boundary obviously lying somewhere between the two extreme conditions. This finding is corroborated by the actual SHOL boundary. In general terms, the results along this axis are affected by two factors, namely torque requirements and pilot workload due to airwake disturbances. In the conditions where the wind speed is greater, the torque requirement is lower and therefore aircraft limitations are not encroached. However, at a certain point, the piloting effort becomes the dominating influence and this is reflected in the higher ratings, eventually moving into the unacceptable region.

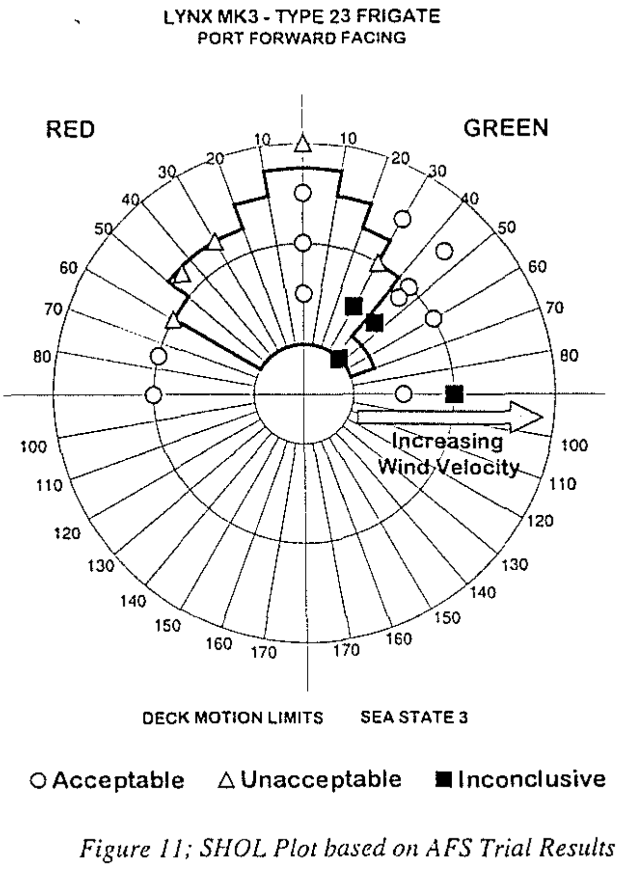

Figure 11; SHOL Plot based on AFS Trial Results

A minimum number of points were tested for the wind vectors from the port side of the ship and again the aim was to identify the border of the actual SHOL. What was being looked for in these points was a boundary condition that was as pessimistic as the actual limit. A more optimistic envelope could be dangerous. The outcome of the AFS tests would indicate that the edge condition is just about aligned with the real-world limit and would probably be drawn inside for guidance purposes.

From previous work and knowledge of the Lynx aircraft it was decided to concentrate a series of test points around the green 40° to green 60° radials. If the aircraft model correctly predicts the poor performance of the tail-rotor, whilst hovering in these conditions, as described in section 4.5, then the SHOL "cut-out" would be evident. The acceptable points beyond the operating envelope for green winds, in Figure 11, can be accounted for through the torque requirement. With the higher wind velocities, the demand for torque will be lower and obviously, there will be less stress on the tail-rotor system. When the advantages of the ambient wind velocity are no longer present then the torque reaction available is seriously reduced. However, the ratings given by the different pilots at the lower velocity wind conditions in this region (green 40° to 60°) were inconsistent. For the points marked as inconclusive, the assessed rating would have been acceptable to one and not to another. There is obviously an anomaly in this particular area which the simulation has not fully realised.

5.4 Trial Conclusions

Overall, the trial was considered successful given the limited simulation time that was available on this occasion. The feasibility of using M&S in FOCFT was confirmed and with improved levels of confidence.

From the results observed in this trial and from the previous trials the boundary of the real world SHOL can be predicted for most conditions using M&S. However, there is reduced confidence in the region of the SHOL that is constrained by tail rotor performance.

Following the experiences gained from this and other FOCFT exercises; there is now a better understanding of the important issues in the simulation of the dynamic interface. As an example, the success of the trial is critically dependent of on the fidelity of the airwake and turbulence modelling.

It is now considered, that the M&S of the dynamic interface problem is sufficiently robust and it can be develop for other vehicle combinations.

6. FUTURE WORK

6.1 Airwake

The current airwake and turbulence model (WAMAS) appears to give representative effects based on an empirical assessment of the flow around bluff bodies. The main rival for the WAMAS model will be computational fluid dynamics (CFD) and this capability is currently being developed at DERA for use in this area. It is envisaged that a combination of techniques will lead to a much better understanding of the physics of the airflow pattern around the flight decks and restricted landing areas.

6.2 Rotor effects

Within the modelling of the dynamic interface, the aerodynamic interactions of the helicopter rotor system with the deck and airwake have not been implemented. Recent research within DERA has highlighted the significant effect that putting a rotor system in a confined area can have. Combine this rotor effect with an energetic airwake and the situation to be modelled becomes complex. Again, CFD is being used to visualise and predict this scenario.

6.3 Deck Operations

Falling outside of the FOCFT scenario but nevertheless of importance to the aircraft operators (and the clearance authorities) are the deck operations of rotor Engage/Disengage and blade Fold/Spread routines. There is a customer requirement to develop the simulation of these scenarios for use in clearance and development work.

