Development of a CH-124 Sea King Helicopter Deck Landing Simulation using a Fiber Optic Helmet Mounted Display System

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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Abstract

Landing helicopters on ship decks at sea is a dangerous endeavor. The difficulty of approaching a small moving platform, variable operational situations, and the likelihood of adverse environmental conditions make viable simulator research and development for Canadian Navy CH-124 Sea King helicopters and Canadian Patrol Frigates.

A deck landing simulation has been designed at the University of Toronto Institute for Aerospace Studies Flight Research Simulator Laboratory that models the low-speed and hover dynamics of the Sea King helicopter and creates detailed imagery of a Canadian Patrol Frigate at sea using a Fiber Optic Helmet Mounted Display. The simulation includes a virtual-reality cockpit environment with pilot controls, an electronic instrument panel, Sea King cockpit noise, and a six degree-of-freedom motion base.

The system has been integrated under CAE SIMex-PLUS software control to execute the GenHel flight dynamic routines and employ an advanced MAXVUE image generation system. Modifications have been made to incorporate realistic ship motion for various sea states and wake effects behind the hangar.

Simulator assessment has been undertaken with helicopter test pilots, and their evaluations have been used to make changes and recommendations for future experimental work at the simulator lab.
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The original GenHel computer code was kindly provided by NASA-Ames and the US Naval Air Warfare Center Aircraft Division.
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1.0 Introduction

1.1 Flight Simulation

Aerospace simulation entails a sophisticated integration of environment and vehicle modeling. A simulation system requires innovative use of real-time computing equipment, high-speed communication networks, advanced image generation capabilities, and specialized simulation hardware components. Often termed 'virtual reality' by mass media, flight simulation attempts to recreate the feel of aircraft flight with visual, motion, tactile, and acoustic sensory cues.

The use of flight simulators in the modern age of aerospace research and development is extensive and their advantages are numerous. With skyrocketing costs of new technology, reduced military requirements, and shrinking government defence and civil aerospace expenditures, flight simulation has a vital role in advanced training of flight personnel in the use of aircraft and aircraft systems. The principal advantages of flight simulation include:

- safety considerations for new, difficult, or impractical tasks (e.g. mission planning and system failure scenarios)
- lower operational and environmental costs, since airframes are not stressed nor fuel burned
• increased efficiency of training time without concern for aircraft availability or optimum weather conditions
• testing of new flight hardware components or software environments (e.g. helmet-mounted displays, enhanced and synthetic vision systems)

Though simulators can cost a lot to purchase or develop and cannot entirely replace the benefits of 'stick-time' in the real aircraft, there is an obvious market for their capabilities. One flying task that has significant simulation benefits is helicopter deck landing on a ship at sea. The inherent difficulty of landing on a small moving platform, unpredictable operational situations, and an extreme training environment emphasize the need for simulator development. The CH-124 Sea King helicopter tasked to land on Canadian Patrol Frigate decks for the Canadian Navy is a prime example.

1.2 CH-124 Sea King Helicopter

The CH-124 Sea King helicopter is the only shipborne helicopter in the Canadian military. Sea Kings are employed with the Maritime Air Group in the Canadian Navy on a variety of tasks including coastal patrol, environmental monitoring, anti-submarine warfare tactics, international peacekeeping missions, and search-and-rescue (SAR).

Sea King helicopters have a gross weight of approximately 8600 kg, a top speed of 151 knots, a fuselage length of 22 m, and a five-bladed, 9.4-m radius rotor. About 30 Sea Kings are currently in service in operational or training roles, operating from both shore bases and on board destroyers, frigates, and support ships. A Sea King helicopter is shown in Figure 1.1.
The age and wear of the Sea King airframes – in service for more than 30 years – stresses the need for flight and task simulations for aircrew training. While a 1995 Canadian defence policy study supports the replacement of the Sea King fleet – it is widely expected that 35 maritime patrol helicopters will be purchased to supplement a January 1998 decision to purchase 15 AW520 Cormorant SAR helicopters – the expected operational life of at least some of the current helicopters will extend beyond the year 2000. The limited number of operational Sea Kings and frequent maintenance requirements make advanced Sea King deck landing simulators extremely viable.

1.3 Canadian Patrol Frigate (CPF)

The Halifax-class Canadian Patrol Frigates (CPF) are multi-purpose frigates that have recently been commissioned by the Canadian Navy. They carry sophisticated sensor and weapon
systems, including torpedoes, surface-to-surface and surface-to-air missiles, utilize advanced sonar and electronic warfare systems, and are capable of launching and recovering Sea King helicopters. The CPF displaces 5000 tons, carries 225 crew members, is 134 m long, and has 46000 shaft hp to provide a maximum speed above 30 kts. A Canadian Patrol Frigate is shown in Figure 1.2.

![Canadian Patrol Frigate](image)

**Figure 1.2 : Canadian Patrol Frigate**

1.4 Project Framework

The University of Toronto Institute for Aerospace Studies (UTIAS) Flight Research Simulator Lab has been contracted by the Department of National Defence (DND) to develop a CH-124 Sea King helicopter simulator using a Fiber Optic Helmet Mounted Display (FOHMD) that will evaluate the ability of subject pilots to land on the deck of a Canadian Patrol Frigate.
As an undergraduate thesis student (1993-94) and project engineer on a Helicopter Deck Landing Simulator (HDLS) contract (1994-96), the author has been involved with the modification, development, and integration of the Sikorsky General Helicopter Flight Dynamics Simulation (GenHel) software. This software package was forwarded by the US Naval Air Warfare Center (NAWC) as a working mathematical model of the UH-60A Black Hawk helicopter in July 1993. The code had been modified by NASA-Ames to operate in real-time for use in a helicopter flight simulator.

The initial modification and validation work can be examined in Reference [1]. It details the development of an instruments-only Black Hawk simulator. Further development of GenHel that immediately followed the undergraduate thesis completion allowed for the inclusion of an out-the-window display employing a Silicon Graphics Inc. Iris 4D/310VGX workstation and transfer of the flight equations to an IBM RISC 6000. The HDLS contract further refined the GenHel model through the work of UTIAS simulator lab project engineers and graduate students. The hardware and software implementations of this contract can be examined in detail in Reference [2].

The goal of this thesis has been to implement a simulation of a Sea King helicopter for the evaluation of its training effectiveness for deck landings on a Canadian Patrol Frigate in various sea states. This simulation includes a virtual-reality cockpit environment with pilot controls, an out-the-window display based on a FOHMD, electronic instrument panel, Sea King cockpit noise, and six degree-of-freedom motion base. It is worthwhile to note that the work does not represent the creation of a full Sea King helicopter flight simulator; it is a deck landing task trainer that has been evaluated for its effectiveness in only a subset of Sea King helicopter activities.

The thesis work completed can be broadly categorized into: system integration of the UTIAS flight simulator hardware, including the conversion of GenHel to operate with a new host
computer system and image generator; software modifications to improve the quality of the Sea King and CPF simulation; and flight model evaluation by Sea King test pilots with deck landing experience. To assist in future experiments to be conducted in the UTIAS simulator lab, these pilots have aided in the development of the deck landing scenario. This scenario, as well as other qualitative and quantitative inputs, will be used in the creation of performance and evaluation tools in UTIAS experimental deck landing investigations.
2.0 Simulator Systems

2.1 UTIAS Flight Simulator

The UTIAS flight simulator is based on a DC-8 simulator cab and contains flight controls for both fixed- and rotary-wing aircraft. It is mounted on a CAE Series 300 hexapod motion system, which is capable of simulating the feel of atmospheric flight in six degrees-of-freedom: three translational modes (surge, sway, and heave) and three rotational modes (roll, pitch, and yaw). Figure 2.1 shows the simulator and its motion base.

