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Dynamic Interface Modelling and Simulation – A Unique Challenge

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Abstract

This paper will outline the technical challenges of dynamic interface modelling & simulation, with a specific example of the Joint Shipboard Helicopter Integration Process (JSHIP). This program, one of the most ambitious helicopter simulation programs undertaken to date, has helped both to understand the potential of rotorcraft simulation today, and to realize the limitations of technology. The benefits, such as reduced (testing and training) cost, increased safety, increased flexibility, and increased availability of the ship and aircraft, are also discussed.

JSHIP is intended to allow interoperability of helicopters from the US Navy, Army and Air Force on shipboard operations. Part of this program involves the modelling and simulation of the dynamic interface between the ship environment and the helicopter. The goal of these simulations is to prove the process for determining wind-over-the-deck (WOD) launch and recovery envelopes using piloted flight simulation. The dynamic interface environment, particularly in the presence of wind, ship motion and low visibility can require a very high workload by the pilot.

In order to validate the fidelity of this simulated dynamic interface, experimental trials have recently been conducted, and in the same way that such trials would be conducted at sea. The simulation system itself was developed by first specifying its functional requirements, and then by allocating and developing physical models of the various sub-systems. These include a Computational Fluid Dynamics (CFD) airwake model of the LHA class ship, a dynamic model of the UH-60 Black Hawk helicopter, and the simulation cueing systems. The CFD-generated WOD profile was validated during sea trials, as were several helicopter launch and recovery scenarios. The simulation trials were carried out in the NASA Ames Vertical Motion Simulator in a specially-designed cab, which features a wide-angle flat-panel display, simulated cockpit instruments, a single axis seat shaker, and an accurate representation of the flight controls.

Introduction

The operation of helicopters to and from ships is a hazardous task and one that is demanding to both the vehicle and its pilot. This represents an environment with restricted access and often severe turbulence in high wind speeds. The factors that contribute to the challenge are attributed to the dynamics of the airwake behind the ship structure, the variation of this wake as a function of the location on the ship deck, and also the translation and rotation of the vessel.

It is foreseen that military and coast guard operations will increasingly rely upon rotorcraft as one of the backbones that make these operations possible. The United States Navy requires a lean, integrated shipboard unit, combining the strengths of Navy, Marines, Air Force, Army and Coast Guard operations from ships. These joint operations will be coalesced in a US DoD (Department of Defense) program called JSHIP – the Joint Shipboard Helicopter Integration Process.

One of the requirements of such joint operations is to determine the maximum limitations of the helicopter in the presence of a ship when operated by a trained pilot. The extent of this limit is called the Wind-Over-the Deck (WOD) envelope. Achieving a large envelope allows greater all-weather capability. On the other hand, determining this envelope is not an easy task. Traditionally, various ship-helicopter combinations are evaluated at sea during varying wind conditions. While this may seem straightforward, it is highly costly, and the conditions needed to determine this envelope may rarely be present in nature. Moreover, since one is indeed attempting to determine the envelope, there may be safety issues involved in such experiments.

In light of the above requirements, it is necessary to have the capability to predict in advance the performance of a given helicopter within the airwake of a given ship. With this capability, it would be possible to determine in advance the maximum allowances for current equipment, as well as for new acquisitions.

This paper will review the state of the art in rotorcraft-ship interface simulation and, using the example of the JSHIP program, detail one of the recent efforts aimed at achieving testing and evaluation capabilities in a synthetic environment. It will begin with a short review of open literature on the subject of helicopter/ship interface modelling and simulation, which help to highlight the primary requirements for piloted simulation.

Wind-Over-The-Deck Envelope Determination

The simulation of rotorcraft in the presence of atmospheric turbulence with sufficient reliability forms a basis for such evaluations. The complexity of these missions, and the variables that come in to play, require such simulations to be carried out by human pilots. However, a first step is to determine what the requirements of the simulation itself are in order that the WOD envelope can be specified within a synthetic environment. Only when there is sufficient certainty in the capabilities of the simulation, and when the limitations of simulation in these applications are well understood, can one begin to consider the replacement of in-flight testing and evaluation by these alternative means.

Introducing the dynamics of these vehicles to the proximity of a ship in a piloted simulation is quite demanding. Pilot workload is high since the helicopter is immersed in the ship airwake, which contains turbulence and gradients in mean flow speed and direction. Turbulence in the airwake leads to a time-dependent disturbance rejection task for the pilot, making it more difficult to maintain position relative to the ship. The flow gradients lead to non-uniform rotor inflow and thus changes in rotor output. In both cases, continuously varying control inputs are required from the helicopter pilot who, by the very nature of the vehicle, is already subject to a high-gain task. When the workload is unacceptably high due to the interface phenomena, the pilot will be unable to achieve consistently safe and accurate landings. So, when the situation borders on unacceptable from a pilot workload perspective, the WOD envelope boundary is defined for that particular wind condition.

A typical envelope is shown in Figure 1. This shows the maximum wind speed and direction relative to the ship under which the helicopter can safely operate in a given set of conditions. A typical process of establishing this envelope is to employ an instrumented helicopter and ship (and a test team of engineers and experimental test pilots) for three to five weeks during which at least 350 landing trials are carried out. These trials begin with the general envelope, and incrementally increase the envelope for each landing spot on the ship. Clearly, this process is sensitive to the weather conditions and availability of the ship and helicopter. If inadequate weather conditions are found, the aircraft must operate within the very restricted general flight envelope shown in the figure.

Real-Time Dynamic Interface Simulation Goals

A method of WOD envelope determination that is reliable, safer and less demanding on the resources is needed. If simulation of the aircraft/ship combination could be reliable enough to accurately determine this envelope, then it would make available a facility for verifying other combinations of vehicles and vessels within a controllable, repeatable and high-precision environment. It could even allow the refinement of rotorcraft and ship designs in the future. While simulation may be an attractive solution, there are many hurdles to overcome if such trials are to be carried out in a synthetic environment.

