FURTHER VALIDATION OF SIMULATED DYNAMIC INTERFACE TESTING TECHNIQUES AS A TOOL IN THE FORECASTING OF AIR VEHICLE DECK LIMITS

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ABSTRACT

Validation results are discussed and compared in confirming the tendency of certain parameters being well represented by simulation with the actual at sea result. The primary objective of this field of study is to determine the feasibility of applying full motion simulators and plug and play simulations in support of dynamic interface at-sea testing and experimentation. Several years of simulated flight test programs using the Merlin CAE Trainer System at RNAS Culdrose (UK) and the Manned Flight Simulator at Naval Air System Command, Aircraft Division at Patuxent River, Maryland have been conducted. A typical simulation consists of modular "plug and play" components contributed by the project participants assembled in a High Level Architecture (HLA) with the combined components reflecting the ship environment, the long and short term prediction methodologies and the ship's response mechanism. The use of 6 degree-of freedom motion flight simulator to forecast physical deck motion and deck motion limits, is discussed.

In the manned version, the simulated flight test has five essential objectives: assess the capabilities of the Cockpit Dynamic Simulator (CDS) to support Ship-Helicopter Operational Limit (SHOL) / Naval Air Training and Operating Procedures Standardization (NATOPS) limits; demonstrate High Level Architecture (HLA) with selected modules; and determine feasibility of applying these simulators in support of dynamic interface at sea testing. The unmanned and manned systems studied focused on specific simulated aircraft-ship interface responses. An application of this simulation is the forecast of deck limits computed by the motion characterization of a platform in terms of, and as a function of, the deflection of landing gear configured for vertical landing aircraft or rolling vertical landing. At-sea validation study results are discussed and compared with simulated scenarios. This computational method employs sufficient performance criteria and correlates well with forecasted quiescent windows of deck motion.

Results are presented in relation to the deck stability problems normally confronted by a helicopter during recovery in progressively difficult conditions. A brief synopsis of several of the integrated HLA modules representing various aspects of the maritime environment is presented.

ABBREVIATIONS

AGL	Above Ground Level
AO FNC	Autonomous Operations Future Naval Capabilities
ASIST	Aircraft/Ship Integrated Secure and Traverse System also RSD
BRC	Base Recovery Course
CBT	Computer Based Training
CD	Clear Deck
CDS	Cockpit Dynamic Simulator
DDG	Guided Missile Destroyer
DI	Dynamic Interface Study
DIPES	Deck Interface Pilot Effort Scale
DLQ	Deck Landing Qualification
DOF	Degree-of-freedom
EI	Energy Index (Value calculated by LPD)
FD	Free Deck Recovery (RAST trap used only)
FDO	Flight Deck Officer
GCA	Ground Controlled Approach
GUI	Graphical User Interface
HARPOON	helicopter handling Sys (UK,USCG)
HCO	Helicopter Control Officer
HLA	High Level Architecture
HSL	Helicopter (Attack) Squadron Light
KIAS	Knots Indicated Airspeed
LCAC	Landing Craft Air Cushion
LPD	Landing Period Designator
LPDLOOP	Landing Period Designator software
LSE	Landing Signal Enlisted
LSO	Landing Signal Officer
MFS	Manned Flight Simulator
MRU	Motion Reference Unit
MST	Mechanical Systems Trainer
NATOPS	Naval Air Training and Operating Procedures Standardization
NAV11	Landing Period Designator software
NIREUS NATO	Interoperability and RE-Use Study
NVG	Night Vision Goggles
ONR	Office of Naval Research
PCCS	Portable Computer Control Station
PTT	Part Task Trainer
RA	Recovery Assist
RAO	Response Amplitude Operator
RAST	Recovery, Assist, Securing and Traversing
RCT	Rear Crew Trainers
RN	Royal Navy (UK)
RNAS	Royal Navy Air Station (UK)
RSD	Rapid Securing Device (also ASIST)
RTI	Run Time Infrastructure
SAIF	Ship/Air Interface Framework
SAMAHE	Helicopter Handling Sys (France)
SHOL	Ship-Helicopter Operational Limit
SMP	Ship Motion Program

SMS	Ship Motion Simulation composed of routines identified as NAV
SSD	Sea Systems Directorate
TCS	Tactical Control Station
TD	Test Director
TP	Test Pilot
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UUV	Unmanned Undersea Vehicle
VLA	Visual Landing Aid
VMC	Visual Meteorological Conditions
VTOL	Vertical Takeoff and Landing
VTUAV	Vertical takeoff and Landing Unmanned Air Vehicle
WOD	Wind-over-deck
WST	Weapon Systems Trainer

INTRODUCTION

Office of Naval Research (ONR)'s Landing Period Designator (LPD) project is part of its Autonomous Operations Future Naval Capabilities (AO FNC) Unmanned Aerial Vehicle (UAV) Technology program. Autonomous Operations (AO), one of twelve Future Naval Capabilities programs, is the capability of performing missions using unmanned vehicles in dynamic and unstructured environments with greatly reduced need for human intervention. Autonomous Operations supports three major communities: UAVs, Unmanned Undersea Vehicles (UUVs) and Unmanned Ground Vehicles (UGVs). This project is part of the UAV Autonomy program which includes intelligent reasoning for autonomy, technologies to enhance see and avoid capabilities, object identification, vehicle awareness, vehicle and mission management, and shipboard landing capability. Its primary transition target is the Vertical Take-Off and Landing Tactical UAV (VTUAV) and the Tactical Control System (TCS), with an eye to the envisioned future programs on the Naval UAV Long Range Plan. The LPD system will support the effort to increase shipboard landing capability of vertical takeoff UAVs. Technologies were targeted which would address the Enabling Capabilities (ECs) that were specific to Naval Autonomous Unmanned Vehicles Mission Needs. LPD was selected because this product directly addressed an Objective Operational Requirement. Additionally, it was anticipated that the LPD would be useful across many Unmanned and Manned air vehicle types and it would be able to interface with all ship classes.

U.K. DEFENCE EQUIPMENT & SUPPORT Organisation (DE&S)

In the United Kingdom, the LPD tool is a promising technology improvement project within the Directorate Safety and Engineering, Sea Systems Group (SSG), Simulation Based Acquisition program.

DE&S equips and supports the UK's armed forces for current and future operations. It employs about 20, 000 people with an annual budget of about £11 billion, its Headquarters is located in Bristol with other sites strategically located across the UK and overseas. DE&S acquires and supports equipment and services for ships, aircraft, vehicles and weapons, along with information systems and satellite communications. In addition, DE&S acquires sustaining and ongoing requirements of food, clothing, medical supplies and temporary accommodation. It is also responsible for HM Naval Bases, the joint supply chain and British Forces Post Office (BFPO). DE&S works closely with industry through partnering agreements and private finance initiatives in accordance with the Defence Industrial Strategy (DIS) to seek and deliver effective solutions for defence.

The Simulation Based Acquisition program is a component of the Sea Systems Group whose mission is to provide whole ship and submarine safety and engineering services to a wide range of customers within the MoD and the naval construction industry of the UK.

Simulation technologies continue to evolve and can now offer a cost effective means of supporting many stages of the Defence Equipment Acquisition Lifecycle. Many complex interactions between systems, operators and phenomena such as ship air wake and ship hydrodynamic flow fields can be accurately predicted, allowing many scenarios to be examined in a ‘virtual environment’ that could never be contemplated using traditional methods.

Simulation investment in the earlier stages of a project can ensure that the project is sufficiently de-risked before the major investment decisions are made. In addition to system performance prediction and risk reduction in the early stages, further benefits are realised if the same simulation technology can be pulled through to support training and in-service activities.

The sharing and re-use of simulation components and resources between nations makes the technology much more affordable. NATO Sub Group 61 is studying how this concept could be fostered by the introduction of new simulation standards.

A number of DE&S naval projects have been working closely with Sea Systems Group to identify suitable applications and are leading the world in re-using key simulation components such as air wake, ship motion and LPD.

-Experimental / Simulated Dynamic Interface

It is important to develop options to reduce the cost and cycle time associated with the test and evaluation process, to enhance the productivity of flight test team members, and to improve the safety of flight test operations, especially in adverse environments. Flight testing is required in both land based and sea based environments with a variety of test aircraft and ships. Simulation is often listed as one option with the potential to help reduce the cost associated with flight testing **[1]**. The simulation of helicopter operations from naval vessels provides a unique set of challenges.