![UTIAS Flight Research Simulator](image-url)
The hardware characteristics of the motion system are detailed in Reference [3]. Included are limits on single degree-of-freedom pure motion. Angular displacement limits are approximately ±20° and translational limits are about ±0.60 m.

2.2 Pilot Controls

The cyclic control forces are provided by a McFadden Systems Inc. Model 292B Universal Variable Digital Cockpit Control Force Loading System. The system can produce up to ±150 lb force in both the roll and pitch axes, which displace approximately ±15°. The electrohydraulic control loader is capable of modelling spring, damping, and inertial forces in response to stick displacement and rates, as well as including the effects of deadband, breakout, and mechanical stops. The stick can be repositioned freely within its travel range with the push of a trim release button or incrementally with a 4-way trim thumb switch. These features allow the pilot precise stick control for different helicopter trim states. The control loader force model and general operation can be examined in References [2] and [4]. The preliminary control loader parameters selected for the Sea King helicopter simulation were based on test flights flown in flight model evaluations in 1996. These cyclic control parameters are included in Table 2.1.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Displacement</td>
<td>± 7.2 in</td>
</tr>
<tr>
<td>Longitudinal Inertia</td>
<td>4.0 lbm</td>
</tr>
<tr>
<td>Lateral Inertia</td>
<td>6.5 lbm</td>
</tr>
<tr>
<td>Spring Gradient</td>
<td>0.48 lb/in</td>
</tr>
<tr>
<td>Longitudinal Viscous Damping</td>
<td>0.26 lb/(in/s)</td>
</tr>
<tr>
<td>Lateral Viscous Damping</td>
<td>0.34 lb/(in/s)</td>
</tr>
<tr>
<td>Breakout Force</td>
<td>1.5 lb</td>
</tr>
<tr>
<td>Breakout Deflection</td>
<td>± 0.48 in</td>
</tr>
<tr>
<td>Trim Velocity</td>
<td>1.45 in/s</td>
</tr>
</tbody>
</table>

Table 2.1: Cyclic Control Loader Parameters
Other pilot controls are included in the cockpit layout. There are linear-spring force pedals for tail rotor control, which displace ±3.7 in and produce 8.0 lb/in. A collective column for heave control incorporates an adjustable friction mechanism and displaces 0-12.2 in. Mode switches on the upper part of the collective can be used for multiple control modes or component operations. (For example, the Sea King haul-down system has been pilot-controlled in this manner.) Figure 2.2 shows the helicopter simulator cockpit.

![UTIAS Helicopter Simulator Cockpit](image)

**Figure 2.2 : UTIAS Helicopter Simulator Cockpit**

### 2.3 Fiber Optic Helmet Mounted Display (FOHMD)

Technology is available for the utilization of high-quality helmet mounted displays, both in simulators and actual aircraft. The CAE Fiber Optic Helmet Mounted Display (FOHMD) has been integrated into the UTIAS Flight Research Simulator, replacing the standard 40° x 30° window box used previously. The FOHMD’s installation and operating configuration are detailed in Reference [5].
The FOHMD displays left eye and right eye images, simulating normal human stereopsis, on high quality display optics. The display images are relayed from two projectors behind the pilot via two fiber optic cables, each containing four million coherent strands. The image is collimated by a Pancake Window eyepiece with a 5% transmissivity, allowing normal viewing of real objects in the simulated cockpit (such as the instrument panel and controls). The display eyepieces are mounted on the side of a lightweight helmet and can be manually adjusted in position and orientation to align the 15-mm diameter exit pupil and the pilot’s eye.

The visual display system field-of-regard is infinite, while the overall field-of-view is adjustable for larger and smaller stereo overlap. The system was designed for three specific levels of overlap (0°, 25°, and 40°), and the value selected for the Sea King simulations was 25°. This configuration gives a field-of-view of 71° horizontal by 34.5° vertical.

In order to create a more realistic cockpit environment, the position and orientation of the pilot’s head (and, therefore, viewpoint) are monitored by a Polhemus Model 3SF0002 3SPACE FASTRAK magnetic headtracker. The receiver is located on the pilot’s helmet and the transmitter on the ceiling of the simulator cab. The tracking signals generated have been enhanced by software designed to correct signal inaccuracies at the boundaries of pilot helmet travel and to compensate for magnetic interference in the UTIAS simulator cockpit. The values are sent to the MAXVUE image generator (see Section 2.5) in order to generate the appropriate display eye point.

The helmet is fitted with an inflatable liner that is pressurized (with hand-held squeeze bulb) by the pilot so as to make a secure fit to ensure that the helmet optics remained aligned with the pilot’s eyes. This inflatable liner fitting method replaced the custom helmet liners formed using a foam casting technique.

A load relief system is anchored to the simulator ceiling to relieve the combined weight of the helmet shell, intercom, liner, optics, and headtracker (approximately 8 lb) and a face-down
pitching moment (approximately 0.90 ft-lb). Reference [5] details the effects of the load relief system, which consists of a constant tension retracting spring (4 lb-force) mounted 2.0 ft above two helmet attachment points, which are joined by mono-filament line to a spreader bar.

Figure 2.3 shows the helmet and its related components.

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**Figure 2.3**: Fiber Optic Helmet Mounted Display (FOHMD)

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2.4 Electronic Flight Instrument System (EFIS)

A Silicon Graphics Iris 3130 workstation is used to display graphically some of the instruments required for Sea King helicopter flight on an Electronic Flight Instrument System (EFIS). The EFIS, though not a true layout of Sea King cockpit switches, dials, and indicators, is meant only to provide adequate representation of those variables required in a deck approach.
(which, in any case, is predominantly a visual task). The EFIS (which updates at 30 Hz) is programmed to display the digital airspeed, altitude, and sideslip angle, an artificial horizon, turn rate, side force indicator, climb rate, heading, engine torque, and engine and rotor % rpm. As mentioned in Section 2.3, the EFIS is visible to a pilot using the Fiber Optic Helmet Mounted Display through the Pancake Window. The EFIS is shown in Figure 2.4.

**Figure 2.4 : Electronic Flight Instrument System (EFIS)**

2.5 MAXVUE Image Generator

The creation of a two-channel out-the-window scene is tasked to a CAE MAXVUE Enhanced B Graphic Image Generator (IG) System. It has the capability of presenting
meteorological conditions, terrain features, sea elements, night/dawn/dusk/day effects, tactical environments, static and dynamic objects, and supporting components in realistic detail sufficient to provide accurate speed, height, and distance cues. The scenes are built from coloured and textured polygons and coloured lights, and can be prepared from terrain input and satellite and/or aerial photograph texturing.

A host computer and magnetic headtracker provide the MAXVUE IG with viewpoint position and orientation within a selected database and the displayed image is refreshed. It is capable of updating each channel's 1.2 million pixels, 3000 surfaces, and 1000 light points at a rate of 60 Hz. The functional specifications of the MAXVUE system are detailed in Reference [6].

2.6 Cockpit Sound System

The flight simulator sound system consists of an E-mu Systems Inc. EMAX digital sampling keyboard, Yamaha TX81Z tone generator, a NAD 3020e amplifier, a Harmon/Kardon Citation-24 power amplifier, and a 4- and 8-channel mixer. Up to sixteen separate channels can be played in real-time while varying the frequency and amplitude of each. The system is linked to the host computer via a Musical Instrument Digital Interface (MIDI). The operation of the sound system is given in Reference [7].

The cockpit noise is a digital reproduction of analog recordings made during a Sea King flight. Pitch and volume levels are dependent upon the helicopter control inputs and flight conditions. The modifications to the Sea King cockpit noise are detailed in Section 4.2.
2.7 RISC 6000 Host Computer

The host computer is a RISC 6000 Model 390 Power 2 workstation. It is responsible for the execution of the simulation management utilities, using pilot control information to drive the software simulating the flight dynamics of the Sea King helicopter, and directing appropriate information to the hardware subsystems via the Ethernet.