Before addressing the potential limitations of dynamic interface simulation, the criteria for the simulation environment should be highlighted. The determination of WOD envelopes requires specific characteristics of the simulation, if live trials are to be reduced or eliminated. Typically, the pilots who would "fly" such simulation trials have sufficient experience with the launch and recovery of helicopters to ships. They are not trainee pilots, and therefore do not need the simulator as a mechanism for developing basic flying skills. In training simulators, the level of fidelity should be directly related to the training need (the level of training required). However, in simulator-based dynamic interface envelope specification, one ideally needs to determine first of all *how* the pilot uses the various sources of information to control the vehicle, and subsequently the levels of fidelity required. In the end, the pilot should apply the same skill-based behaviour and control strategy, demonstrate a similar level of performance, *and* perform the task with workload levels similar to those encountered in the aircraft for the simulation-based dynamic envelope testing to be consistent with at-sea trials.

Rasmussen[1] suggested that there are three levels of behaviour that are required to safely operate a complex device. The lowest or most basic level is called *"skill-based"* behaviour, in which the human perceptual-motor system acts as a continuous controller. The outputs of the sensors - primarily the visual system, the vestibular system and the proprioceptive system - are perceived as continuous signals and are used then to generate the control inputs.

The next level is called *"rule-based"* behaviour, where perceived stimuli are the "signs" that mark changes in conditions or required procedures. Based on these signs, the new rule is selected, after which the execution is performed with the learned automated sensory-motor patterns, or skill-based behaviour.

Finally, the "*knowledge-based"* level of behaviour deals with functional reasoning to predict future changes within the environment.

In the real environment, the pilot uses information available – through motion of the vehicle with respect to the outside world, visual instrument readings, aural warnings and audio signals - to perceive, evaluate and execute the correct output. This means that all three levels of behaviour must be integrated by the pilot in order to generate the correct output.

Humans are also adaptive by nature. However, when evaluating the fidelity of the simulation, it is imperative that this level of adaptation be minimised and, if possible, identified. While a number of human performance parameters can be quantified, the evaluations of simulations of this type often rely on subjective judgements by the pilots.

Modelling and Simulation Challenges

The simulation of any particular task environment cannot be a perfect reproduction of that environment. By the same token, each measurable attribute of the task environment does not need to match the same parameters encountered in real life. It should however be *perceived* by the pilot as being similar, to the extent that his resulting performance is not noticeably different than in real life.

While it may not be necessary for simulation to fully replace at-sea testing, there needs to be an understanding regarding the technical capability of modelling and simulation in order to achieve reliable results for each part of the envelope. In this way, the few remaining points on that envelope could be filled in through live trials, for example, for the most extreme conditions.

The helicopter/ship dynamic interface problem will now be explained from both a modelling and a simulation standpoint. This concise description will be followed by a discussion of acceptable fidelity criteria.

Modelling the Dynamic Interface

The simulation of rotorcraft in itself is a challenge. The response of rotorcraft to turbulence in particular is far more complex than, for example, for fixed-wing aircraft. Helicopters always operate in the lowest part of the atmosphere, where turbulence length scale is relatively small, and due to the fact that the lifting surface moves through the local atmosphere, the effects of the disturbances are severe[2]. Because of this, the modelling of the ship airwake and its effect on rotorcraft behaviour is considered one of the most significant technical challenges[3].

Ship airwake

While it is necessary to deal with the fully-coupled problem of the helicopter within the unsteady flow field, the first step is to map the ship airwake itself and thereby estimate what inflow the flight vehicle may encounter in proximity to the ship. A range of off-line numerical simulation studies have been carried out to model the flow behind ships. Recent improvements in CPU performance and the availability of vast amounts of memory have greatly reduced previous limitations in solving these models in real time.

Despite the relatively straightforward geometry of many ships, the flows downwind of the superstructure are complex and greatly increase the difficulty of flying helicopters into this region. It is thus not surprising that helicopter flight close to ships is challenging. Essentially, the same aerodynamic structures (in particular, edge vortices, separating shear layers, attachment lines and re-circulation zones) feature at every wind yaw angle[4].

A number of previous efforts have attempted to predict ship airwakes, some of which are cited here. In 1998, Zan et al[5] mapped the flow field in the vicinity of the flight deck of a Canadian Halifax-Class Patrol Frigate at 0-deg and 20-deg yaw angle using a Navier-Stokes CFD approach, and experimental wind-tunnel comparisons. They found that there was a good correlation between data obtained from the wind-tunnel and full-scale sea-trials, and that either of these could be used to validate their CFD data. Furthermore, the influence of relatively small equipment on the ship itself (in their case, on the corner of the bluff-body hangar) can significantly influence the results. CFD, in general, was found to correctly predict the flow topology but to over-estimate the velocity gradients. Woodfield and Tomlinson indicate that the separation of the flow behind the ship is a primary modelling difficulty, and that the model developed at DERA in Bedford is acceptable in predicting the flow behind the ship [6]. Tate [7] (1995) shows how this model has been incorporated into the manned flight simulator of the same facility in order to successfully predict many aspects of the dynamic interface in a synthetic environment.

Helicopter/Ship Interaction

Adding the helicopter to the airwake adds complexity to the problem, as the rotor, tail rotor and body influence the wake itself. There is also the interaction of the rotor with the deck (ground effect). The degree to which each effect is present at the dynamic interface depends on a number of factors, like the size of the ship and helicopter, the local wind speed and direction, and possibly ship motion. Ground effect is normally modelled by an infinitely wide ground plane, but for a finite surface such as a ship flight deck, the ground effect will decrease, and also will vary as the helicopter rotor approaches the deck edge.