As described in earlier articles **[2]** simulated dynamic interface strategies have been developed over a number of simulation programs. The earliest High Level Architecture (HLA) simulation was called NIREUS (NATO Interoperability and RE-Use Study) which was followed by the SAIF (Ship/Air Interface Framework) programs. The purpose of these complex programs is to use the HLA standards to integrate air vehicle simulations, ship simulations and environment models to aid assessment of the dynamic interface for a range of helicopter / ship and UAV / ship combinations. The initial phase of the SAIF program has been focusing upon SHOL prediction where operations may involve recovery in, amongst other environmental factors, high levels of turbulence to new naval vessels. Primary future SAIF objective is to use the simulation to minimise the time and cost required for first of class sea trials for ships operating Merlin and Wildcat air vehicles.

This report updates the comparative tests made in the Manned Flight Simulator (MFS) in the US and Merlin Trainer Simulator in the UK designed to evaluate simulator uses to support Ship Helicopter Operating Limits (SHOL) analysis for manned and unmanned rotorcraft. The purpose of conducting these tests independently is two-fold. First, dynamic interface activities are defined as they apply to SHOL tests and aircraft/ship dynamic interface expertise and analysis. Second, to provide a platform to test devices like the LPD software to demonstrate the aid; for example, to signal the initiation of helicopter launch and recovery. The objective is to recover the aircraft aboard a moving vessel within reasonable safety margins regardless of the seaway. The report details the technical results of simulated launch and recovery events using full motion simulators which is compared to the same events at sea. This report assesses aircraft and deck availability improvements by using the Energy Index (EI) to signal the top of recovery. Percent of improvement for operational availability is demonstrated. Preliminary discussions on how the results were validated at-sea complete the article.

HELICOPTER-SHIP LAUNCH AND RECOVERY

DYNAMIC INTERFACE

Dynamic Interface is defined as the study of the relationship between an air vehicle and a moving platform. It is performed to reduce risks and maximize operational flexibility [Healey, 1982]. Globally, DI is concerned with the effects that one free body has in respect to another. Historically, this means the effects that a ship may have on a recovering or launching air vehicle. However, recent studies have concluded that the same principles apply to other motion related activities, such as, the boarding of Landing Craft vessels or LCACs into the wells of Amphibious Warfare Ships, the docking of submarines or the launching of unsophisticated missiles.

Dynamic Interface is divided into two broad categories: experimental or at-sea measurement and analysis, and analytical which is concerned with mathematical analysis and solution [Ferrier, B. & Semenza, J., 1990]. The methods are not mutually exclusive. Neither method alone can produce a comprehensive and timely solution of the DI problem.

The traditional approach is experimental DI. It investigates operational launch and recovery of vehicles, engaging and disengaging of rotors, vertical replenishment and helicopter in-flight refuelling envelopes. "Shipboard suitability testing" assesses the adequacy, effectiveness, and safety of shipboard aviation. Testing methodologies and procedures have been standardized by laboratories, such as NAWCAD (Patuxent River) assisted by NSWC (Carderock), and Qinetiq

(Boscombe Down). While experimental testing has numerous objectives, the primary focus is on launch and recovery envelope development and expansion.

United States Navy

The procedures for launching and recovering various helicopter types aboard a ship can be differentiated on whether the helicopter handling system is present and used (Rapid Securing Device (RSD) and whether the launch or recovery will occur in day Visual Meteorological Conditions (VMC), night VMC, or in Instrument Meteorological Conditions (IMC) with Night Vision Device (NVD) launch and recoveries being a subset of VMC launch and recoveries. Ships containing helicopter recovery systems have three deck configurations for recovering a helicopter aboard a small deck: clear deck, free deck; and Recovery Assist (RA).

A clear deck landing means the RSD is stowed and the helicopter will be landing without the use of the RSD or RA systems. A free deck landing means the RSD is positioned in the landing area, the pilot flies the helicopter to a position above the RSD, and lands the helicopter, placing the RA probe into the RSD which is then used to secure the helicopter to the deck of the ship (Figure 1). Lastly, to execute an RA landing, the pilot flies to and establishes a hover over the flight deck. From the aircraft, the RA probe is then lowered to the flight deck via a messenger cable. Flight deck personnel attach the RA cable to the RA probe, which is then reeled back up to the aircraft and secured. Once the RA cable is secured to the aircraft, the ship establishes hover tension (850 to 2000 lbs) onto the RA system which stabilizes the aircraft over the RSD. When the pilot is ready to land, the ship selects maximum tension (4000 lbs), which hauls the aircraft down into the RSD. The RSD then clamps around the RA probe, securing the aircraft to the flight deck.

FIG.1 – SH-60 AND RSD TRAP

The distinguishing characteristic between an approach flown to a small deck in day VMC, night VMC, or day and night IMC is the approach profile flown by the aircraft. A day VMC approach (Figure 2) is commenced from at least 1.5 nm behind the ship at not less than 200 ft above ground level (AGL) at approximately 80 Knots Indicated Airspeed (KIAS) heading along the ship's base recovery course (BRC).

The pilot then flies toward the stern of the ship, aligning his approach path with the ship's line-up line meeting a series of altitude and range gates that terminates with the aircraft at one-quarter nm and 125 ft AGL astern the ship with a closure rate suitable for the given conditions. The closure rate (the difference between aircraft ground speed and the ship's speed of advance) depends on several factors such as sea state, ship motion and visibility. During a night VMC approach, the pilot flies to a point at least 1.2 nm behind the ship at 400 ft AGL at 80 KIAS aligned with the ship's BRC (Figure 2).

The pilot then flies to intercept the stabilized glideslope indicator (SGSI) green/amber interface and maintains glideslope to arrive behind the stern of the ship at a suitable closure rate (Figure 3). An IMC approach is flown much like a Ground Controlled Approach (GCA) at any suitably equipped airfield. A controller aboard the ship will guide the pilot to a point astern of the ship by providing heading and altitude commands. Unlike an approach to an airfield, however, the pilot slows his rate of closure as the aircraft approaches the stern of the ship.

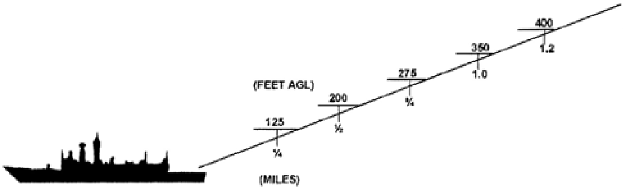


FIG.2 – SMALL DECK NORMAL NIGHT APPROACH PROFILE

AMBER-RED INTERFACE CROSS REFERENCES*	
DISTANCE (nm)	ALTIMETER (ft above water)
1	350
3/4	275
1/2	200
1/4	125

*SGSI-to-water distance is 45 ft (typical FF/FFG/CG)

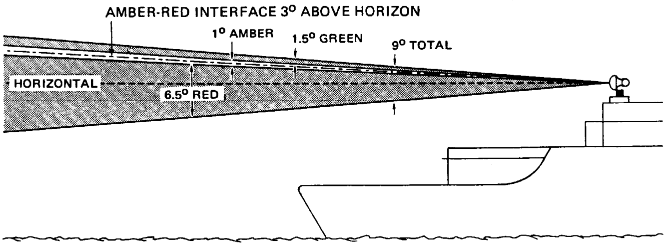


FIG.3 – STABILIZED GLIDESLOPE BEAM

Regardless of the initial approach profile flown, the final phase of the approach to landing aboard ship is flown purely using visual cues.

Royal Navy into Wind Port Approach

The Royal Navy conducts two distinct approach profiles for landing aboard a vessel underway; forward facing (from both port and starboard) and into-wind. As the into-wind approach has many similarities to the standard USN flight profile, this paragraph will concentrate on the forward facing profile, in particular port approach. The aim of the forward facing port approach is to fly a constant angle approach to a point slightly behind and above the flight deck (Figure 4). Particularly at night, the profile is commenced from a 'gate' position - nm astern the vessel on the Red-165 (Port side 165° from ship's head) at 125 ft and 60 kts groundspeed (min 40 KIAS to max 80 KIAS).