A 80186-based single-board computer with an Ethernet board links the simulator host computer to the existing Multibus I chassis which interfaces to the simulator motion and sound systems. The aircraft controls are linked to a VME-based analog-to-digital board, which is linked to the host computer through a BIT3 system. Figure 2.5 shows the hardware systems and the processes through which they communicate.

![Simulation Hardware Overview](image)

*Figure 2.5: Simulation Hardware Overview*
2.8 GenHel Flight Equations

The NASA-Ames/NAWC GenHel flight software is a non-linear representation of a single main rotor helicopter, accurate for a full range of angles-of-attack, sideslip, and rotor inflow. Six rigid body degrees-of-freedom are modelled. GenHel utilizes a blade element approach in calculating rotor forces as functions of angle-of-attack and dynamic pressure. Other GenHel features include a tail rotor thrust model with non-linear inflow effects, a six-component fuselage model based on wind tunnel data, an empennage model, engine/fuel control model, four modes of automatic flight control system (AFCS), and a simple ground effect and turbulent gust model.

As mentioned in Section 1.4, GenHel was developed into an instruments-only simulation and follow-on contract development allowed for the inclusion of an out-the-window display using an Iris 4D/310VGX and transfer of the flight equations to an IBM RISC 6000.

Upon acceptance of the HDLS contract, the decision was made to utilize the GenHel software for the simulation of the Sea King. GenHel was modified to include:

- dynamic modelling of the Sea King. This involved a conversion of the physical characteristics and a revised automatic flight control system (AFCS) that converted the Black Hawk helicopter model into a Sea King low speed and hover model. Extensive off-line testing and piloted simulations took place after the development work, and are detailed in Reference [8].

- a landing gear model to simulate the forces and constraints of deck contact. Three wheel/strut units of the Sea King are modelled with detailed non-linear spring and viscous oleo representations. The physical properties of the landing gear system are based on Seahawk static and dynamic compression tests at the Australian Aeronautical Research Laboratory (ARL)-Melbourne. (The difference between Sea King and Seahawk tire/oleo models was considered to be negligible, but the relative contact point
geometries were changed.) The option of a translating, rotating landing surface was added to the ARL model as well. The tire and oleo deflection and tire deformation, sliding, and dragging models are given in Reference [2].

- a representation of the Recovery Assist, Secure, and Traverse (RAST) system. The RAST model consists of variable-length, variable-force winch/cable effects and a trap simulation modelled with strong restoring forces and moments to hold the simulated helicopter on the moving deck. The equation for the RAST system are given in Reference [2].

- an airwake model to represent aerodynamic disturbances around the ship. The National Research Council (NRC) provided a wind-over-deck model, which is described and its modifications detailed in Section 4.1.

- a digital representation of Sea King cockpit noise, whose parameters are illustrated in Section 4.2.

- ship motion characteristics for various sea states. With assistance from the Defence and Civil Institute for Environmental Medicine (DCIEM) and Defence Research Establishment Atlantic (DREA), ship motion time histories were interfaced with the GenHel software. The Fredyn and TISIM CPF motion software packages are detailed in Section 4.3.

- a computer-generated image of a frigate deck with proper visual references. The MAXVUE CPF model and database are outlined in Section 2.10.

- an enhanced turbulent gust model. Interpolations based on two turbulence generators model the atmospheric disturbance over the helicopter rotor disk with a Simulation of Rotor Blade Element Turbulence (SORBET) scheme (Reference [9]), which creates a two-dimensional distribution that changes with time and spatial location.
- distributed interactive simulation (DIS) capability to allow remote system control of CPF position. The DIS protocol and implementation in the UTIAS simulator lab are given in Reference [10].

The GenHel flight dynamics software is capable of trimming the pilot control inputs to a desired helicopter position and airspeed, and is configured to operate off-line for analysis of computer-driven control inputs and in real-time for use in piloted simulation.

2.9 SIMex-PLUS Environment

A new software environment has been introduced to simplify the integration of the MAXVUE image generator with the UTIAS simulator, the CAE-developed Simulation Management Utility (SIMex-PLUS). This software has been designed as a general simulator management utility with emphasis on configuration control, software construction, and simulator operation. In addition to storing all simulation software, it maintains a project's development and use, guides multiple-user access, and organizes all levels of development and executable building. The SIMex-PLUS software is run on the RISC 6000 host computer described in the Section 2.7.

SIMex-PLUS is designed to interact smoothly with synchronous (required each program iteration) and asynchronous (intermittent) processes, allow collective access to a global variable set called the common database (CDB), and allow use of CAE debugging and test software like the computerized test system (CTS-PLUS) and performance monitoring utility (PFU).

In order to have all FORTRAN and C source files (the components of the GenHel flight dynamic software) access the CDB, all routines are pre-compiled to provide common variable descriptions and equation summaries.

The dispatcher schedules modules – like the flight equations, output to the MAXVUE, or sampling the pilot controls – to be processed at a specific iteration rate. The synchronous and
asynchronous dispatchers require tables defining critical and non-critical bands, depending on whether a given module must be executed with every iteration. The synchronous dispatcher schedule is described in more detail in Section 3.2.

The SIMex-PLUS environment is described extensively in Reference [11].

2.10 CPF Image Model and Waterworld Database

The deck landing simulation requires a detailed display of the Canadian Patrol Frigate. An SGI Modelview program of a CPF was obtained from the Defence and Civil Institute for Environmental Medicine (DCIEM) and modified extensively to be drawn using the MAXVUE binary separation plane (BSP) rendering approach under SIMex-PLUS control. These computational refinements are explained in Reference [2].

The CPF image was enhanced to include additional detail in the rear hangar face and landing deck area to provide relevant visual cues to the simulator pilot. Figure 2.6 shows the MAXVUE CPF and its landing deck. Some of the database image features include:

- phototextured deck surface
- phototextured rear hangar face and observation booth
- phototextured Landing Safety Officer's (LSO) booth
- sloping hangar face structures
- pitch and roll horizon bars (not currently operational as moving models independent of the CPF)
- protruding and recessed objects on hangar face
- deck railings and safety nets
- antenna and its superstructure
- phototextured lower rear deck objects
Figure 2.6: MAXVUE CPF Image
The database area, called Waterworld and containing the moving CPF model, consists of two (distant) textured islands with generic forest and farmland texture and a moving-wave ocean surface terrain. The nominal environmental conditions are clear, blue sky with high intermittent clouds in bright daylight.

2.11 Sea King Cockpit Mask

An accurate silhouette of the Sea King cockpit, called a cockpit mask, is generated by the MAXVUE and maintained in alignment with the simulated, physical structure. Figure 2.7 shows the obstructions blocking what the pilot 'sees' through the cockpit windows. The figure shows a viewing angle along the centreline of the helicopter from approximately six feet aft of the instrument panel. The frame outline (in black) indicates the following windows: two ceiling; two side; three front; and two chin.

Figure 2.7: Sea King Cockpit Window Mask
3.0 System Integration

3.1 GenHel Software Integration

The version of GenHel in operation at UTIAS at the beginning of this thesis project was controlled with a RISC 6000 Model 355 workstation as the host computer and had a Perkin-Elmer 3250 controlling the timing of a simple ship database displayed on an SGI Iris 4D/310VGX and acting as the interface to the sound and motion systems.

The construction of the full SIMex-PLUS-controlled version of GenHel, complete with the interface to the MAXVUE image generator, EFIS, FOHMD, sound and motion systems, and McFadden control loader had to be completed prior to any evaluation or experimental work. Figure 3.1 shows the system integration. The emphasis was to link RISC 6000 host computer control of SIMex-PLUS GenHel to the simulation components shown.