FAST3D is an example of an algorithm that was developed for determining the unsteady airwake behind a ship with the inclusion of a helicopter downwash model (along a specified flight path). The algorithm predicted satisfactorily significant wind velocity variations in the landing deck region.

Piloted Simulation of the Dynamic Interface

Several organisations within the UK, Canada, Australia and the USA have collaborated to develop airwake models targeted at improving simulation of the dynamic interface[3]. They suggested (in 1998) that the most promising approach for piloted modeling and simulation in the short term would be to incorporate look-up tables produced using an airwake model.

The flight of a helicopter into the airwake is a combination of manoeuvring and disturbance rejection. It is characterised by a high-gain manual control task, where information from multiple sources is sensed by the pilot and processed by his Central Nervous System through which the control responses are generated.

Visual information is of particular importance, since the pilot uses this to perceive speed, rate of closure (and sink rate), location and attitude with respect to the designated landing position. The sea surface may also provide important visual information, since otherwise there is very limited information beyond the ship itself. Therefore, field-of-view (particularly downward), scene content, and resolution will likely be important parameters.

Physical motion of the pilot is very closely (and quickly) coupled with the perception of self motion, together with the visual information. When there are limited visual cues (night, low visibility), the pilot may rely increasingly on the motion cues. In any case, vestibular motion cues are necessary in order to achieve the same level of skill-based control behaviour, and similar levels of workload[8]. How *much* motion, just as how much visual information, remains an open item. Both of these depend significantly on the exact task variables.

The effects of motion sickness can also be mitigated with the presence of good motion cues. However, this is an issue that should not be overlooked with complacency. Experienced pilots in particular, when exposed to a synthetic environment in which there is a slight but perceptible mismatch between these cues, can experience discomfort or even sickness.

System-Level Fidelity

The integration of the entire simulation needs to be considered. Having high-fidelity components does not guarantee the same fidelity over the entire system. Latency issues must be addressed to ensure that the cueing devices respond to control inputs in a manner consistent with the aircraft. Typically, calculation and communication times within the simulation result in motion and visual cueing responses that are delayed with respect to the aircraft response. Research into human motion perception has shown that the pilot adjusts his control strategy even when the time between control input and the response of the cueing system is 50ms [9] . Additionally, the motion and visual responses should be harmonised to minimise cue mis-match. Recommended tolerances are task dependent and are often disputed, but the difference between the response of the motion and visual systems should certainly be no more than 40ms[10] and preferably lower for a high gain task such as landing on a ship. Furthermore, motion cues should not lead visual cues. Failure to address these issues may result in simulator-induced sickness and, ultimately, invalid data.

Criteria for acceptable simulation

Before acquiring simulation equipment (despite its cost effectiveness) to perform dynamic interface testing or training, it is necessary to specify the required fidelity of the simulation itself. While simulation is not reality, it should not generate negative effects (such as simulator-induced sickness), or lead to erroneous results. The fidelity of each component should be established and should meet a minimum set of criteria, or fidelity requirements. In this type of complex task, however, it is more than the fidelity of each individual component that matters. The fidelity of the integrated simulation is what really counts, and must be sufficient to provide accurate results.

Fidelity requirements for civilian helicopter training simulators can be found in the FAA Advisory Circular 120-63[11]. However these guidelines do not apply directly to dynamic interface testing, and an extension of these criteria may not be appropriate since we are dealing primarily with military modelling practices. Moreover, tolerances are task-specific, and the criteria selected for the simulation should take this into account.

Dynamic Interface Modelling and Simulation in the JSHIP Program

The Joint Shipboard Helicopter Integration Process (JSHIP) is a Joint Test and Evaluation (JT&E) program sponsored by the Office of the Secretary of Defense Deputy Director, Developmental Test and Evaluation. Its specific purpose is to increase the interoperability of joint shipboard helicopter operations for helicopter units that are *not* specifically designed to go aboard Navy ships (e.g. Army and Air Force helicopters). The dynamic interface modelling efforts within JSHIP integrate many of the newest developments in simulation science and technology in order to compare state-of-the-art simulation with the real world.

The JSHIP Dynamic Interface Modeling and Simulation System (DIMSS) primarily seeks to develop a process to predict WOD envelopes using piloted simulation. The process is being validated by applying it to a specific ship-aircraft combination – a US Navy LHA Class vessel and an UH-60 Black Hawk helicopter. This combination was selected because of its applicability to joint operations and because there was the possibility to use a validated mathematical model of the helicopter.

The DIMSS process, as demonstrated by application to the UH-60/LHA combination, has involved a number of stages:

1. Existing, models and subsystems, as well as research and development (R&D) simulators and trainers, were investigated in order to identify candidate models and host simulation facililities. Using this and existing fidelity standards as guidelines, the required fidelity levels for the subsystems and models were estimated. Where necessary, the fidelity of specific sub-systems was improved to achieve the required levels.
2. The models and subsystems were integrated in the selected host facility, the Vertical Motion Simulator (VMS) at NASA Ames Research Center, California.

3. Piloted simulations were conducted to determine the necessary level of simulation fidelity for the dynamic interface task by varying the fidelity of the visual, body force and aural cueing subsystems and comparing the results against real-life data.
4. WOD envelopes for the UH-60/LHA combination were developed with experimental test pilots using the same testing technique that is used for WOD envelope development at sea. For this evaluation, 4 levels of system fidelity were tested, comprising a matrix of 2 visual and 3 body force fidelity levels.

DIMSS VV&A Strategy

The DIMSS approach is underpinned by a formal process of Verification, Validation and Accreditation (VV&A). Verification refers to confirming that each system has been built according to its specifications, while validation involves comparing simulations with real-world data and confirming whether there is sufficient similarity. Accreditation refers here to the final certification by designated advisors and, ultimately, an accreditation authority.