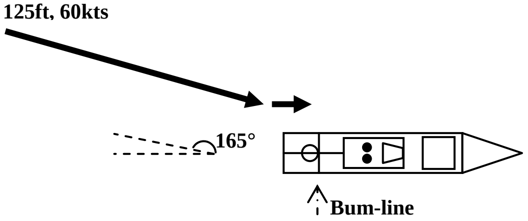


FIG.4 – PORT APPROACH FORWARD FACING LANDING

From the gate position a controlled approach is conducted with a progressive descent and deceleration to arrive at a point slightly behind and above the flight deck in a slow hover taxi; at night the approach angle is supplemented by a 3° Glide Path Indicator. The aircraft is then taxied forward the last 10 yards, on the same heading as the ship's heading, while ensuring there is approximately one rotor span lateral clearance between the rotor disc and the flight deck. The aircraft is thus brought to the hover with the pilot sitting abeam the bum-line, one rotor span laterally and 10-15 ft vertically displaced from the flight deck (Figure 5). The bum-line is used as a reference to prevent any fore and aft drift with respect to the flight deck. Once in the hover, and if possible during the approach, the deck motion is assessed to determine the frequency and severity of motion. This allows the pilot the opportunity of predicting a suitable quiescent period for landing. If a suitable quiescent period can not be forecast, the ships course and speed may be altered to provide more favourable flight operation conditions.

FIG.5 – MERLIN ON T45 DESTROYER

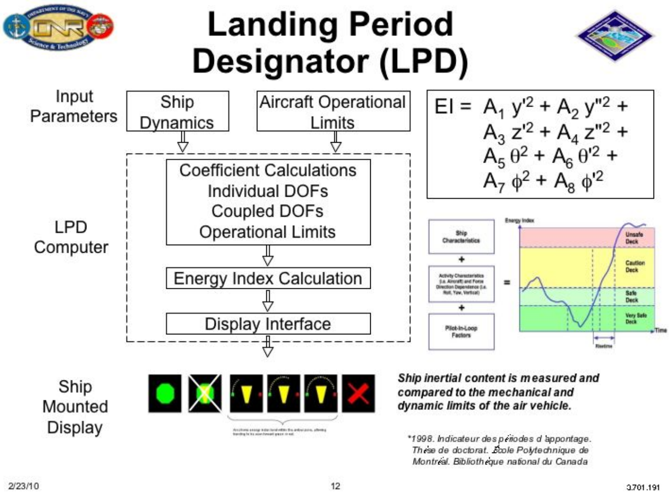
Once it is assessed that a quiescent period is approaching, the aircraft is moved laterally along the bum-line until in a hover over the centre of the flight deck at 10-15 ft. The aircraft is then descended vertically, with no drift, aiming for a firm, but not heavy, landing.

Energy Index Measurement/Metric

In order for the helicopter to operate to the deck without a deck officer, it needs to know what the ship is doing now and what it will be doing during the final descent to touchdown. The Ship Motion Forward Prediction Federate, based on the LPD EI algorithm, is designed to identify quiescent periods of ship motion suitable for the recovery of the helicopter. The algorithm uses real-time information on what the ship is doing, permitting a computation on what it may be doing in the very near future. The LPD essentially performs the function of an experienced LSO, but without the guesswork.

The EI algorithm was integrated into the HLA using a software wrapper. This wrapper enables the LPD unit to exchange data with the other modelling components. The aircraft limits, which form part of the initialization data used during HLA start up, are expressed as the ship's EI. The EI value is correlated to the level of kinetic and potential energy contained in the ship. The ship can only displace from a very low energy state to an aircraft out-of-limit condition by the introduction of a certain quantity of energy from the sea. When the index is low the ship is stable and the ship motion is small. When the index value is below the high-risk threshold, the landing deck motion is acceptable for aircraft recovery.

The thresholds of the various energy levels are directly based on the combination of ship characteristics (measured) and aircraft limitations (defined). A limit is defined by the impact that a certain ship motion condition may impose on the structural integrity or dynamic response of a given helicopter. The sum of these limits produces a red line that is drawn on the EI scale for a given ship (see Figure 6).



Landing Period Designator (LPD)

Input Parameters

Ship Dynamics

Aircraft Operational Limits

$$EI = A_1\,y'^2 + A_2\,y''^2 + A_3\,z'^2 + A_4\,z''^2 + A_5\,\theta^2 + A_6\,\theta'^2 + A_7\,\phi^2 + A_8\,\phi'^2$$

LPD Computer

Coefficient Calculations
Individual DOFs
Coupled DOFs
Operational Limits

Energy Index Calculation

Display Interface

Ship Mounted Display

Ship inertial content is measured and compared to the mechanical and dynamic limits of the air vehicle.

**1998. Indicateur des périodes d'appontage. Thèse de doctorat. École Polytechnique de Montréal. Bibliothèque national du Canada*

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FIG.6 – DECK STATUS AND RISETIME

The time required for the deck motion to rise from minimal motion (or very safe deck) to unacceptable motion is called the risetime. In terms of the EI scale, the risetime is defined as the period of time that is measured from the end of a green signal to the positive side of the red line. This is given as ($T_3 – T_1$) as shown on Figure 6. The risetime is a thumb print characteristic of the ship's response and remains fairly constant for each ship class.

The very safe deck is a special condition in which there is insufficient energy in the aircraft-ship system to raise the deck out of limit for some defined time period or risetime, and it is this concept that was used in the simulators to indicate that the deck was safe to initiate landing.

By employing deck quiescence as the metric for aircraft recovery, deck limits expressed as a static value become redundant. The EI LPD software (LPDLOOP or NAV11) is used to assess deck energies as a function of the mechanical and dynamic limits of an air vehicle. Quiescent periods are identified by which an operator or computer may signal the pilot or UAV AFCS to descend. The recorded or computed motion time histories containing the corresponding EI results, were evaluated. Each green deck point was analyzed. Theoretically, any green deck point could serve for the initiation of recovery. Assuming that the rise time for a given vessel remains constant, the aircraft descends within the rise time value and the aircraft is assured a recovery within the deck motion limits. Essentially, the methodology summarized above is a formulation to quantify operating beyond the static deck limits as defined in NATOPS or SHOL. Figure 7 displays graphically beyond static limit operations. The base envelope is taken from 10 knots of ship speed. As before, any points within the hour-glass structure are conditions within limits and contain no appreciable probability of out-of-limit deck motions. Outside of the structure contains motions which are considered by static reference as out-of-limit.

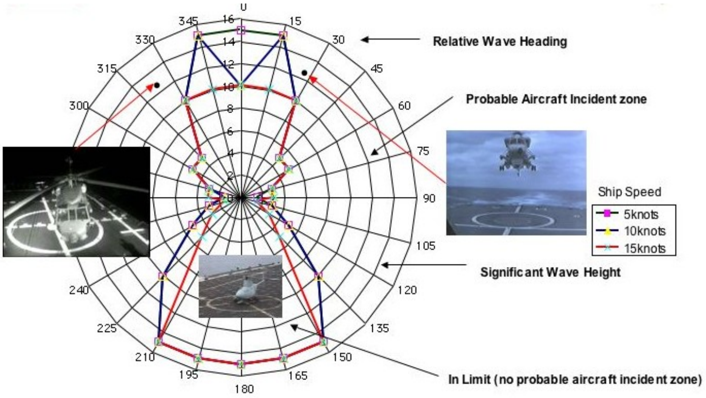


FIG.7 – SAFE MOTION OPERATIONS

A schematic representation of how the LPD is used for UAV auto recovery to signal the onset of the descent (and of deck quiescence) is displayed in Figure 8. Throughout the approach and initial hover (M_1), LPD is monitoring the deck. It is only at the M_0 position (low hover) that the UAV autoland system would accept a Green Deck signal from the LPD. The recovery can occur at any point within the green zone as indicated by the “signal to the top” arrow on the EI trace. In a fully functional autoland program, should the vehicle be in a descent at an unsafe deck point, a signal would be sent to the Landing Algorithm Federate to stop or abort the recovery[7].

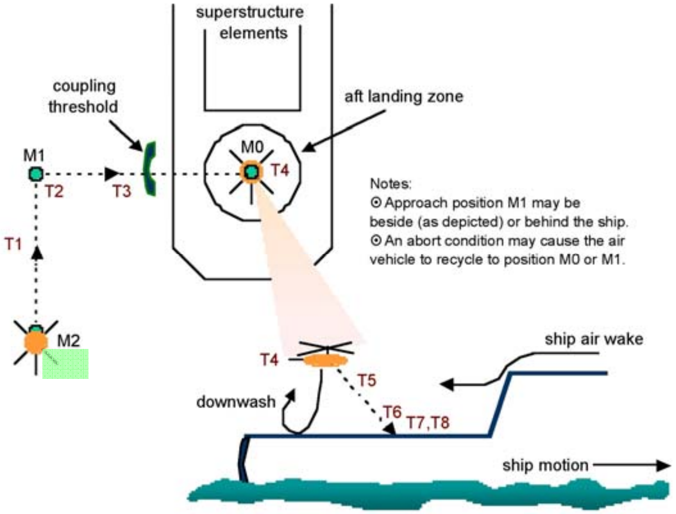


FIG.8 – LPD APPLICATION IN NIREUS

The position of M0 is not fixed but input as the part of the initialization data for the HLA federation.