Much of the integration work was based upon the Bell-205 helicopter SIMex-PLUS configuration in operation in the UTIAS simulator lab, especially in the initialization of the single-board computer interface and configuration of the motion base washout routines, though extensive modifications had to be made to the manipulation of the flight equations, control inputs, and moving model instructions.
3.2 Simulation Synchronous Control Layout

As outlined in Section 2.9, certain modules must be processed at a specific iteration rate. The size and complexity of the GenHel flight equations and the detail residing in the CPF-Waterworld database allowed for a simulation update rate of 60 Hz. The SIMex-PLUS software was required to schedule a number of tasks relating to real-time control of the entire simulation. These modules are detailed in Figure 3.2. Their total execution time does not exceed 16.67 ms; if their execution time is less than 16.67 ms, the scheduler delays the start of the next loop so as to fix the 60 Hz update rate.

Not shown is the 30 Hz (33.3 ms time steps) band. In the Sea King deck simulator, there was only one module defined to operate at this priority, the vis_out routine, which calculates the flight instrument variables and sends them to the SGI Iris 3130 workstation that updates the EFIS. In more complex simulations, these lower-priority bands would be used extensively for subsystems not requiring high-frequency updates. For example, navigational information can be conveyed at lower rates without loss of realism.
3.3 Nonreal-time and Real-time GenHel Control

In order to bring the GenHel flight dynamics software under SIMex-PLUS control, a variable set called the common database (CDB) was constructed. The standard form of organizing related variables in FORTRAN is through common labels, which simplifies the
program sharing of all variables contained within the block of data governed by each label. While SIMex-PLUS allows this methodology, it augments it with the CDB system, which consolidates these variable groups under strict process control and user access guidelines. The GenHel flight variables were thus organized into pertinent sets for CDB implementation.

The GenHel trim process required a major overhaul. In its previous operational state, there were few distinctions between running in trim mode and operating with real-time control inputs, either from a pilot or from a recorded data file. SIMex-PLUS control of the simulation required more rigid operational control. Its nonreal-time and real-time tasks had to be separated.

The GenHel software's original method of trimming the helicopter to a starting position and velocity was governed by repetitions of the flight equations with iterative changes to control input values, helicopter orientation, and engine torque until the desired conditions were satisfied. The nonreal-time routine (sksimurt.for) was tasked to perform these trim operations with a GenHel version under user control, while the real-time GenHel version (flighteq.for) operations were to be under control of the 60 Hz synchronous processor.

Because of various versions of nested initialization loops in GenHel's 40 subroutines, problems arose if there existed a GenHel trim version in the nonreal-time executable and GenHel flight version under real-time synchronous control. Two separate versions of the software, though linked by a common database, could not guarantee error-free start-up and complete variable initialization, since many of the subroutines utilized non-CDB control variables that would have to be properly initialized in both GenHel versions without retrimming the flight version. Error-prone execution and program halts forced a change in the nature of the user control-flight control task split.

The nonreal-time tasks include the initialization of the image database parameters, helmet mounted display settings, starting flight conditions, flight control input choices, ship motion settings, and input/output data management, and the execution of the GenHel trim
functions. This nonreal-time routine (updated sksimnrt.for) was constructed based on a similar program for a Bell-205 helicopter simulation. The sksimnrt.for algorithm is outlined in Figure 3.3. In addition to initialization and user control of the trim operations, this routine allows the user to make real-time changes to the flight conditions, such as modifying turbulence or directing program termination.

The flighteq.for routine indicated in Figure 3.2 and mentioned above is part of the 60 Hz band of critical routines. It increments all program counters, directs the execution of the GenHel flight equations, monitors possible crash conditions, and controls graceful fadeout upon run termination. The flighteq.for algorithm is outlined in Figure 3.4.

The essence of the connection between sksimnrt.for and flighteq.for is the directing of the GenHel flight equations into trim or flight mode. This allows synchronous control of GenHel even though the instruction is coming from the operator interacting with the simulation via a host computer terminal. This can occur because flighteq.for is still scheduled to process at 60 Hz whether GenHel is trimming, flying in real-time, awaiting commands, fading out, or completed. The flighteq.for module continues until the entire SIMex-PLUS configuration in unloaded from host computer control.
Figure 3.3: Nonreal-time Operator Interface (sksimnrt.for)
Figure 3.4: Real-time Control Algorithm (*flighteq.for*)
3.4 System Integration Debugging

Without detailing the software-level fixes to construct a working simulation, it is worth outlining some of the problems encountered during the development process. The augmentation of the GenHel code to operate under SIMex-PLUS control was not a seamless conversion. Various problems extended the development time period.

Most difficulties encountered were related to common database-local variable initialization conflicts. These errors manifested themselves in a variety of manners.

(1) Start-up transients – only 50% of the required torque was present on the EFIS after trim completion

(2) Altitude drop – consistent drop of approximately 20 ft upon initiation of piloted simulation, independent of starting position or airspeed

(3) Reduced altitude control – collective control input effects impaired

(4) Inaccurate turbulence calculations – downward gust too strong and incorrectly independent of time

When the system integration process was complete, control input files from the previous operational UTIAS GenHel version were used to test the SIMex-PLUS version of the software. Simulation data showed the Sea King flight paths to be equivalent, in both stationary- and moving-deck landings.
4.0 Software Modifications

4.1 Airwake Modifications

The Applied Aerodynamics Laboratory at the National Research Council (NRC) provided a wind-over-deck model for representing the interference effects that the ship and its superstructure have on the inflow to the helicopter and its rotor (see Reference [12]). Derived from wind tunnel data and full-scale frigate trials, the airwake model calculates the ratio of the resulting wind to a selectable mean wind-over-deck with an analytic function:

\[
\frac{V_{\text{airwake}}}{V_0} = a_0 + a_1 x' + a_2 y' + a_3 z' + a_4 x'^2 + a_5 x' y' + a_6 y'^2 + a_7 x' z' + a_8 z'^2 + a_9 y' z' + a_{10} x' y' z'
\]

where \( V_{\text{airwake}} \) – resulting wind velocity in the \(( x', y', z' )\) directions

\( V_0 \) – wind-over-deck velocity (assumed to be directed aft along the ship’s longitudinal axis). Sum of atmospheric wind and forward ship speed.

\( a_0 \ldots a_{10} \) – coefficient set for each of \(( x', y', z' )\) directions

The wake-affected area is defined in a rectangular box with its front against the hangar face and its base at the level of the landing surface. The size of the box is relative to the height and width of the hangar wall over which the mean wind is passing, as shown in Figure 4.1. The volume is
defined by twice the hangar height above the deck, the length of the hangar base left and right of
the deck longitudinal centreline, and five times the hangar height measured aft from the hangar
wall.

Figure 4.1: NRC Shipwake Disturbance Zone

As will be detailed in Section 4.3, the preferred wind conditions for landing are not
directly along the longitudinal axis of the ship. What is modelled by the NRC airwake software
is precisely what approaching helicopter pilots prefer to avoid (i.e., the changing wind patterns
due to flow over the ship’s superstructure). The CPF usually attempts to sail 15° to starboard of
the wind, so as the pilot traverses from the port side, the wind for most of the approach is ‘clean’.
It is only when the pilot’s view of the horizon is obscured by the ship that the airwake effects
become significant. Modifications of the NRC code have been made to allow for this magnitude
of heading offset. It is realized that the nature of the approximations that were adopted in the NRC experiments and data collection are slightly extended, but the resulting inaccuracies are small relative to the overall effects on flight performance. (The approximate effects of the lateral wind component modify the wind-over-deck equations slightly; they are shown in Reference [2].)