To successfully validate both the simulation, and the individual models and subsystems, an important step in this particular program involved the execution of flight tests to obtain validation criteria data. A LHA class ship and UH-60 aircraft were instrumented and helicopter flight trials were conducted to develop at-sea WOD envelopes for comparison against simulator data. Additional at-sea and land-based tests were conducted, including the measurement of wind profiles for comparison with airwake model data and recording of cockpit sounds for validation of the sound model.

An international accreditation team of recognised experts from the military, academia and industry was formed to provide oversight of the verification and validation tests and to make an accreditation recommendation. The team met on a regular basis to discuss the DIMSS process and simulation results, and also to comment on the requirement for additional tests and data.

The final integration in the VMS took place in late 2000, after which full testing and evaluation began. Prior to discussing the results of these evaluations, the system configuration will be described, the fidelity matrix explained and the piloting tasks detailed.

DIMSS Modelling Elements

The basic elements of the DIMSS simulation are described below, including the different visual and body force fidelity levels tested. It should be noted, however, that early DIMSS evaluations addressed more fidelity levels than are described here.

Helicopter Aerodynamics Model

The real-time aerodynamic model, based on the Sikorsky General Helicopter Flight Dynamics Simulation, "Gen Hel" [12], is a non-linear representation of a single main rotor helicopter, applicable over the full range of angles of attack, sideslip and rotor inflow. Six rigid-body degrees-of-freedom, as well as the main rotor flapping, lagging, air mass and hub rotational speed degrees-of-freedom, are modelled. Each main rotor blade is modelled by a blade-element approach, and the total rotor forces and moments are produced by summing the forces from each blade, which are determined from aerodynamic, inertial and gravitational forces. The induced velocity at the rotor disk is represented by a Pitt-Peters inflow model. Tail rotor thrust is represented by linearized Bailey theory[13], and aerodynamic interference effects are either empirically determined or derived from analysis-oriented simulations.

The real-time engine model was developed by NASA Lewis Research Center to model the T700-GE-700 engine of the UH-60A Black Hawk. The model is capable of representing the operating condition of the major internal engine components as well as the engine thermodynamic cycle.

Airwake model

The DIMSS ship airwake model is intended to provide a time-accurate representation of the turbulent airflow in the vicinity of an LHA class ship throughout a range of relative wind conditions, typically incremented every 15 degrees. Airwake data has been specified as a series of 3-dimensional 10Hz time histories at a grid of points over the flight deck and towards the port side of the ship. These data sets are predicted by a Navier-Stokes computational fluid dynamics (CFD) flow solver using an unstructured, hybrid grid. Since no atmospheric boundary layer has been modelled, the inflow conditions are constant, and the airwake is not influenced by either ship motion or by the influence of the helicopter rotor.

In order to ease the handling of data in real-time, the airwake model was reduced in size by implementing the model only in the region of aircraft operations for port-side landings and take-offs. The reduced CFD grid consists of 56,661 points in the vicinity of the ship. See Figure 2.

Ship Motion Model

The ship motion model provides 6 degree-of-freedom (pitch, roll, yaw, heave, sway and surge) motion representative of an LHA-class ship in a range of sea states. It is a frequency-domain batch process that calculates the ship's motion characteristics, based on an input file containing the hull geometry and design speed.

Cockpit Sub-system

A specialised cab was built by NASA Ames Research Center specifically for the DIMSS program. This cab was based on modifications to an existing helicopter research cab. It features an interior representative of the actual UH-60 helicopter, and a wide-angle display system (addressed in the visual sub-system description hereafter).

Within the cab is a control loading system, comprised of 2-axis cyclic, collective and pedals commercial control loaders. The system was programmed to replicate the control feel of an UH-60 aircraft by matching control force and deflection data measured in an UH-60 aircraft.

Simulated instruments are graphically displayed on two cathode ray tubes (CRT's) mounted on a panel directly in front of the pilot seat. A 9-inch CRT displays the engine instruments while the flight and navigation instruments are displayed on a 14-inch CRT.

The aircraft sounds were modeled by the VMS based on an existing UH-60 model and modified by cockpit sound recordings provided by JSHIP. The sounds were presented to the pilot via a 7-speaker system providing sound directionality and including a sub-woofer.

Visual Subsystem

The visual cues provided to the pilot are particularly important while the helicopter is in the proximity of the ship. In the DIMSS program, these cues were created by a computer image generator, utilising a database of the ship and dynamic sea surface. To determine necessary fidelity, a range of image generator/database fidelity levels was tested (described below), although the display system itself remained the same in all cases.

Implementing a realistic display system on board the VMS cab in itself posed a considerable challenge. This simulator does not allow the incorporation of the large dome-type or projector-based collimation systems commonly found on military and civilian simulators today. Instead of using collimating window displays (which are commonly applied on other VMS cabs), it was decided to use a rear-projected display. In this type of system, the image is projected from above onto a flat mirror which then presents the same onto a flat translucent screen. The pilot views the image from the other side of this screen. In the DIMSS simulation, this five-channel system provided a crisp and bright image with nearly invisible edges and, most importantly, it was possible to accommodate this system into the VMS cab.

The field-of-view provided by the visual system is shown in Figure 3. From the pilot eye reference point (ERP), the field-of-view covers 230 degrees horizontal by 70 vertical. The window frame patterns of the UH-60 were mapped from the ERP and represented as structure in the cab.

Two image generators (ESIG and XIG) and 2 levels of visual database complexity (Levels I and II) were tested. The ESIG 4530 was developed by Evans and Sutherland in 1995 and was installed at the VMS in 1997 as a three-channel system and upgraded to a five-channel system in 1998. The XIG is made by Carmel Applied Technologies, Inc. (CATI). The Level I ship visual model was developed by VMS and the ocean model was developed by Evans and Sutherland. The Level II visual models were developed by CATI.