6.4 SHOL testing programme

As identified above, one of the main motivating factors for the development of M&S in FOCFT has been the expected increase in SHOL testing activity over the next few years. Opportunities are being actively pursued which will allow a programme of model development to be integrated with further AFS trials. The aim of the programme will be to move from the developmental case to a mature capability.

The likely early applications for this capability will be combinations of Merlin, Lynx, Sea King on the new Royal Fleet Auxiliaries (RFAs) AO class and the replacement RN Amphibious Assault Ship - LPD(R). In addition, the marinisation of the WAH-64 (Apache) will require FOCFT to the amphibious platforms.

6.5 Methodology

The process described in detail by Finlay [1] does not consider the use of M&S in DI testing, as the option has not to date been available. Now the potential capability exists there is the opportunity to review the methodology and to integrate M&S. To this end, a review has been proposed which will:

- Capture the FOCFT process and its requirements.
- Identify possible M&S applications for supporting the process and the levels of simulation fidelity needed.
- To define a practical methodology for implementing proposed M&S procedures.
- To identify limits to current M&S capability and attendant risk factors and potential areas of future development.

7. CONCLUSIONS

First of Class Flying Trials are conducted for all new helicopter types and new classes of ships (which have an aviation capability). These trials, which could be part of the MA Release, are required to establish the safe operating envelope for the ship/helicopter combination. The MA Release is currently drafted solely on flight testing although it is considered that M&S does have role in the future.

One of the main drivers behind the introduction of M&S methods into FOCFT has been the perceived increase in the SHOL testing activity over the next 10 years. Also, there is sufficient pressure on the MoD sponsor – DGA(N) - to produce SHOLs cost effectively, to inspire the dedicated research programme.

The major benefit of using M&S are seen to be the more effective use of expensive sea trial time through targeted test plans based on the experiences of the simulator work. In addition, it may be possible to safely expand the operational envelopes issued to the fleet based on increased knowledge from simulation.

Simulation of the dynamic interface problem is technically very demanding with the integration of several high fidelity models into a single simulation. Outside of this research programme there is very little experience of this type of work.

Dynamic Interface testing is carried out by the T&E department at DERA Boscombe Down and their aim is to provide the widest possible envelope in terms of wind speed and direction relative to the ship. The SHOL produced is issued to the ship's personnel so that when the ship is conducting flying operations the safe wind-over-deck conditions can be maintained.

The DERA programme of research into the use of M&S in FOCFT aims to identify a methodology which integrates and uses simulation. In early 1997 the programme was initiated to look into all DERA simulation capabilities including the rolling platform and DERA Boscombe Down and the Advanced Flight Simulator at DERA Bedford. The rolling platform has been disregarded from further investigation due to the restrictions imposed by an unrepresentative visual environment.

A series of AFS trials has been conducted to develop and integrate the various models and to prove the feasibility of the concept. This series has culminated in a trial in April 1998 that was most successful in predicting the published SHOL boundary.

8. ACKNOWLEDGEMENT

The research reported in this paper was conducted under DERA project support research funded by the UK Ministry of Defence customers Director Operational Requirements (Sea) and Director General Aircraft (Navy).

9. REFERENCES

1. Finlay B A, "United Kingdom Approach to Deriving Military Ship Helicopter Operating Limits", AGARD CP-509-19 Nov 91.

2. Woodfield A A, Tomlinson B N, "Ship airwakes – a new generic model for piloted simulation.", Paper presented to the AGARD Flight Vehicle Integration Symposium on "Flight Simulation – Where are the challenges ?", Braunschweig, Germany, May 1995.

3. Jones J G, "Statistical Discrete Gust Method for predicting aircraft loads and dynamic response.", J Aircraft, April 1989, 2, (4), 382-392.

4. Anon, "Flightlab Theory Manual", Advanced Rotorcraft Technology, California, USA.

5. Ellin A D S, "An in-flight investigation of Lynx AH Mk5 main rotor / tail rotor interactions.", Presented at the Nineteenth European Rotorcraft Forum, Italy, September 1993.

6. Turner G P, "Benefits of blade element rotor models for simulation of the helicopter / ship dynamic interface.", DERA Unpublished Report, September 1997.

7. Andrew R N, Loader P R, "The Assessment of ship sea-keeping performance in likely to be encountered wind and wave conditions.", Presented at the RINA International Symposium on Wave and Wind Climate Worldwide, London 1984.

10. GLOSSARY

AFS	Advanced Flight Simulator
AO	Auxiliary Oiler
CDP	Chief of Defence Procurement
CFD	Computational Fluid Dynamics
DERA	Defence Evaluation and Research Agency
DGA(N)	Director General Aircraft (Navy)
DI	Dynamic Interface
DRA	Defence Research Agency
FOCFT	First of Class Flying Trials
LMS	Large Motion System
LPD(R)	Landing Platform Dock (Replacement)
LPH	Landing Platform Helicopter
M&S	Modelling and Simulation
MA	Military Aircraft (Release)
MoD	Ministry of Defence
OOW	Officer of the Watch
pff	port forward facing
RAF	Royal Air Force
RFA	Royal Fleet Auxiliary
RN	Royal Navy
sff	starboard forward facing
SHOL	Ship Helicopter Operating Limits
T&E	Test and Evaluation
TTCP	The Technical Co-operation Program
WAMAS	Woodfield Aviation Modular Airwake for Simulation
WAR	Woodfield Aviation Research