Simulated Dynamic Interface System

To house the dynamic interface programs, existing flight simulators are used with external federate models. These are introduced to provide ship and environment functionality such as real time representation of ship motion and the air wake flow field. Each external federate function can then be introduced and run on a remote computer, separate from the core flight simulator. A key objective is to provide a system capable of conducting SHOL assessments during ship development and prior to sea trials. It is envisaged that a cost-effective combination of simulation and first-of-class flight trials at sea will maximize the operating envelope for the various new ship platforms from which a manned or unmanned rotorcraft is intended to operate. Real-life flight trials are expensive operations and are also limited by the prevailing weather conditions available for the duration of the test period.

Whether a simulation represents an unmanned or manned system, the system must be capable of accurately responding in a variety of environmental conditions. The easiest is to evaluate the device in a closed and controlled environment. The primary difference between a manned and unmanned system revolves around pilot driven commands and controls. The pilot is represented in the simulated UAV system by a series of flight laws and mission commands. The primary elements of the imagined UAV system are generalized: UAV, Data Link, Tactical Command Station (TCS), Portable Computer Control Station (PCCS), and traverser and landing grid, and an automatic recovery system. Each of these systems are federates along with the simulated environment which were also composed of federates.

A typical HLA design defines 6 separate federates (Figure 9), connected via the HLA Run-time Infrastructure (RTI) software. The structure is applicable to either a manned or unmanned scenario.

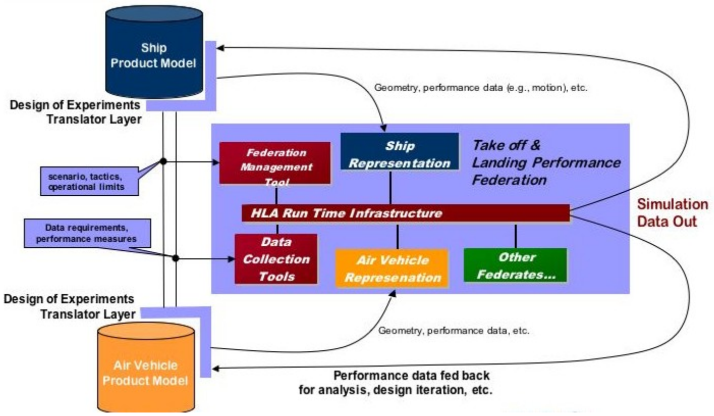


FIG.9 – FEDERATION ARCHITECTURE

The initial software package was designed to use a full motion simulator (in the manned case) and a TCS (in the UAV case), to estimate system effectiveness as a function of simulated ship motion, visual environment and synthetic operational systems, and to compare the results to related analytic data [2].

By discipline the Federation is reduced to Figure 10.

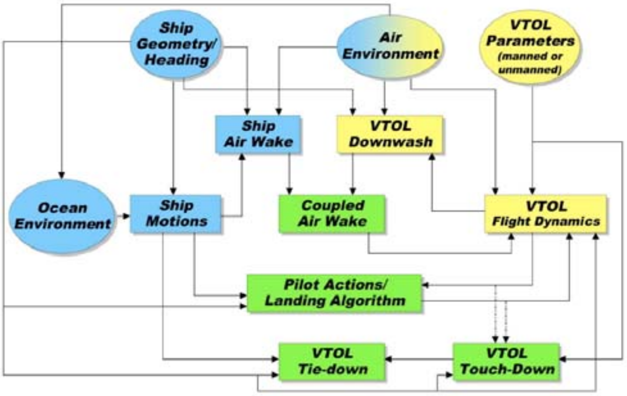


FIG.10 – HLA FEDERATION BY DISCIPLINE

As displayed in Figure 11, the UAV Tactical Control Station federate is integrated to the federation though gateways at the Inertial Navigation, Tracking Sensors and the operator control station. When the air vehicle is hovering in the appropriate position for recovery, the EI signals the onset of quiescence and through the uplink sets the air vehicle on its descent to the deck.

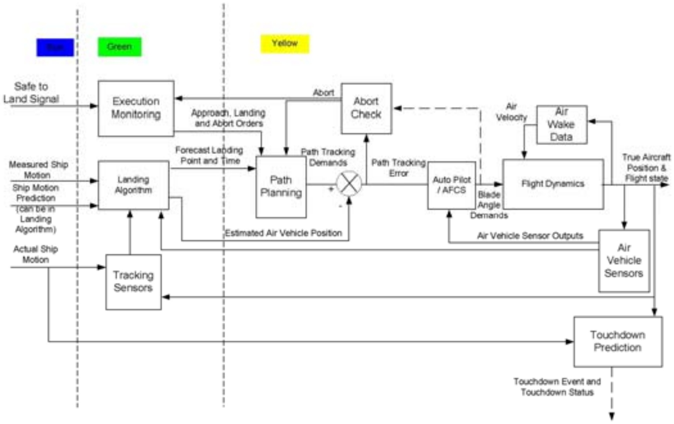
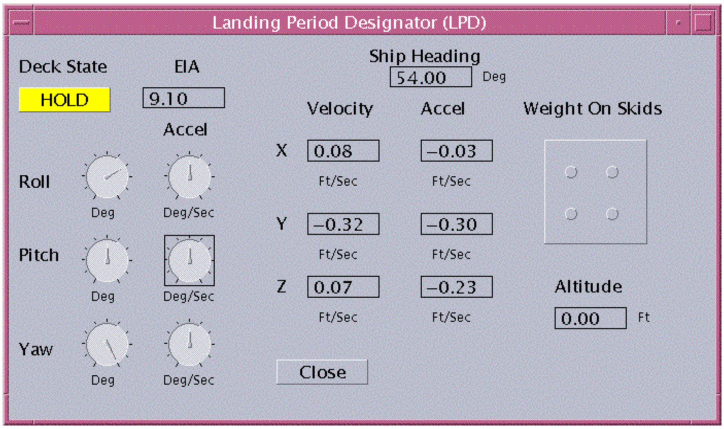


FIG.11 – AUTOLAND CONCEPT

Figure 12 displays the basic TCS Monitor graphical user interface (GUI) which displays the EI and colour land command.


Landing Period Designator (LPD)

Deck State: HOLD

EIA: 9.10

Ship Heading: 54.00 Deg

	Velocity	Accel
X	0.08 Ft/Sec	−0.03 Ft/Sec
Y	−0.32 Ft/Sec	−0.30 Ft/Sec
Z	0.07 Ft/Sec	−0.23 Ft/Sec

Altitude: 0.00 Ft

FIG.12 – UAV DECK MONITOR GUI

In the manned version, the test bed at RNAS Culdrose (which mirrors that of the US MFS) is essentially an HLA simulator. The Merlin Simulator Facility is located in a purpose built 28,000 m^3 building at Royal Naval Air Station Culdrose. The facility comprises a Cockpit Dynamic Simulator (CDS), 3 Rear Crew Trainers (RCT), 6 Part Task Trainers (PTT), Computer Based Training (CBT) classrooms, a Mechanical Systems Trainer (MST) and a Weapon Systems Trainer (WST).

The CDS offers a full motion simulator, which is an exact copy of the cockpit of the aircraft. Its state of the art graphics allow a very realistic training environment for aircrews. Figure 13 displays the external view of the simulator.

FIG.13 – MERLIN SIMULATOR

The Pilot’s view from within the simulator is shown in Figure 14.

FIG.14 – PILOT'S VIEW

TEST OBJECTIVES

Focusing on the ship motion characterization aspect of aircraft/deck interface study using a common measured metric, several tests are conducted in the simulator which are later repeated by the actual devices at-sea.

The indicator for success was the pilot’s ability to safely and repeatedly recover the aircraft in the range of desired conditions, such that the deck lock could be engaged. Pilot/operator flight evolutions were consistent with current flight patterns. Evolutions were programmed for day and night and under progressively difficult deck conditions. In addition to the objectives indicated earlier, particular attention was made to recovery times and deck motion envelope limits.

Primary Testing Objectives and Conditions

a) Day and night and under progressively difficult deck conditions;

b) Programmed deck SHOL by aircraft;

c) Standard Circuit: First Circuit LPD off. Thereafter: LPD ON, LPD OFF first day then night, same order. The pilot rated workload and described task cue.