Body Force Cueing Subsystem

A primary reason for hosting this exercise on the VMS system was the availability of its large-amplitude motion system, making it possible to test a range of body force fidelity levels by scaling downwards from a system with the capability of relatively long-term sustained translational motion cues. Co-ordinated adaptive motion drive algorithms were used to generate the motion commands [14], and their parameters tuned based on experience gained during prior experiments aimed at quantifying motion cueing requirements in rotorcraft simulation [10, 15]. The VMS motion system is shown in Figure 4, and provided the first of two simultaneously applied body force cueing systems.

The second body force cueing system used in this experiment was a seat shaker, which could provide low-amplitude, high-frequency cues in heave correlated to the normal acceleration generated by the rotor dynamics and vehicle airspeed[17]. In earlier evaluations, a dynamic seat was used instead of the seat shaker. The seat could provide low-amplitude, high-frequency cues in 3 axes (heave, surge and sway), and sustained acceleration cues through changes in the seat position. While the results showed that the dynamic seat provided positive cueing, it was unfortunately unavailable for the final simulation trial.

The VMS was also used to "simulate" the general motion envelope of a 60-inch stroke hexapod[18, 19] in order to provide data on the applicability of these more common devices when performing WOD tasks.

Fidelity Matrix

Combinations of motion and visual cueing system capabilities were evaluated, as part of the effort to determine the required fidelity of an acceptable test and evaluation system. This fidelity matrix is shown in Table 1.

Table 1 indicates how the fidelity matrix was constructed to capture the system performance using high-end, medium, or low-end simulation capabilities.

Experimental Set-up

The experiments were then conducted in the NASA Ames VMS facility. The objectives of these trials were as follows:

- To conduct and evaluate day and night simulated shipboard landings and take-offs using the LHA / UH-60 combination for a range of simulation fidelity levels
- To record pilot ratings, pilot comments and aircraft data with which to validate the simulation against real-life data

Table 1 – Basic elements of the JSHIP DIMSS simulation elements

Sub-System	Sub-System Fidelity Level	Description	Fidelity Configuration			
			A	B	C	D
Body Force Cueing Sub-system	1	Vertical-axis seat shaker			X	
	2	Simulated "hexapod" motion-base with seat shaker		X		X
	3	Full VMS motion base capability with seat shaker	X			
Visual Cueing Sub-System	1	High-performance Image Generator[1]; with high-fidelity ship and ocean models	X	X		
	2	PC-Based visual[2], with limited-fidelity ship and ocean models			X	X

[1] *The High Performance Image Generator was an Evans & Sutherland ESIG-4530*

[2] *The Pentium III dual-processor PC-Based Image Generator: Evans & Sutherland SimFusion operating with the Carmel Applied Technologies Inc. X-IG software.*

- To support the accreditation process
- To qualitatively evaluate the fidelity of the sub-systems

Repeated launch and recovery operations were performed by four qualified experimental test pilots to collect launch and recovery data at 4 LHA landing spots and to develop full WOD envelopes at two spots. Cueing system fidelity was varied during the trial in order to produce results for 4 levels of total system fidelity, or 'fidelity configurations'.

To represent typical at-sea conditions, four sets of ship motion conditions were used during the simulation test. These motions varied as a function of the WOD - low ship motion was assigned to low WOD speeds, and greater ship motion was assigned when the WOD speeds were higher. However, all ship motion conditions were within those experienced during at-sea tests.

To minimise the potential for pilot fatigue, sickness and learning, the sortie length was restricted to approximately 1 hour. Pilots were briefed to not discuss their opinions with each other until after the end of the simulation. Pilots were given the opportunity to re-familiarise themselves with the simulation at the beginning of each sortie, by flying a practice approach, landing and take-off. During the simulation, pilots were not told which fidelity configurations they were testing and were given no information on what fidelity levels were available.

The goal of the pilots was to approach the ship, hover above a designated landing site, land and take-off, rise to a hover, and depart from the ship using the standard at-sea technique. Note that there are 10 landing sites on an LHA type ship. For this experiment, 4 of these were selected, representing different conditions. The fore-deck sites tend to have limited visual information, since most of the ship is behind the helicopter when it is close to the deck. The aft landing sites provide a large amount of visual information but, depending on the wind direction, are subject to the flow behind the ship superstructure.

Data recording

Pilot ratings were awarded for the landing and take-off maneuvers using the same 5 point scale that is used in at-sea dynamic interface testing, known as the Deck Interface Pilot Effort Scale (DIPES). The scale, shown in Figure 5, requires the pilot to assess both workload and performance, in a similar manner to the Cooper-Harper Handling Qualities Rating scale, but without the tightly defined tolerances. Ratings of 3 or below indicate that the wind condition being tested is safe for landings or take-offs; a rating of 4 or 5 places that condition outside of the flight envelope.

A total of 48 parameters related to the helicopter, 7 related to the ship, and 10 related to the environmental conditions were recorded during the trial. Additionally, the position, orientation and velocity of the helicopter relative to the deck landing sites at touchdown were recorded, to indicate the accuracy of the pilots in these simulated landings. Video and audio of the flying pilot were also recorded throughout.