A further modification was required for the NRC airwake. Figure 4.2 plots the ratio of the wind-over-deck component in the $x'$-direction to the wind-over-deck velocity for four different heights $z'$ above the deck. From the contour plots, it can be seen that the longitudinal component (that is, aligned with the forward direction of the frigate) of the wind-over-deck does not approach the wind-over-deck velocity value (i.e., 1.0) at the edges of the box.

![Figure 4.2: $V_{airwakex'}/V_0$ Contour Plots for Different Heights above Deck](image)

Figure 4.2: $V_{airwakex'}/V_0$ Contour Plots for Different Heights above Deck
Though contour plots of $y'$-direction and $z'$-direction ratios (not shown) indicate that, in theory, there would be no crosswind or downwind at the edges, simulations showed otherwise. Certain $(x', y', z')$ coordinates on the box edge gave non-zero winds in the $y'$- and $z'$-directions.

The effect of this deficiency may seem benign, as it could be thought to resemble a small turbulent gust or a changing freestream windspeed. However, helicopter flight through this edge discontinuity had two adverse effects:

1. The helicopter could have a sudden decrease in headwind when approaching the landing deck from astern (or, alternatively, an increase in headwind when approaching from port). With the controls trimmed to provide an airspeed for a slow approach to the ship from astern, a sudden drop in the slowing effects of the oncoming wind caused the helicopter to surge forward. Flight tests showed a repeated pattern of helicopters flying too close to the hangar face before a recovery could be made. (The case of an increased apparent headwind has the opposite effect; the helicopter is forced backward.)

2. The surge explained in (1) caused not only an inaccurate approach path, but a sudden forward specific force transmitted by the motion base. While the motion cue was technically correct – since it was simulating the specific forces determined by the flight equations – it led only to pilot confusion. The magnitude of the acceleration spike was comparable to the vertical specific force felt upon landing, and was unacceptable.

An adjustment was programmed to filter the onset of the airwake effects in each direction. A second-order low pass filter was placed on the calculated wind-over-deck component. The filter's Laplace transform is shown below:

\[
\frac{V_{\text{filter}}}{V_{\text{airwake}}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n + \omega_n^2}
\]

where $V_{\text{filter}}$ = filtered wind velocity
The new value of wind is thus given by implementing the following equations:

\[
\begin{align*}
\ddot{V}_n &= \omega^2 (V_{n,\text{airwake}} - V_{n-1,\text{filter}}) - 2\xi \omega \dot{V}_{n-1} \\
\dot{V}_n &= \dot{V}_{n-1} + \Delta t (1.5 \ddot{V}_n - 0.5 \ddot{V}_{n-1}) \\
V_{n,\text{filter}} &= V_{n-1,\text{filter}} + \Delta t (1.5 \dot{V}_n - 0.5 \dot{V}_{n-1})
\end{align*}
\]

where \( n \) – current time step

\( n-1 \) – previous time step

The parameters of the filter were chosen to be sufficient to reduce the onset spike but to retain the characteristics of the wake effects. During a simulation with motion, there still exist small specific forces, but any further filtering could cause unwanted delays or oscillating wake effects. A response to a step input wind of 10 kts is plotted in Figure 4.3.

![Figure 4.3 : Low Pass Filter Effect on Wind Velocity](image)
To demonstrate the positive results of the airwake correction calculations, a piloted approach was recorded and replayed to plot (see Figure 4.4) helicopter surge specific force and airspeed information as the helicopter entered the airwake zone. As is shown, the effect of smoothing the gradually-decreasing airspeed (lower plot) prevents specific-force values of almost 0.5 G (= 5 m/s²) from being transmitted to the simulator cab.

Figure 4.4: Improved Airwake Effects for a Sample Deck Landing Approach
4.2 Sea King Cockpit Noise Improvements

Changes have been made to volume and pitch levels for the hover and cruise channels in response to suggestions made in October 1997 preliminary test flights. There exist simple models for volume and pitch determination based on airspeed and collective control input. There are two noise channels that are digital samples of Sea King cockpit recordings taken in hover and in 120-knot cruise. The channels are played simultaneously but governed by different models (see Figure 4.5) based on pilot recommendations.

The MAX volume indicated refers to the maximum volume from the digital sample (which can also be adjusted by the amplifier as well). The MAX pitch refers to the digital sample pitch, which was thought to be slightly high. As indicated, the hover dominates the total cockpit noise at low airspeeds and cruise dominates at high airspeeds. There is also an adjustment to the pitch of the hover channel as the collective input decreases to levels that would indicate the pilot has brought the helicopter to rest on the frigate deck.
Figure 4.5: Volume and Pitch Effects from Hover and Cruise Cockpit Noise Samples

4.3 CPF Ship Motion

New software has been designed at Defence Research Establishment Atlantic (DREA) to generate six degree-of-freedom motion histories for simulated CPF open water maneuvers. This software package is called TISIM, and it replaces the ship motion data that was generated using the Fredyn 5.0 package developed by the Maritime Research Institute Netherlands. The physical properties of the CPF can be entered into the TISIM variable set, and ship motion data can be generated based on the speed and direction of the ship and wind models. Wave conditions can be set to characterize different levels of sea severity.
Currently only one motion history file is active at UTIAS. An attempt was made to produce ship data representing the limiting conditions for Sea King-CPF freedeck landings (that is, landings not requiring the aid of the RAST system). The conditions limit roll and pitch maximum amplitudes to 10° and 3°, respectively. These limiting conditions correspond to sea state 5, which is usually accompanied by 25-knot wind velocities.

DREA simulations concluded that these roll/pitch conditions could not be met simultaneously in a unidirectional seaway. (Roll angles are high at low ship speeds and in beam seas, while pitch angles are high at high speeds and towards head seas.) The chosen solution models the preferred landing condition of R15-40, which means 15° relative wind from ‘red’ (port) at 40 knots wind-over-deck (25 knots winds plus 16 knots of ship speed). The ship speed used to model these conditions should be maintained in the simulation, whereas the motion is still accurate for a range around the nominal 25-knot wind velocity value used. In most of the deck landing simulations at UTIAS, only a 10-knot wind velocity was used. This kept the helicopter airspeed in the flight envelope for which the Sea King dynamic model was optimized (i.e., below 30 knots airspeed).

Some characteristics of the R15-40 are summarized in the Table 4.1.
Table 4.1: Characteristics of TISIM R15-40 CPF Ship Motion

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind and Sea Direction</td>
<td>360°</td>
</tr>
<tr>
<td>Ship Heading</td>
<td>15°</td>
</tr>
<tr>
<td>Ship Speed</td>
<td>16 knots</td>
</tr>
<tr>
<td>Wave Height</td>
<td>3.25 m</td>
</tr>
<tr>
<td>Wave Period</td>
<td>11.5 s</td>
</tr>
<tr>
<td>RMS Roll Angle</td>
<td>1.0°</td>
</tr>
<tr>
<td>RMS Pitch Angle</td>
<td>1.2°</td>
</tr>
<tr>
<td>Maximum Roll Angle</td>
<td>3.0°</td>
</tr>
<tr>
<td>Maximum Pitch Angle</td>
<td>3.6°</td>
</tr>
</tbody>
</table>

The TISIM dataset that has been implemented at UTIAS is a file containing 30 minutes of data sampled at 5 Hz. This is only meant to be representative, as future, experiment-ready time histories will likely be 10 hours of data sampled at 30 Hz. This will accomodate beginning ship motion simulations at random starting points to ensure that experimental conditions are not distorted by repeatable ship response during a landing approach.