In the manned helicopter scenario, the LPD pilot display is attached to the upper starboard side of the hangar (Figure 15). It is in plain view over the flight deck and in full view from hover. From this location on the starboard side of the ship, the indicator is visible during either stern approach (USA) or the port approach (UK) and hover. If the SH-60 is simulated in its positive pitch-up attitude, the indicator light visual might be at the limit of the field of view.

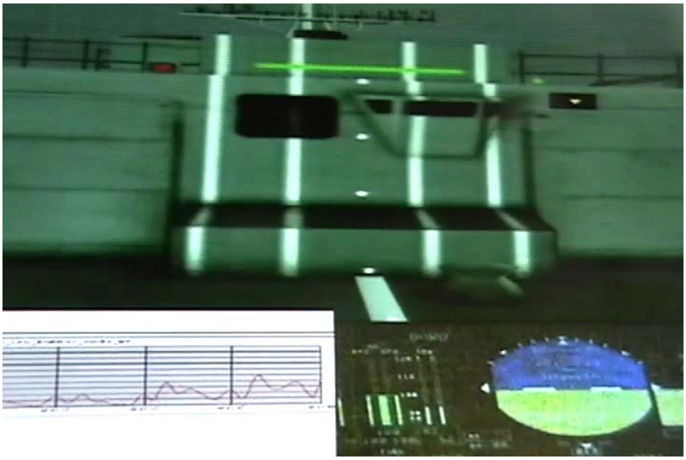


FIG.15 – USN MFS SHIP WITH LPD DISPLAY

The LPD calculates the EI and broadcasts it over the simulator visualization system. Depending on the value of the EI, the appropriate symbol is illuminated on the LPD indicator visual box. Figure 16 displays the light on the actual ship.

FIG.16 – THE LIGHT INDICATOR ON DDG 88

In the UAV scenario, such as the NIREUS program (Figure 17), no external indicator is required. External view images were programmed to visually demonstrate the initiation of recovery which was correctly and repeatedly identified by the LPD federate in the auto recovery system.

FIG.17 – SIMULATED UAV AUTO LANDING

Figure 18 displays several of the many platforms programmed to receive the NATO generic VTOL UAV created by simulation.

FIG.18 – NATO FLEET PROGRAMMED FOR UAV AUTO RECOVERY PROJECT

SIMULATED TEST SUMMARY

-UAV

Figure 19 shows an example of a simulation.

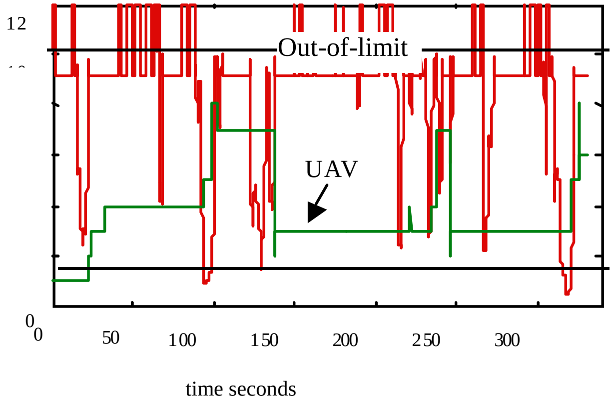


FIG.19 – EXAMPLE UAV SIMULATION

The UAV status trace on Figure 20 represents the position of the UAV; where 1 is the UAV approaching M_1, 2 is hover at position M_1, 3 is given as the transition to M_0, 4 is the hover at M_0, 5 is the final descent and 6 is touchdown. The aborts are given by 6 (back to M_1) or 8 (back to M_0).

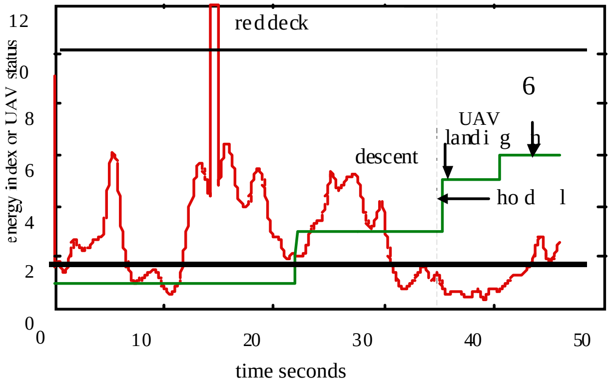


FIG.20 – SAMPLE UAV RECOVERY

In the NIREUS implementation of LPD, the autoland simulation ignores the LPD deck status until the UAV arrives at hold position M_0. LPD is then interrogated looking for the first LPD green deck. The decision to wait for LPD green deck ensures that the UAV descent can be safely achieved. Once the LPD green deck is acquired, the UAV descends to the deck. During decent, LPD continues to monitor the ship motion and will signal to the UAV to abort should an unusual ship displacement occur that takes the deck out of limits.

Figure 20 shows the UAV in transition to position M_0 (where the green trace is equal to 3). It holds briefly at M_0 and then descends to the deck. On recovery there may have been a bounce indicated by a sudden sharp rise and then definitively indicates recovery by the value 6. Closer inspection of the recovery period showed that, as soon as the UAV arrived at the M0 wait position, the EI was showing green deck. In this case the autoland system operated well. The HLA appeared to have passed the green deck signal; the UAV descended over a 5-second period to the deck, which was within limits for recovery.

-Manned Simulation compared to recorded data

Several test pilots were involved in both the US and UK simulations. One of the US test pilots was also selected to conduct the LPD evaluation aboard USS PREBLE (DDG 88) which followed the last US simulated DI test. Between the two programs, hundreds of evolutions were conducted in conditions with various relative wave direction and wave height. Winds were kept between 10 to 30 knots vectored in the direction of the relative wave angles (winds are computed as a constant force). Ship speed was maintained mostly at 10 knots, while some testing was conducted at 20 knots. The visibility was either day or night with several scenarios conducted during rain or snowstorms.

Simulation flights focused on the test matrix. As most aspects of the flight and ship characteristics are cross-referenced, it was relatively easy to develop tendencies and cause and effect principles during the course of the test. The three primary study graphics are presented in Figures 21 - 23.

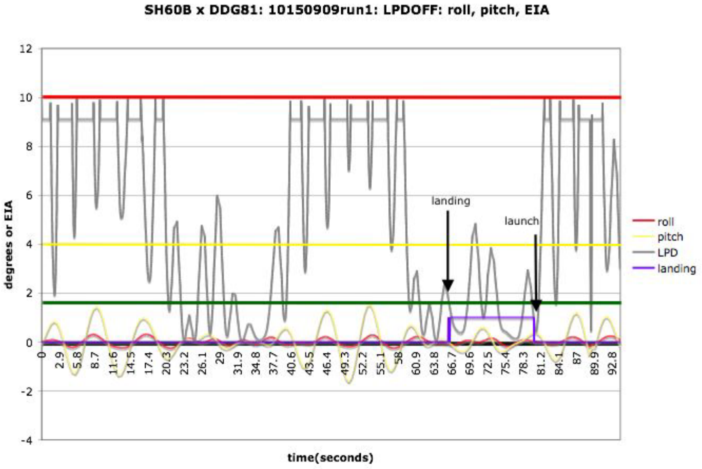


FIG.21 - DAY

Figure 21 shows a time history, with LPD off, the recovery event occurred on a green-amber or safe deck, and the launch occurred from quiescent deck. The corresponding translational traces showed similar displacements at launch. Oleo compression (Figure 22) appeared normal with the tail wheel striking firmly first, but with high engine torque measured at several points through the evolution (Figure 23). This might be attributed to pilot adjustment to simulator flight operations.