Results

While it is difficult to summarise the results of 8 weeks of simulation trials, the following general observations can be noted:

- The difference between pilot ratings awarded in the simulator and aircraft for similar wind conditions typically ranged between 0 and 1 point, with spreads of up to 2 points apparent at the highest workload condition. For this reason, flight envelopes developed in the simulator by different pilots were not identical. However, it is important to remember that, during at-sea tests, it is usual for only one pilot to test each wind condition; it is possible that, if multiple pilots were used at-sea as they were in the simulator, a similar spread in pilot ratings would be encountered. In defining WOD envelopes developed in a simulator, one could either select the most conservative ratings awarded by the pilots as the basis for the boundary, or take a mean of the ratings across all the pilots. For the DIMSS evaluation, mean simulator ratings were within 1 point of the corresponding aircraft rating at all wind conditions.
- Only relatively benign wind conditions were encountered during at-sea tests, resulting in a validation envelope that was restricted not by pilot workload or aircraft control limits, but purely by the

prevailing winds. Thus the envelopes predicted in the simulator were significantly larger than those developed at-sea. If nothing else, this emphasizes the necessity for a simulation that can be used to predict the full range of environmental conditions. Owing to the benign conditions, only one high workload condition was encountered during at-sea testing at landing spot 8 in a wind of 30 knots from 30 deg. off the starboard bow. In these winds, a shear layer is shed from the aft edge of the island superstructure and crosses the deck near spot 8 (on the aft of the ship deck), causing significant turbulence in this region. Based on the ratings and comments of the pilot who flew the same conditions in both the aircraft and simulator, this condition was accurately replicated. Further analysis of control activity is on-going. Figure 6 shows how the DIPES ratings increase in a wind of 30 deg at spot 8 but not at spot 2, where no shear layer exists.

An analysis of variance (ANOVA) of pilot ratings revealed no strong statistical differences between the fidelity configurations tested, although pilot workload with configuration D appeared to be slightly lower than with configurations A and B, resulting in larger predicted flight envelopes when using configuration D. Figure 7 illustrates this effect. It is suspected that the lower workload may be attributable to artefacts in the PC-based Level II visuals, such as aliasing and intermittent scene jumping, which detracted from the realism of the simulation. Both issues could be resolved by recent technological advances, and there is no reason to doubt the utility of PC-based visual systems for this application. The results indicate, however, that it is the fidelity of the airwake that matters most for WOD envelope development in a simulator; the fidelity of the remaining subsystems, as long as they are of sufficient fidelity to not detract from the simulation, is of secondary importance.

It should be noted that the reduction of the simulation data is not yet complete and the results stated here only reflect a subset of the final analysis.

Conclusions

The interactive simulation of the wind-over-the-deck launch and recovery conditions remains a challenge. This task involves precision manoevering by the pilot in the presence of continuous disturbances due to the ship airwake. This paper has shown some of these challenges, and particularly, how the US Navy JSHIP program has attempted to create an environment for simulation-based determination of the wind-over-the-deck envelope.

Since this paper describes a very large research effort, only the salient conclusions are provided:

- While the fidelity of each component is critical, the total system fidelity must also be carefully examined.
- The pilot requires well-co-ordinated visual and motion cues in order to carry out this task and with an acceptable workload.
- The JSHIP program to date has examined a relatively light helicopter in combination with a large, flat-decked ship. While these results, if applied to other combinations of vehicles, should be applied with caution, the tools and knowledge are now present, including the facilities at NASA Ames Research Center.

Recommendations for Future Work

Additional at-sea testing for validation of the predicted envelopes would be a valuable means of further understanding the process described herein.

Continued research into the fidelity requirements for both the WOD envelope development application, and of the perception and control process of the human pilot, would be justified.

Investigation of the coupling effect between the rotor and the airwake would demonstrate how important these effects are, and whether their real-time modelling for piloted simulation is justified.

This requires modelling and simulation of the aerodynamics associated with ship airwakes, as well as rotorcraft aerodynamics.

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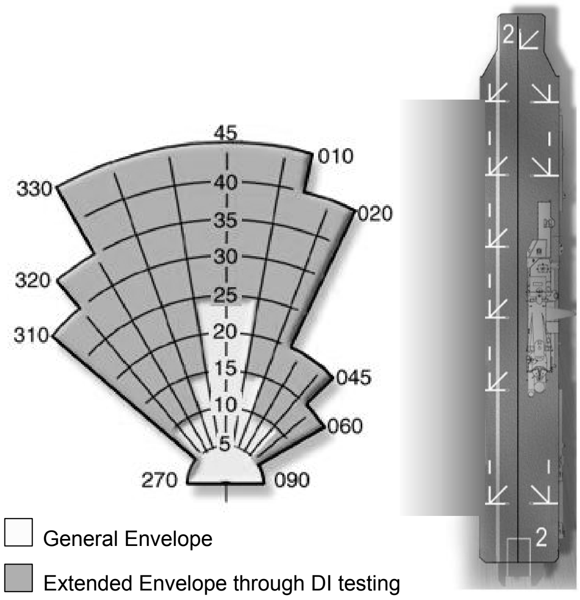

Figure 1 *– Wind-over-the-Deck (WOD) Launch and Recovery Flight Envelope for a specific landing site on an LHA Ship*

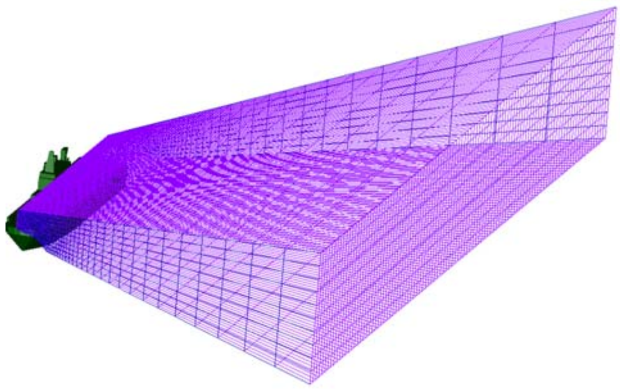

Figure 2 *- The LHA Ship airwake grid defined in the simulator*

Figure 3 *- DIMSS UH-60A helicopter Cockpit Field-of-View; LHA ship in background*