A sample file showing 60 s of ship data is plotted in Figure 4.6 (x (surge), which is positive in the forward direction of the ship, y (sway), which is positive to starboard, and z (heave), which is positive down) and Figure 4.7 (ϕ (roll), positive for starboard down, θ (pitch), positive for bow up, ψ (yaw), positive for heading increase). The x, y, and ψ data are superimposed on the ship translational position from a nominal ship speed and direction. (The nominal values in most simulations were based on the ship speed and heading in Table 4.1.) Note that the magnitude of the heave motion is nearly triple that of the surge and sway effects, and that roll and pitch changes exceed disturbance magnitudes in yaw.
Figure 4.6: Translational Ship Motion Components
Figure 4.7: Rotational Ship Motion Components
Preliminary flight trials using the position data as introduced by either the Fredyn or TISIM software displayed poor helicopter motion characteristics after deck contact was made. Inaccurate motion cues resulted from the execution of GenHel's landing interface modules when even modest ship velocity was simulated. The cues were unrealistic to the point of convincing the test pilot that the helicopter was either bumping on and off the deck or flying above the deck in severe turbulent air.

The problem was found to exist in the implementation of the position data. A linear interpolation of ship position gives a step-like characteristic to the ship velocity values, which are required in the landing gear tire and oleo models. These sharp steps were transmitted to the GenHel flight equations and, thus, to the motion base.

A cubic spline fit was performed on the ship data so that each time step could have an accurate coefficient set to calculate ship velocities. The code for fitting a cubic spline to a dataset was modified from its original form in Reference [13] and is given in Appendix A. The ship data from the TISIM software was read into the program at an update rate of 2.0 Hz (to match the update rate of the cubic spline program, which was coded for the 2.0 Hz Fredyn data). Spline coefficients were calculated for each 0.5 sec interval. The equation for ship position and velocity in any interval is then given by:

\[
p = c_0 + c_1 \Delta t + c_2 \Delta t^2 + c_3 \Delta t^3
\]

\[
\frac{dp}{dt} = c_1 + 2c_2 \Delta t + 3c_3 \Delta t^2
\]

where \( p \) – position variable representing \((x, y, z, \phi, \theta, \psi)\)

\( c_0, c_1, c_2, c_3 \) – coefficient set for each position variable in 0.5 s interval

\( \Delta t \) – time elapsed since the start of each 0.5 s interval
Flight attempts with the above equations proved unsatisfactory, however. Plots of helicopter specific force showed substantial noise when the landing gear was in contact with the ship deck. Close examination of the cubic spline-determined ship position showed near-imperceptible spikes with magnitudes in the order of thousandths of feet. (These tiny irregularities in the position were believed to be inherent flaws in the cubic spline algorithm when dealing with large datasets.) To further aggravate the problem, the errors' order of magnitude increased as the order of magnitude of the position of the ship increased. For example, as the ship x-position passed through 1000 ft, the error moved into hundredths of feet. Though small, these errors were sufficient to cause a vibration in the motion response.

To eliminate this inaccuracy, it was necessary to examine the primary source for transmitting forces in the landing gear model. This was the force due to the displacement in the spring model used to represent the tire and oleo forces. To smooth the ship position and, therefore, the displacement from one iteration to the next, the method of calculating the new ship position at every time step was changed. The cubic spline equation for determining position variables was removed, while the velocity equation was left in place. Since small discontinuities in velocity would be damped out by the viscosity in the landing gear model, a smooth position fit could be calculated by a simple numerical integration of the velocity at any time step. The ship position is thus given by:

\[ p_n = p_{n-1} + p_n \Delta T \]

where \( \Delta T \) - time for each update of GenHel (16.67 ms)

The resulting position information was smoother than the original spline-fitted data, and the effects of the small velocity perturbations were negligible.
4.4 Sea King Rotor Disk Model

The MAXVUE system did not have a generic rotor disk model available for use, but a compromise was made using the Bell-412 image already operational in the MAXVUE image library. (Reprogramming the geometry of the Bell-412 model was not feasible.) Figure 4.8 shows a comparison of the Sea King rotor size (radius \( R_1 \)) and Bell-412 rotor size (radius \( R_2 \)). The radius of the Bell-412 model is 7.1 m, as compared to 9.4 m for the Sea King rotor. To display the most visible section of the rotor disk to the pilot, the hub was moved forward the 2.3 m difference. Though the visible portion of the rotor arc is not accurate, preliminary pilot testing proved the small discrepancy imperceptible.

\[
\begin{align*}
R_1 &= 9.4 \text{ m} \\
R_2 &= 7.1 \text{ m}
\end{align*}
\]

Figure 4.8: Sea King Rotor Disk Model
5.0 Pilot Evaluation

Two experienced helicopter test pilots were asked to evaluate the validity of the Sea King deck landing simulation. Each test pilot had extensive Sea King deck landing experience, both in simulators and actual aircraft, and a minimum of 2000 hours of helicopter flight and 100 hours in helicopter simulators.

Both pilots had the opportunity to assess the simulator systems relating to the Sea King deck landing scenario over a period of two days. Total simulator time was approximately 2-3 hours each. Their comments were recorded and are summarized in the following sections.

5.1 Pilot Controls

Pilot #1 was comfortable with the cyclic control travel and the trim thumb switch rate, but felt the spring force gradient was too low. Pilot #2 thought the location of the cyclic stick was slightly low, the release response too damped, and the stick to be lacking any 'slop' or deadband near the trim point. He also was satisfied with the trim release and the thumb switch functions, but thought that the stick force upon trim release was too light.
As expected from preliminary pilot testing during the HDLS contract in 1996, both pilots felt that the pedal forces were too light and that the restoring effect of the spring was inaccurate. The pilots commented that Sea King tail rotor pedals are much stiffer and heavily-damped.

Pilot #2 felt that the rotation point of the collective control was too close to the handle, but both pilots agreed that the difference in the control motion would have little adverse effect on the simulation.

Improvements in the cyclic control feel were made immediately by changing some of the McFadden control loader parameters. Adjustments were made to the deadband, damping, breakout forces, and spring model until the pilots were satisfied with the cyclic response. Though initial problems were attributed to the breakout force and slope characteristics, it was decided that the original values were satisfactory and breakout modifications are not among the changes indicated in Table 5.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Gradient</td>
<td>0.48 lb/in → 0.96 lb/in</td>
</tr>
<tr>
<td>Longitudinal Viscous Damping</td>
<td>0.26 lb/(in/s) → 0.07 lb/(in/s)</td>
</tr>
<tr>
<td>Lateral Viscous Damping</td>
<td>0.34 lb/(in/s) → 0.15 lb/(in/s)</td>
</tr>
<tr>
<td>Deadband</td>
<td>0 in → ± 0.12 in</td>
</tr>
</tbody>
</table>

Table 5.1: Modified Control Loader Parameters

Though the control loader parameters were optimized as much as possible, there was no way to affect the stick forces upon trim release. Physical properties of the pedals and collective, and the height of the cyclic stick, are unalterable. The flight tests proceeded without difficulty with these properties unchanged.
5.2 FOHMD and Virtual Cockpit

Care was taken to ensure that the pilots adjusted the seat to the optimum Sea King cockpit position. The FOHMD optics were then aligned precisely for each pilot’s eyes and the alignment parameters recorded for subsequent flights. The parameter values are listed in Table 5.2. The ( ) denotes Pilot #2, while all other values are equivalent for both pilots.

<table>
<thead>
<tr>
<th></th>
<th>Left Eye</th>
<th>Right Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spigot Gap</td>
<td>0.23 in (0.365 in)</td>
<td>0.45 in</td>
</tr>
<tr>
<td>Vertical Offset</td>
<td>0.30 in</td>
<td>0.36 in</td>
</tr>
<tr>
<td>Fore-Aft Offset</td>
<td>0.15 in</td>
<td>0.05 in</td>
</tr>
</tbody>
</table>

Table 5.2: FOHMD Alignment Parameters

Each pilot was asked to reposition the cockpit mask relative to his viewpoint. Pilot #1 and Pilot #2 had the mask shifted 17.5 cm down from the CAE-selected eye point, and Pilot #2 chose an additional 10-cm mask shift to the left. These selections have been stored for future reference, and one of the position sets will be defined as the experimental standard. (For the evaluations, each pilot flew with his viewpoint preferences.)