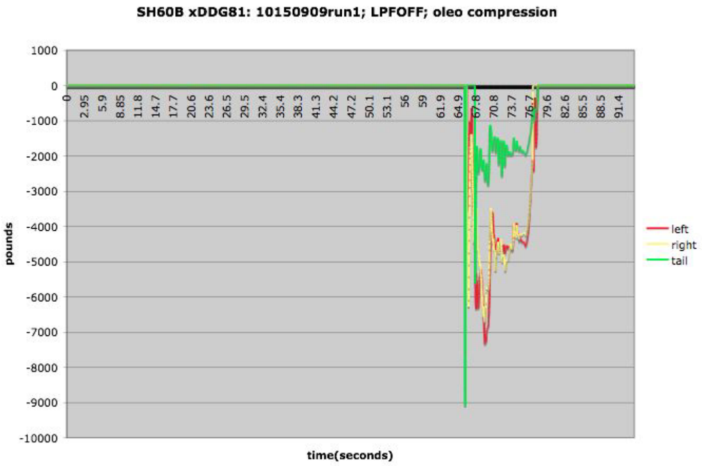


FIG.22 – FORCE ON WHEELS

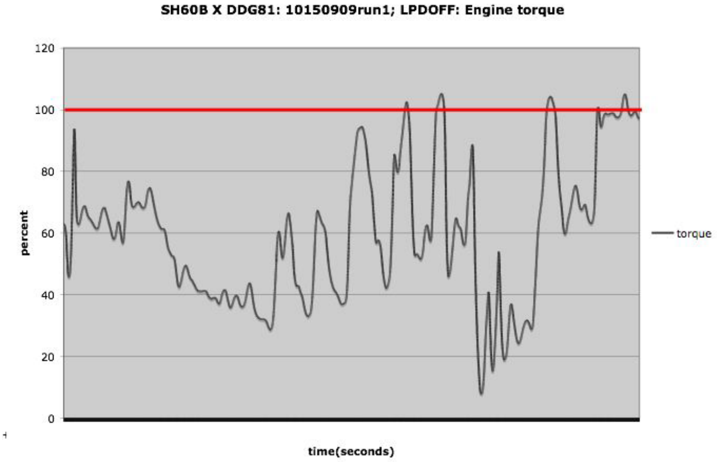


FIG.23 – ENGINE TORQUE

Figure 24 (UK example) LPD on, is composed of the launch and recovery events, EI, ship’s roll, pitch and yaw traces along with the deck energy levels.

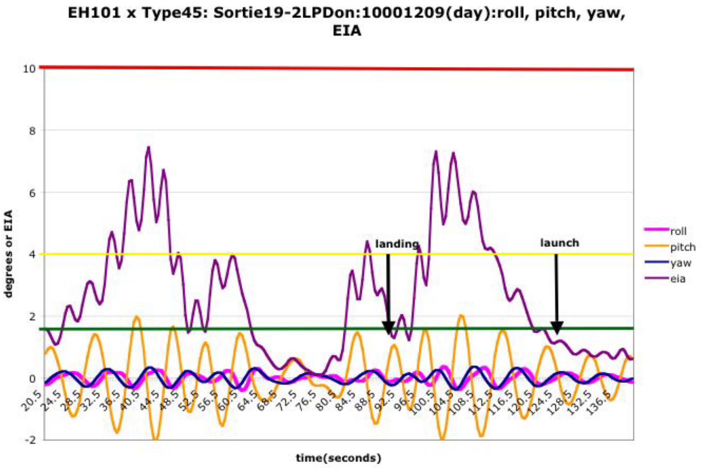


FIG.24 - DAY

Oleo compression trace appeared to show a peak compression on the nose gear (Figure 25).

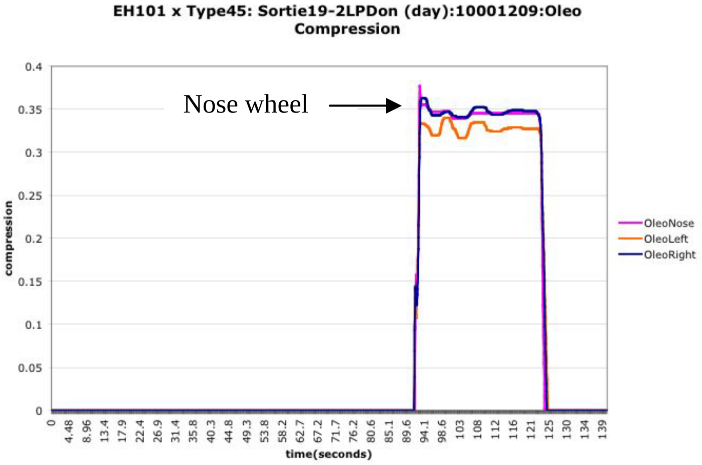


FIG.25 – OLEO COMPRESSION TRACE

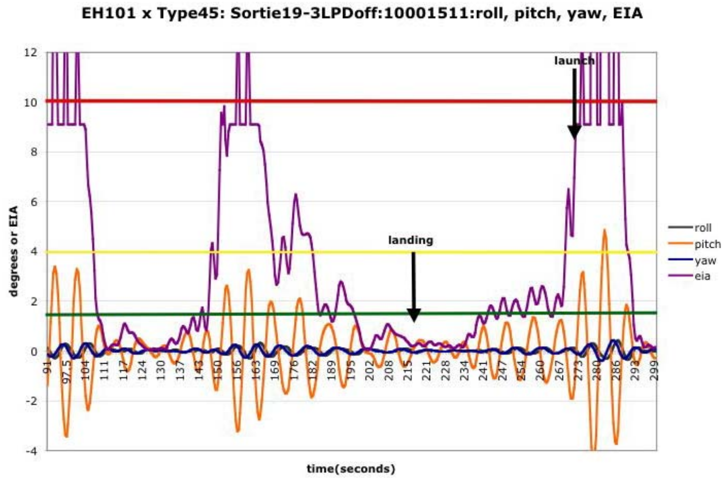


FIG.26 – DAY OPERATIONS

Figure 26 time history, with LPD off, the recovery event occurred on a quiescent deck, but the launch happened from a high amber or caution deck. The deck was very nearly out-of-limit. The corresponding translational traces showed similar large displacements at launch. Oleo compression appeared normal, but high engine torque was measured at launch (Figure 27). Figure 28 compares boarding times with and without the LPD indicator. The figure also compares pilot responses in the MFS and the Merlin Simulator. From the figure, boarding times are improved, particularly at night, with the LPD illuminated.

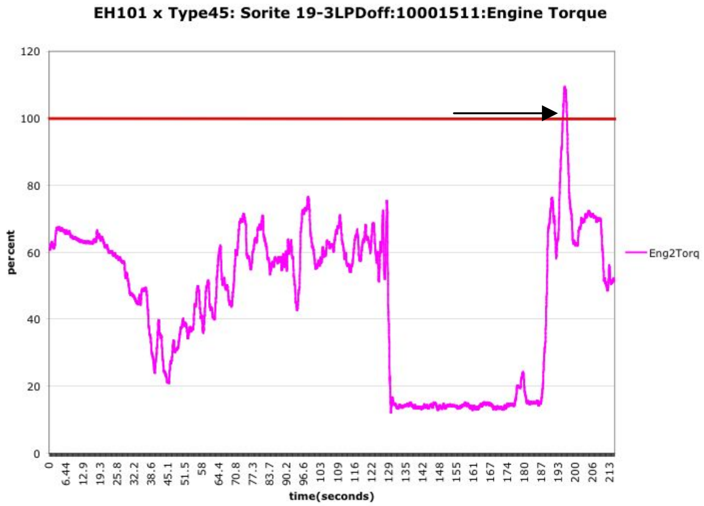


FIG.27 – ENGINE TORQUE

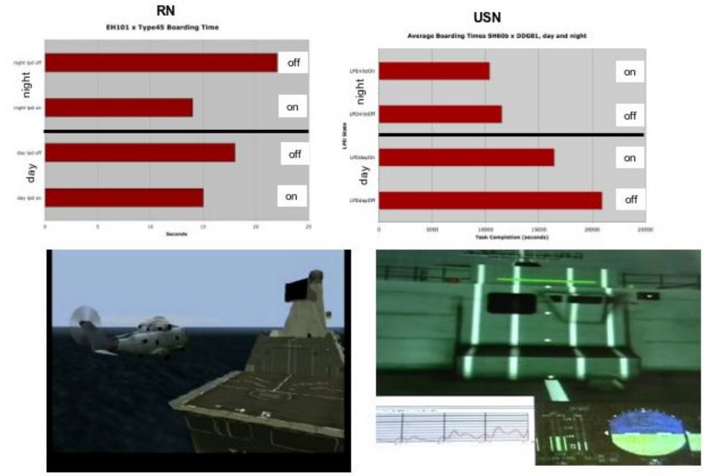


FIG.28 – BOARDING TIMES

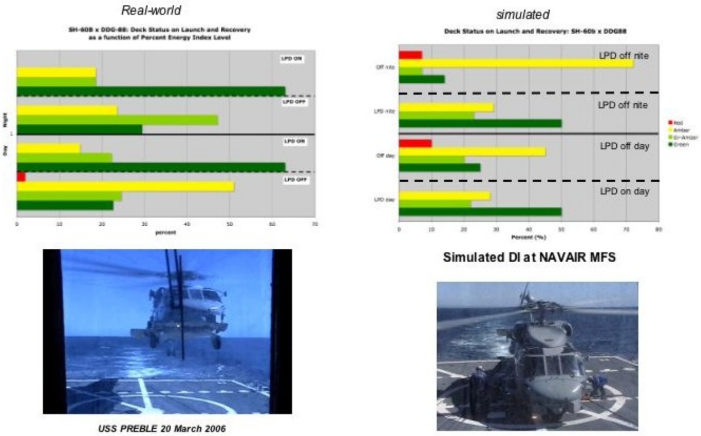
COMPARED TEST SUMMARY

DECK RECOVERY - MANNED

The LPD was applied as a visual landing aid and operated as a federate. The Manned Flight Simulator was modified to implement a federated operation allowing individual simulation components to be replaced with a minimum of change to the other components. Among the issues analyzed was the fundamental question as to whether or not the LPD could be used to improve launch and recovery activities. The answer to that question would manifest itself in the recorded data and would be supported by pilot commentary and observations.