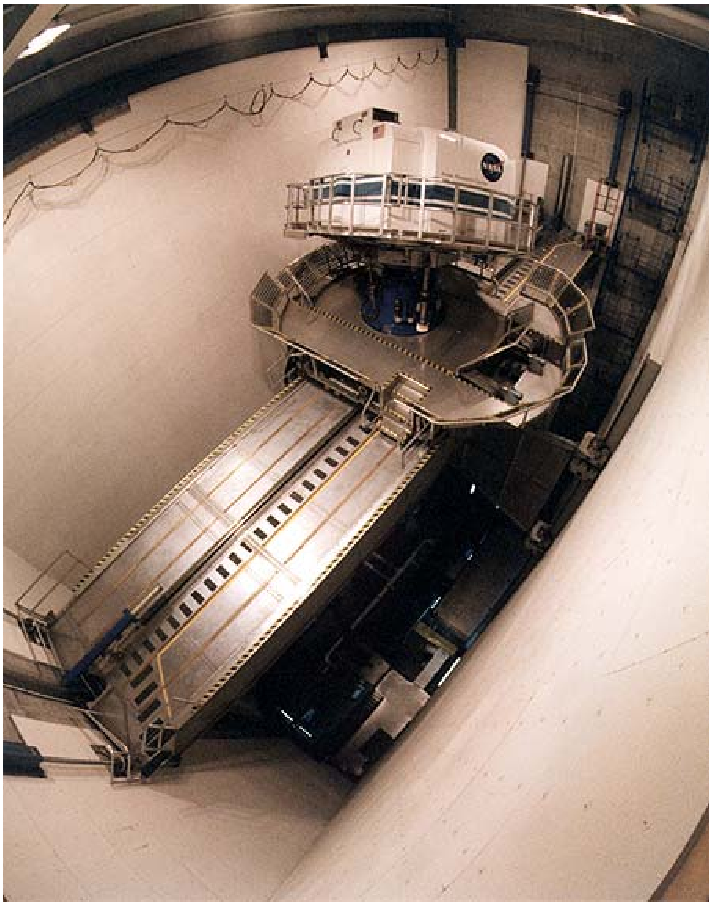

Figure 4 *– NASA Ames Vertical Motion Simulator*

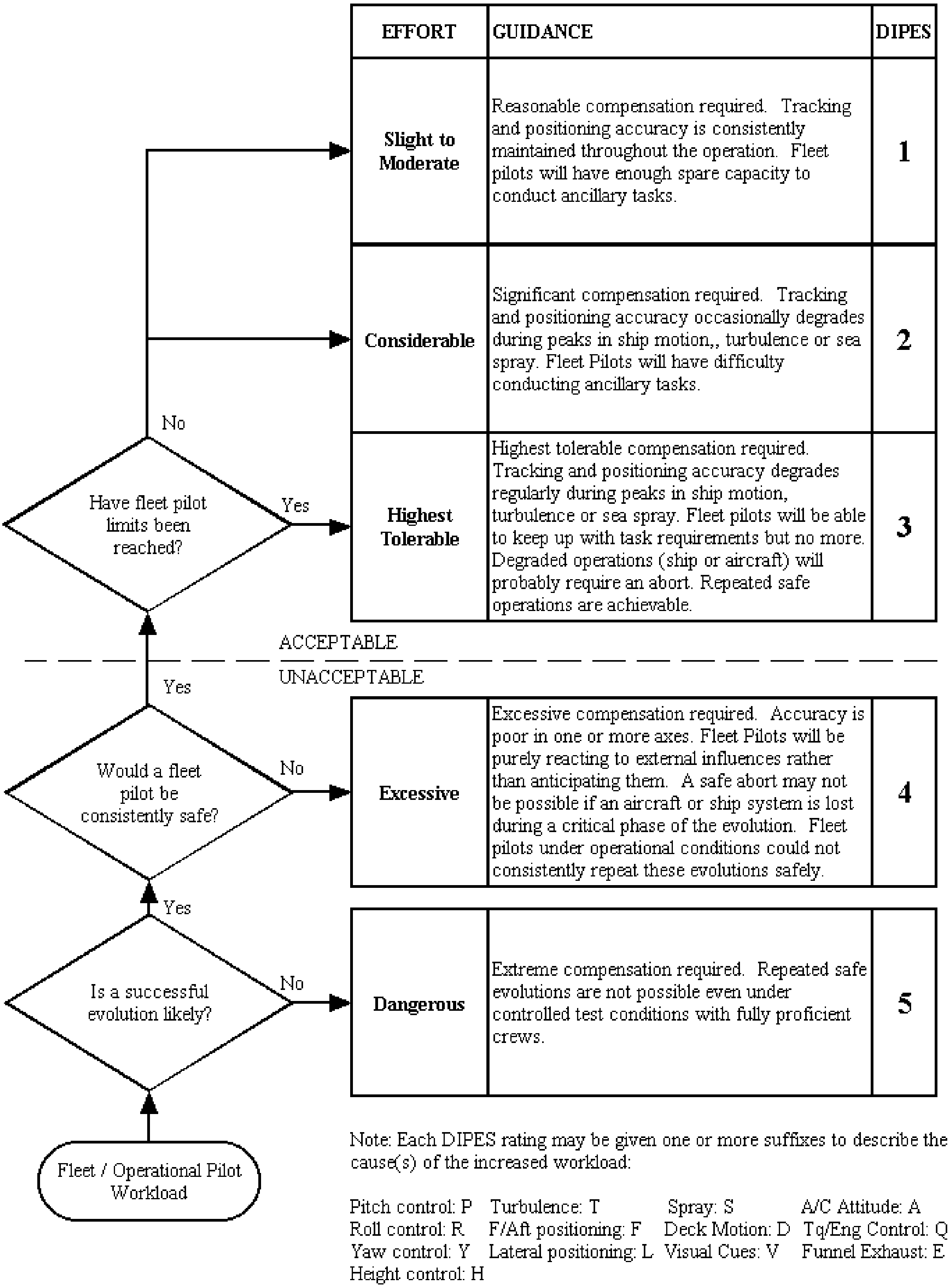

***Figure 5** - The Deck Interface Pilot Effort Scale (DIPES)*