Pilot #1 and Pilot #2 had the same reaction to the relative size of the individual cockpit windows. Both felt that the field-of-view through the windows was too large for three reasons:

1. There were no visual obstructions (like the co-pilot or the pilot’s own knees) to block the view of the front right chin window or the left side window.
2. The top of both chin windows appeared to be too high, thus making the view too unobstructed by the frame between the front and chin windows.
3. Front and side windows appeared too large.

In addition, Pilot #2 observed that the chin window was not curved enough, which gave the false impression of a more pointed fuselage.
During the deck approach, both commented that the field-of-view was excellent in providing adequate approach cues, but the loss of peripheral vision caused by the hangar face in near-deck hover was disconcerting to the pilots.

Though complimenting the out-the-window scene detail, each complained that large head movements to establish the helicopter position over the deck were disorienting. This problem was exemplified by loss of low-hover precision flight whenever the pilots turned to look down through the right-side window to find their fore-aft position in preparation for final touchdown. The pilots pointed out that it is predominantly the responsibility of the co-pilot to direct the fore-aft positioning while the pilot controls the lateral positioning and height above the deck. Similar disorientation problems resulted from quick head motions away from the deck, and Pilot #1 said he could sense the image update lagging behind his head movements.

The pilots had no difficulty distinguishing detail on the EFIS as viewed through the transparent cockpit mask, though Pilot #2 added that the instrument display would be used rarely in the deck landing approach and never in low hover.

Pilot #1 and Pilot #2 found the moving rotor blade model to be sufficient in apparent speed and position relative to the viewpoint.

5.3 CPF and Waterworld Database

Both pilots expressed high praise for the quality of the CPF image, both in approach and near-deck hover. They felt that the visual cues were superior to any simulation they had flown previously and provided good height information for both deck approach and final touchdown. They added that they would prefer a ship wake to be displayed along the water surface to eliminate the sense that the CPF is 'flying' over the surface of the water. It was remarked that improved wave texture would also be a helpful addition.
The pilots commented on the false cues from the pitch and roll horizon bars on the hangar roof. Since they were not moving relative to the CPF, the pilots complained of difficulty in discerning the helicopter orientation in low hover.

After landing on the deck, Pilot #2 stated he felt the viewpoint was too low. He added that the hangar wall seemed too close, but did suggest that the closeness of it might have been influenced by his lack of peripheral vision with the helmet mounted display. Pilot #1 had a sense of closeness to the hangar face and tended to touchdown slightly aft of the optimum deck position. Pilot #2 felt that the visual cues from the hangar face foreground / horizon background were excellent.

5.4 Sea King Cockpit Noise

The pilots disagreed on the quality of the Sea King cockpit noise reproduction. Pilot #1 was satisfied with it, but Pilot #2 was not. He did state, however, that he could not distinguish whether the sound volume and/or pitch was wrong or merely sounded unlike a Sea King due to the dampening effect of a different helmet. Throughout the evaluation, flights took place without mention of positive or negative effects of the cockpit noise.

5.5 Sea King Flight Model

Both pilots had noticeable difficulty in controlling the helicopter's pitch and roll attitude. Each had a first impression that the simulation model's response to cyclic control inputs was not damped enough. They complained of accidental overcontrolling and pilot induced oscillation (PIO) in the Sea King attitude - more pronounced in roll than in pitch - and both stated the
problem was magnified with the loss of the horizon reference upon entering the low hover position. The workload required to maintain near-deck hover was thought to be excessive.

Pilot #1 found that he compensated for the PIO by consciously making fewer cyclic inputs to prevent overcontrolling, making tracking the ship deck difficult.

Pilot #2 performed some control input tests while flying away from the deck in order to determine the accuracy of the flight model. He disliked the yaw coupling effects; while a Sea King should respond to pedal inputs with changes in roll attitude, the simulation incorrectly reacted with pitch changes.

The response of the simulated helicopter attitude to lateral and longitudinal cyclic control step inputs was found to overshoot in both roll and pitch. Pilot #2 felt that the Sea King's automatic flight control system (AFCS) should more accurately model the attitude hold system that a Sea King helicopter utilizes. In addition to the overshoot, it was felt that the new attitude based on a fixed cyclic input stabilized at the wrong value. The overshoot and inaccurate orientation added to the difficulties in roll/pitch control in near-deck hover.

Both pilots felt the heading hold portion of the (AFCS) was adequate in maintaining heading during a normal approach and landing, but should be more effective than was demonstrated for larger cyclic inputs (like the inputs to test roll and pitch attitude overshoot mentioned above). They observed that the yaw response to pedal inputs was appropriate for the commanded pedal inputs. The heave response to collective inputs was judged to be accurate.

(After pilot evaluations were complete, the Sea King AFCS authority was increased from its programmed value of 12% of full control. (This value increases with airspeed to limit some of the model responsiveness at cruise. Reference [8] details the AFCS logic.) The authority increase should dampen some of the roll/pitch response to cyclic control inputs. The testing of the new AFCS has not yet been evaluated.)

Pilot #2 observed that the dynamics of the Sea King model and relevant visual cues were adequate for a simple circuit around the simulated CPF.
The turbulence model was tested. Pilots did notice a difference in the specific forces generated by the motion base, but commented that the overall effect was fairly gentle. They did add that the 10 knot atmospheric wind being simulated would not cause much turbulence, and that the simulated effect was reasonable.

5.6 Motion Cues

With the addition of motion cues, the pilots felt the specific forces transmitted during the touchdown and takeoff were excellent. Pilot #1 thought the feel of the ship motion while stationary on the deck was equivalent to actual CPF motion. Both pilots thought the rumble felt from the motion base after touchdown was incorrect and caused the cockpit window mask to vibrate slightly, but this disturbance was not felt to be distracting. (This vibration seems to be inherent in the landing gear model for translating ship deck landings.)

Pilot #2 did not feel that the motion washout in the roll, pitch, and yaw axes was accurate. He found the transmitted angular motion cues to be jerky. He also complained of slight motion sickness when the motion base was being used.

The PIO problems were reduced with the addition of motion cues, but remained a distraction to the pilots. Both pilots suggested that the roll motion cue in detecting helicopter orientation was poor.

As the evaluations progressed, the pilots began to complain of random bumps from the motion base unrelated to their control inputs. Pilot #1 identified them as yaw disturbances, while Pilot #2 felt thumps in both the heave and yaw directions during a deck approach. The motion base disturbances in yaw were traced to a faulty potentiometer measuring the pedal displacement in the simulator cab. This inadvertent noise on the pedal control channel resulted in false motion cues. The potentiometer has been replaced and normal operation resumed.
5.7 Deck Contact

There existed problems with helicopter movement relative to the deck after touchdown. Some of the landings resulted in a forward slide toward the hangar face, forcing the pilots to react by lifting off. Not all landings had this result, but it appeared that relative translational velocity between the helicopter and ship at touchdown aggravated the inaccuracy. Pilot #2 had a tendency to touchdown with a slightly higher descent rate than did Pilot #1, and more of his landings resulted in the post-touchdown slide problem.

An error was discovered in the calculation of the tire frictional forces that caused, rather than prevented, tire slide across the deck. The landing interface model correctly restricted relative helicopter motion in the tire deformation equations, but the frictional force direction error magnified any touchdown translational speeds. Therefore, landings with speeds below which the deformation equations could bring the motion to zero were adequate. The tire forces were corrected and the deck sliding problem cleared up.