As mentioned earlier, one of the key factors related to increased operational capability in landing helicopters aboard ship is the ability to repeatedly launch and recover safely from a ship moving in response to the seaway. The successful repetition of the same event raises the overall confidence in conducting the launch and recovery evolution. One of the objectives in using the LPD is to recover on a quiescent or near quiescent deck, regardless of the condition of the seaway. The primary objective is to assess operational improvement as a function of environmental conditions, with and without LPD. The metric of success is the choice of recovery with LPD on quiescent or near quiescent deck which equates to a minimum of ship motion. The data for this metric is recorded and displayed.

Figure 29 displays the average distribution, by percentage, of LPD status during launch and recovery events. The distribution (marked real-world) represents the combined results of the participating pilots. The diagram compares the at-sea result with the equivalent simulated sum. The two cases are similar but the simulated case contained a greater number of launch and recovery events. This may be due to the simulated environment encouraging taking greater risk on the part of the pilot or operator. There were no red deck events recorded while LPD was ON. The nighttime events with LPD-ON appear approximately the same between test environments.


Real-world

SH-60B x DDG-88: Deck Status on Launch and Recovery as a function of Percent Energy Index Level

simulated

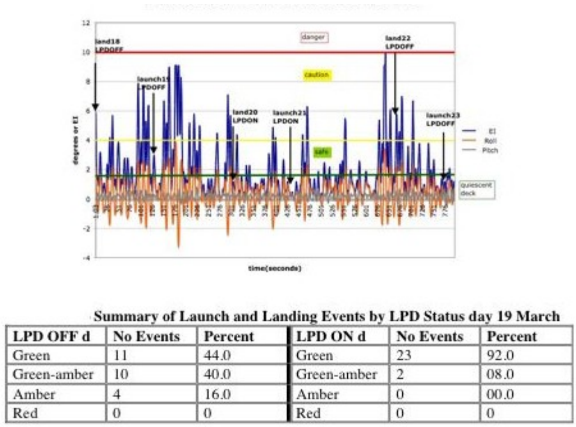
Deck Status on Launch and Recovery: SH-60b x DDG88

Simulated DI at NAVAIR MFS

USS PREBLE 20 March 2006

FIG.29 – DISTRIBUTION OF LPD STATUS

Figure 30 displays the launch and recovery events during a particular session of manned operations. As in the tendencies recorded in the simulator and at sea, launch and recovery events with the LPD switched on occur in lower ship motion while launch and recovery events with the LPD off shows near random results. The chart displays the corresponding table of launch and recovery events for the entire day session. With respect to the percent distribution of deck energies, 44% of the attempts occurred with LPD off from a green quiescent deck whilst 92% were to/from a green deck with the LPD on. Green-amber or safe deck accounted for 40% of cases with the LPD off, while only 8 % of the remaining events with LPD on were to a green-amber deck. About 16% of the attempts occurred to an amber deck with the LPD off. There were no amber events recorded with the LPD on. The session did not record launch and recovery events to a red deck.



Summary of Launch and Landing Events by LPD Status day 19 March

LPD OFF d	No Events	Percent	LPD ON d	No Events	Percent
Green	11	44.0	Green	23	92.0
Green-amber	10	40.0	Green-amber	2	08.0
Amber	4	16.0	Amber	0	00.0
Red	0	0	Red	0	0

FIG.30 - L AND R EVENT SUMMARY

Another key factor related to increased operational capability in landing helicopters onboard ship, is the ability to repeatedly launch and recover safely from a ship moving in response to the seaway. One of the objectives in using the LPD is to rapidly but safely recover to a quiescent or near quiescent deck, regardless of the condition of the seaway.

Figure 31 is divided into Day and Night operations, with and without LPD for the launch and land events. Referring to the Day portion of the graphic, with LPD off, it took longer to manoeuvre the aircraft and for the pilot to achieve a landing solution than with the LPD on. Referring to the night portion of the graphic, with LPD off, the same tendencies are exacerbated at night. The improved recovery times are attributed to improved confidence on the part of the pilots making the landing decision. The quicker recovery time of night evolutions to day evolutions is attributed to the availability of fewer cues for the pilot to achieve a landing solution. The deck status conditions were also recorded and studied during the simulated DI.

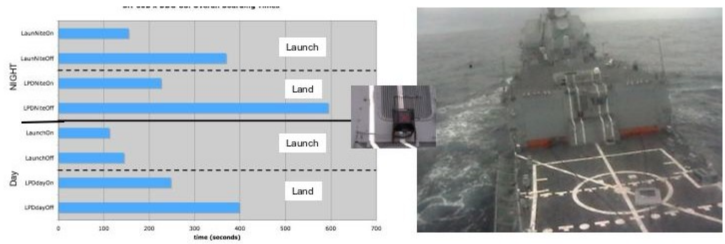


FIG.31- BOARDING TIMES TO THE DECK

DECK RECOVERY - UNMANNED

A test of concept was performed during the USN Joint Project Office MAVUS project using the Bombardier, Inc CL-327 co-axial UAV. The project culminated with an at-sea TECHEVAL ending in 2003. The program featured a number of “firsts” including an autoland proof-of-concept using the EI approach. Figure 32 displays an early MAVUS test using the CL-227 version UAV on an FFG 7 class vessel. The time history graphics in the centre of the figure displays simulated motions along with the EI computation indicating to the ground control station (later the TCS) when to command UAV descent. The air vehicle tended to hover at about 3 metres over a Recovery Assist, Securing, and Traversing (RAST) track controlled custom made grid. On land signal, the air vehicle descended at about 1 metre/second, landing on the grid in less than 4 seconds from the low hover position. This is well within the rise time minimum of the FFG 8 ship class.

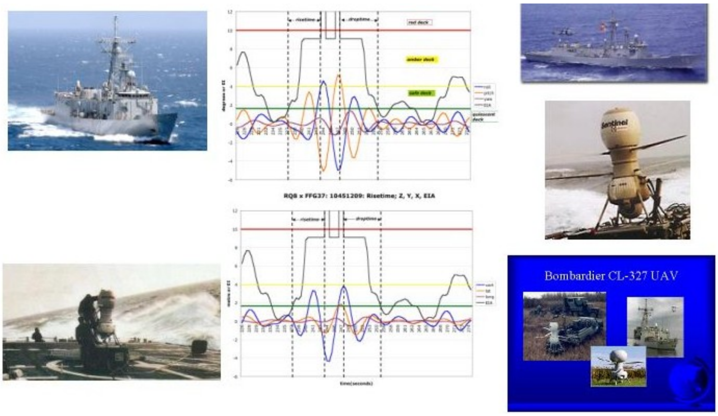


FIG.32- CL-327 X FFG39 MAVUS TRIAL

Here aircraft stability at touchdown on or near the grid in real-time is calculated using ship motion as a function of the aircraft model. The aircraft model is considered an extension of the ship. The aircraft experiences ship transferred forces and moments, which create rectilinear and angular accelerations on the air vehicle. The accelerations can be numerically integrated to determine the position and attitude of the helicopter relative to the ship as function of time for various ship motions. In essence, the aircraft motion is the result of the sum of all forces to which it is exposed. This is the inspiration to use the EI today, to measure and predict deck motion to complete launch and recovery events. Figure 33 displays EI based measures from a recent test of the MQ-8B Fire Scout aboard USS MCINERNEY (FFG 8).