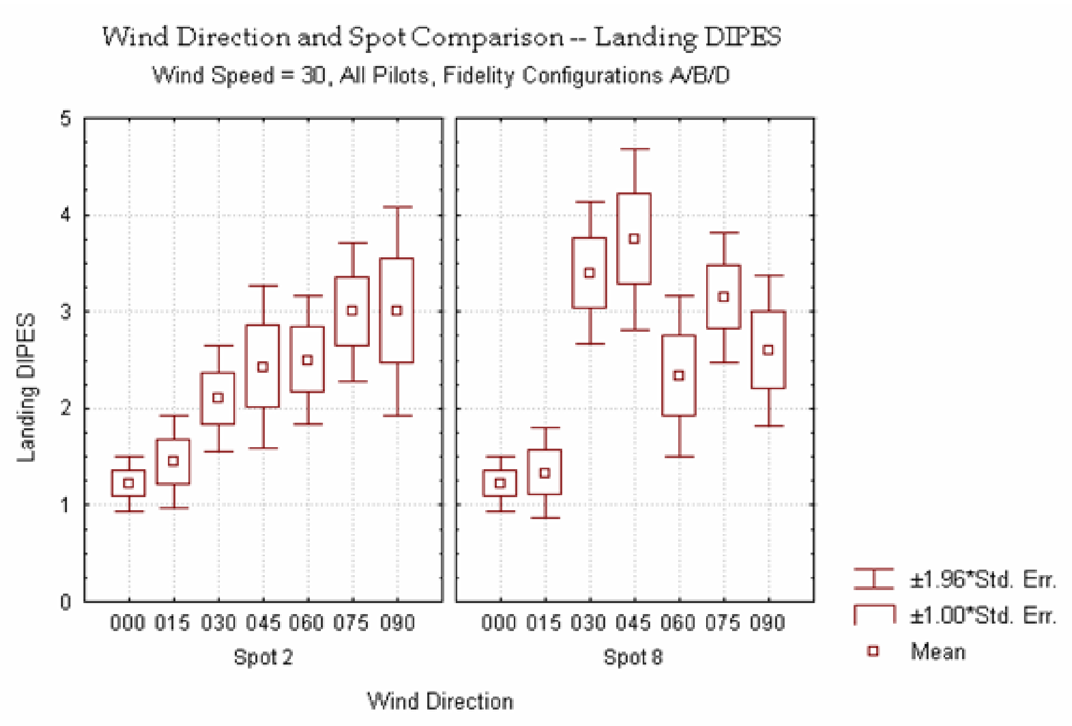

Figure 6 *- Range of Pilot Rating with Wind Direction at Landing Spots 2 and 8*

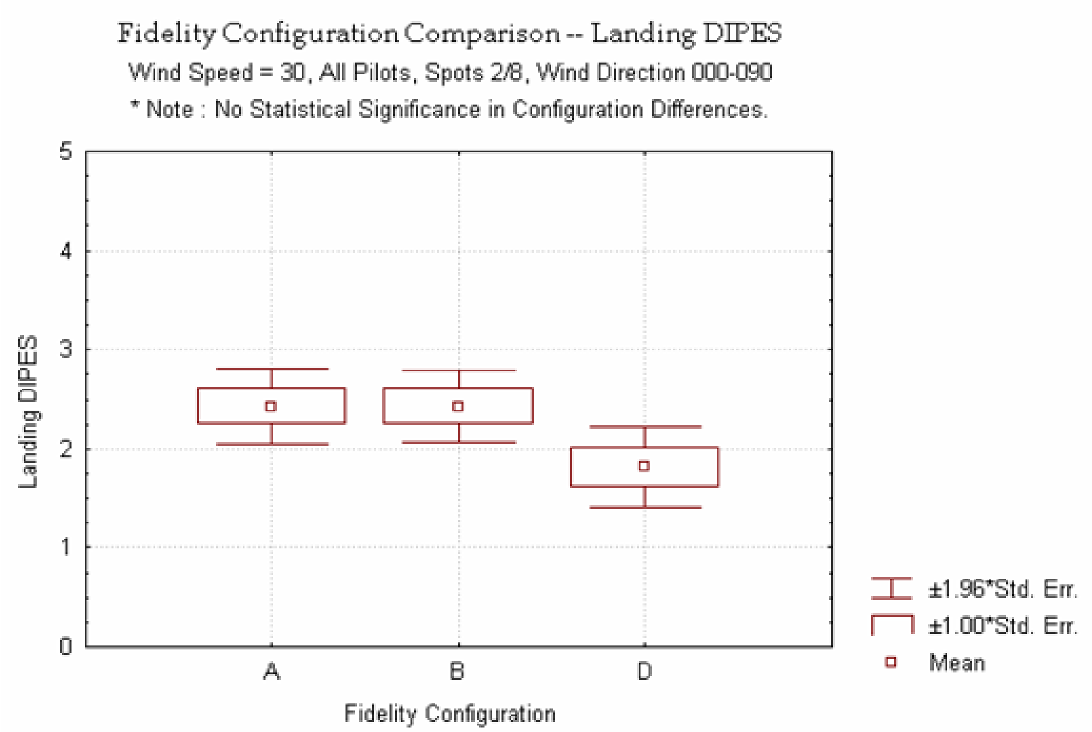

Figure 7 *- Fidelity Configuration Comparison*