Pilot #2 recommended that the crash protection coded in the GenHel flight model be loosened in its restriction of descent rate. He remarked that the 500 ft/min descent rate limit in the Sea King landing simulations was too easy to hit during the last stages of the deck landing process. (He pointed out that touchdowns at the Sea King operational limit of 480 ft/min descent are not uncommon.) The GenHel software crash protection descent rate limit has been changed to 600 ft/min from 500 ft/min) to accommodate harder landings on the moving ship deck.

5.8 CPF Ship Motion

Pilot response with different levels of ship motion was predictable. Each pilot attempted landings at 20%, 50%, and 100% of the CPF heave, roll, and pitch response for the ship motion
file detailed in Section 4.3. (The comparatively small surge, sway, and yaw magnitudes were left at their TISIM values during all simulations with ship motion.) Expectedly, the pilots had increasing difficulty in tracking the ship deck. Pilot #1 in particular commented on the perceived difficulty in predicting a ship quiescent period for a safe touchdown. The pilots recommended the 50% freedeck-limit CPF state for future experimental work.

5.9 Sample Approach

To have a reference deck approach and landing, each pilot was asked to perform what he considered to be a normal approach and touchdown. The results were recorded. Since Pilot #2 chose a slower approach to a comfortable hover position astern and to the port of the CPF, the flight path data was shifted so that the starting times coincided. Figure 5.1 shows a top view of the x-y approach path. Figure 5.2 shows the (x,y,z) components of the helicopter centre-of-gravity relative to the (x,y,z) components of the optimum touchdown point (i.e., the centre of the trap).

Figure 5.1: Sea King-CPF Approach Path for Sample Deck Approach and Landing (Top View)
Figure 5.2: Sea King-CPF Relative Positions for Sample Deck Approach and Landing
6.0 Conclusions

The integration of the GenHel flight dynamics software into the UTIAS simulator and under SIMex-PLUS software authority has been achieved. The software interface to the MAXVUE image generator, single board computer, and digital instrument display has been completed. The real-time execution of the flight equations and nonreal-time user interface have been programmed for simulations with recorded or pilot control inputs.

The helicopter model has been improved with the addition of filters to the ship superstructure airwake disturbance near the ship deck, adjustments to the Sea King cockpit noise, and the addition of a moving rotor disk display. Canadian Patrol Frigate motion time histories have been linked into the flight model and image generator, and the position/orientation values have been smoothed to improve the deck contact characteristics.

The simulation now includes an advanced flight dynamics program that models the response of a Sea King helicopter in a simulated database with a high-resolution image of a CPF at sea displayed on a stereoscopic helmet mounted display. An electronic flight instrument display, a representation of Sea King cockpit sound, the force-feel characteristics of cyclic, collective, and pedal controls, and six degree-of-freedom motion are used to enhance the realism of the virtual cockpit.
Test pilots have evaluated the simulation and analyzed some of its features. They gave useful input into the position and response of the pilot controls, the position of the viewpoint and windows within the virtual cockpit, and the expected view from the deck landing position. They suggested significant changes to the Sea King flight control system, but were nonetheless impressed with some aspects of the simulation such as the moving CPF image, the landing deck detail, and the feel of the simulation touchdown and takeoff. For future experimental reference, they have recorded deck landings at their recommended level of ship motion.

Further work on the deck landing simulation should include additional modifications to improve the fidelity of the Sea King-CPF simulation. Based on pilot recommendations and other deck landing experimental issues, some of the following will be implemented in further work at UTIAS:

- a reprogramming of the CAE-developed Sea King cockpit window mask installed on the MAXVUE image generator to adjust for pilot complaints of exaggerated field-of-view and inaccurate fuselage shape
- testing of increased Sea King model AFCS authority. Should the increase not be sufficient, more sophisticated alterations to the cyclic control damping and heading hold parameters will be analyzed.
- the addition of a moving map display that will allow the simulator operator to handle the copilot interactions in directing the fore-aft position of the helicopter over the deck
- a repositioning of the ship away from the visual influence of the islands, increasing the detail of the wave texture and/or creating a ship wake to show the CPF path
- the addition of moving pitch and roll horizon bars to improve low hover visual cueing
- a review of the landing gear equations and CPF deck parameters to correct the height of the viewpoint above the deck surface
- smoothing of the motion base vibrations during contact with the ship deck
- an improved user interface, so as to allow easy initialization and real-time control of helicopter flight parameters, environmental conditions, and frigate motion
- the addition of collision detection to notify the pilot and/or user if the helicopter rotor blade makes contact with the CPF hangar or superstructure
- the creation of new TISIM ship motion data to approximate the 50% freedeck limits that the test pilots recommended
References


Appendix A

Cubic Spline Routine for Fitting TISIM Ship Motion Data
program cubic_spline

real xi(3600), c(4,3600)

open(1, file='SHIP.DAT', form='formatted')

read(1,*) n1
read(1,*) (xi(i), c(1,i), i=1,n1), c(2,1), c(2,n1)
n = n1 - 1

call spline(n, xi, c)
call calccf(n, xi, c)

open(2, file='COEFS.DAT', form='formatted')
write(2,501) (xi(i), c(1,i), c(2,i), c(3,i), c(4,i), i=1,n1)
501 format(5E12.5)

open(3, file='FUNCTION', form='formatted')
x = xi(1)
do 10 j=1,3600
   fx = pcubic(x,n1-1,xi,c)
   fxx = pcubic2(x,n1-1,xi,c)
   write(3,*) x, fx, fxx
10 x=x+0.1
end

subroutine spline(n, xi, c)
dimension xi(3600), c(4,3600), d(3600), diag(3600)
data diag(1), d(1) /1.0, 0.0/
npl = n+1
do 10 m=2,npl
   d(m) = xi(m) - xi(m-1)
10 diag(m) = (c(1,m) - c(1,m-1))/d(m)
do 20 m=2,n
   c(2,m) = 3.0*(d(m)*diag(m+1)+d(m+1)*diag(m))
20 diag(m) = 2.0*(d(m) + d(m+1))
do 30 m=2,n
   g = -d(m+1)/diag(m-1)
   diag(m) = diag(m) + g*d(m-1)
30 c(2,m) = c(2,m) + g*c(2,m-1)
nj = npl
do 40 m=2,n
   nj = nj - 1
40 c(2,nj) = (c(2,nj)-d(nj)*c(2,nj+1))/diag(nj)
return
end

subroutine calccf(n, xi, c)
dimension xi(3600), c(4,3600)
do 10 i=1,n
   dx = xi(i+1) - xi(i)
   divdf1 = (c(1,i+1) - c(1,i))/dx
   divdf3 = c(2,i) + c(2,i+1) - 2*divdf1
   c(3,i) = (divdf1 - c(2,i) - divdf3)/dx
10 c(4,i) = divdf3/dx/dx
return
function pcubic(xbar,n,xi,c)

dimension xi(9000),c(4,9000)
data i /1/

dx = xbar - xi(i)
if (dx) 10,30,20

10 if (i .eq. 1) goto 30

i = i-1
dx = xbar - xi(i)
if (dx) 10,30,30

19 i = i+1
dx = ddx

20 if (i .eq. n) goto 30
ddx = xbar - xi(i+1)

19 if (ddx) 30,19,19

30 pcubic = c(1,i) + dx*(c(2,i)+dx*(c(3,i)+dx*c(4,i)))

return
end

function pcubic2(xbar,n,xi,c)

dimension xi(9000),c(4,9000)
data i /1/

dx = xbar - xi(i)
if (dx) 10,30,20

10 if (i .eq. 1) goto 30

i = i-1
dx = xbar - xi(i)
if (dx) 10,30,30

19 i = i+1
dx = ddx

20 if (i .eq. n) goto 30
ddx = xbar - xi(i+1)

19 if (ddx) 30,19,19

30 pcubic2 = c(2,i)+2*dx*c(3,i)+3*dx**2*c(4,i)

return
end