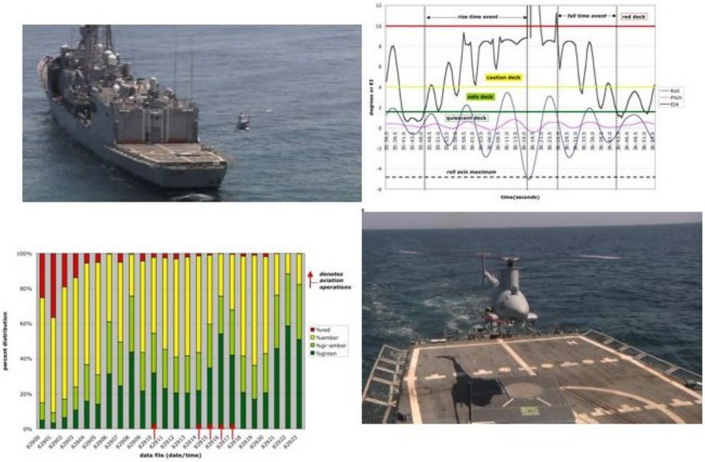


FIG.33 – MOTION CHARACTERIZATION

The Quad chart shown in Figure 33 contains a time history trace containing rise and fall time events along with the corresponding ship pitch and roll traces. For an eventual autoland system to function, an autoland command would be sent to the air vehicle during hover in an appropriate designated position over the deck. Assuming a descent rate similar to other maritime helicopters, the aircraft touches down well within the rise time of the ship. Still referring to Figure 33, the lower left corner of the Quad chart displays a typical 24 hour period of ship motion recordings showing the distribution of deck energies per hour recording, and the hours in which flight operations occurred.

As in the manned version of the test, a key factor related to increased operational capability in landing VTOL or fixed wing aircraft onboard ship is the ability to repeatedly launch and recover safely from a ship moving in response to the seaway. The operational benefits of an unmanned air vehicle are increased if it can be safely captured autonomously, i.e. without the aid of an experienced LSO to a quiescent ship. The aircraft will still need to be flown to the deck, but the computer resolves the difficult assessment of quiescent point identification.

CONCLUSIONS

The primary goal for conducting dynamic interface analysis is to expand existing operating envelopes and increase air vehicle availability thereby improving overall naval effectiveness. The objective of dynamic interface study is to determine the maximum safe air vehicle/ship platform operational limitations. Given an air/ship system and inherent operational limitations, DI strives to increase tactical flexibility for any set of environmental conditions. Modelling and simulation is used to rapidly delineate system limitations. The calculated system limitations provide experimental DI with the necessary data to more effectively set testing strategy to probe the limiting conditions.

The paper described the development of a simulation that functions through a HLA Federation creating a reasonable representation of real world operations. This is achieved within a controlled environment permitting greater opportunity to evaluate a candidate system well before the system is brought to sea. Initial at-sea testing for both manned and unmanned air vehicles shows a favourable tendency to reflect predictions made by simulated computations. Whilst there remain some improvements to be made, the demonstrations have been, thusfar, successful.

In the development of this study, an overview of the ship motion and dynamic interface simulations and modelling has been described with the emphasis on undercarriage encountered forces and air vehicle response stability. Validation of the results is a priority because of the potential problems affecting ship-helicopter operating deck limits to be programmed for air vehicle automatic recovery. Beyond the basic problem of data verification and validation, the analytic procedure demonstrated above may be used to cross-correlate between proposed aircraft-ship deck limits and the vehicle expected physical responses.

While the focus of the report was on air vehicle final approach and recovery, deck issues significant to air vehicles after recovery include chock and chain, aircraft on deck manipulation, handling and servicing.

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ACKNOWLEDGEMENTS

This article is dedicated to the loving memory of **Dr. Peter J. F. O’Reilly**, a founding father of the dynamic interface discipline, and one of the first people to propose the use of the Energy Index to automatically recover Unmanned Air Vehicles. The authors gratefully acknowledge the contributions made to this article by **CDR Jeffrey R. Von Hor, USN (ret)** and **LCDR Stephen Crockatt, RN** both formally Instructors at the US Naval Test Pilot School.

BIOGRAPHIES

Dr. Bernard Ferrier is Engineering Head of the ONR Aircraft - Ship Dynamic Interface Program at Hoffman Engineering Corp. The DI Office Program includes the design and manufacture of the Landing Period Designator, assembly and conduct of simulation programs related to dynamic interface focusing on the assessment of a wide variety of air vehicles, ship board handling systems and ship classes. Prior to joining Hoffman and BMT Syntek Technologies Ferrier led the Anteon Corporation’s (Analysis & Technology now General Dynamics Information Technology) Dynamic Interface Program for the last six years covering a wide variety of UAV, USV, and manned- ship projects. Prior to joining Anteon, Ferrier led the CL227 interface program at Bombardier, Inc (aka Canadair) in Montréal, Québec Canada and Arlington, Virginia. Prior to joining Bombardier, Ferrier was a rotor dynamist and project leader of the dynamic interface project of the AH-64 at the McDonnell Douglas Helicopter Company (now Boeing) in Culver City (California) and Mesa (Arizona). He received his last doctorate in helicopter/ship interface engineering at the École Polytechnique de Montréal (Québec) Canada.

Dr. John Duncan is Program Manager of the UK MOD Defence Equipment & Support, Directorate Safety and Engineering, Sea System Group's Simulation Based Acquisition. The Group's focus is on ship board maritime technology development and modelling techniques used for the interface of manned an unmanned air and sea vehicles. DR. JOHN M. DUNCAN is the chairman of the NATO Naval Group 6 Sub-Group 61 on virtual ships. He was previously chairman of the NATO Specialist Team on Simulation Based Design and Virtual Prototyping for ship acquisition. He led the STSBDVP development of Allied Naval Engineering Publication 61 on ship virtual prototyping. He is also leading application of long-haul distributed simulation to address systems interoperability requirements for the CVF, next generation UK aircraft carrier. Dr. Duncan received his Ph.D from Durham University, Durham (UK).

John Nelson is a rotary wing ship suitability engineer assigned at the Naval Air Systems Command at Patuxent River, MD. He has 12 years of experience testing fixed and rotary wing aircraft aboard ship. His projects include EA-6B and F/A-18E/F carrier suitability tests and shipboard tests with numerous helicopters and the MV-22B tiltrotor. He was lead engineer for the USS SAN ANTONIO (LPD 17) First of Class test program. He is currently assigned to the MQ-8B Fire Scout program and conducted the first MQ-8B shipboard flight tests. He received his B.S. from Worcester Polytechnic Institute and his M.S. from Syracuse University.

Dean Carico is a senior aerospace engineer in the Rotary Wing Ship Suitability Branch in the Integrated Systems Evaluation, Experimentation, and Test (ISEET) Department at the Naval Air Systems Command at Patuxent River, MD. He has over 39 years experience working on Navy and Army flight test and related analytic/simulations programs. Dean was the lead engineer in the Navy's first rotorcraft operational flight trainer (OFT) evaluation for SH-2F Device 2F106. As the Rotary Wing Aircraft Test Directorate Simulation Specialist during the late eighties, Dean was lead engineer in a multi-year program on Rotorcraft Simulation to Support Flight Testing. As the first Dynamic Interface Section Head, Dean initiated a combined flight test and analytic program in 1983. Dean was lead in an internal science and technology program that focused on determining the effect of math model complexity in analyzing the rotorcraft shipboard landing task. He is currently the Navy lead in a high performance computing program that focuses on developing analytical options to improve flight test performance, stability and control. He has also generated several small business innovative research programs that focus on enhancing rotorcraft land and ship-based flight testing.

Dean has masters' degrees in Aerospace Engineering from Princeton and in Engineering Science from the Navy Postgraduate School, and is an engineering graduate from the USNTPS. He received the Meritorious Civilian Service Award for testing in a combat zone in 1973, and the Richard L. Wernecke Award for technical excellence in rotorcraft test and evaluation in 1997. He received the SFTE Director's award in Sep 2003.

David J. Ludwig is an aircraft technologies program officer at the Office of Naval Research working a variety of Unmanned Air Vehicle and Rotary Wing Aircraft technology development programs. Mr Ludwig began his career at the Naval Air Test Centre, Patuxent River, MD. Early in his career, he served as an aerial refuelling (AR) technical specialist conducting a variety of AR developmental tests of the KC-10 and KC-135 tanker systems, aerial refuelling pods, and the S-3 tanker system. He was a lead mechanical systems engineer for the V-22 Integrated Test Team during the EMD program and the H-1 Upgrades program. He served as Maritime and Rotary Wing Mechanical Systems and Propulsion Branch Head within the Integrated Test and Evaluation Department at Naval Air Systems Command. Mr Ludwig earned his Bachelor of Science degree in Mechanical Engineering from the University of Maryland and is a 1992 graduate of the U.S Naval Test Pilot School. Mr Ludwig is currently pursuing a Masters of Science degree in Aerospace Engineering at the Florida Institute of Technology.