VALIDATION OF SIMULATED DYNAMIC INTERFACE TESTING AS A TOOL IN THE FORECASTING OF AIR VEHICLE DECK LIMITS AND DECK LANDING AIDS

BY

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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 use of 6 degree-of-freedom motion flight simulator to forecast physical deck motion and deck motion limits is discussed. Full flight test programs using the Merlin CAE Trainer System at RNAS Culdrose and the Manned Flight Simulator at Naval Air Test Centre, Aircraft Division (Patuxent River, Maryland), are described. Using a real-time ship motion-based helicopter recovery monitoring system, pilots perform flight-testing evolutions (DLQ) just as they would at sea. The simulated flight test has 5 (five) essential objectives: assess the capabilities of the Cockpit Dynamic Simulator (CDS) to support or conduct SHOL/NATOPS limits; demonstrate High Level Architecture (HLA) federation along with selected modules e.g. air wake; evaluate recovery safety improvements offered by experimental systems, such as the Landing Period Designator; and determine feasibility of applying these simulators in support of dynamic interface at sea testing. The method, which has been implemented at both centres, gives good performance and correlation with apparent quiescent windows of deck motion. The theoretical approach is described. Results are presented in relation to the stability issues normally confronted by a helicopter at the instant of recovery in progressively difficult conditions. A brief synopsis of several of the integrated HLA modules representing various aspects of the maritime environment, is presented. The summaries include development, simulation and testing of various helicopter recovery aids which were applied during the simulator test. Measurements of instantaneous degree-of-freedom velocity and acceleration are

reported, and preliminary comparisons are made with, and between, aided launch and recovery and non-aided evolutions.

Introduction

The simulation of helicopter operations from naval vessels provides a unique set of challenges, requiring realistic modelling of the interactions between the aircraft, the ship platform, and the environment. The aim of the NIREUS (NATO Interoperability and RE-Use Study) and SAIF (Ship/Air Interface Framework) 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 is focusing upon SHOL prediction where operations may involve recovery in high levels of turbulence to new naval vessels.

This report summarises and compares tests made in the Manned Flight Simulator (MFS) in the US and Merlin Trainer Simulator in the UK designed to evaluate simulator uses to describe Ship Helicopter Operating Limits (SHOL) for manned/unmanned shipboard aviation recoveries. The purpose of conducting these tests independently is two fold. In the first instance, dynamic interface activities are defined as it applies to SHOL trials and aircraft/ship dynamic interface expertise and analysis. The second is to provide a platform to test VLA devices like the Landing Period Designator (LPD) software to demonstrate the aid, for example, to signal the initiation of helicopter launch and recovery from the DDG-88 ship model. The objective is to recover the aircraft on-board a moving vessel within reasonable safety margins regardless of the seaway. The report details the technical results of simulated Deck Landing Qualifications (DLQ) using the Landing Period Designator in the Manned Flight Simulator. The simulated DLQ is a required precursor of the planned manned and unmanned deployment test of the LPD at sea. This report assesses aircraft and deck availability improvements by using the Energy Index to signal the top of recovery. Energy Index quiescent recovery opportunities are presented outside the boundaries of current operating limits. Impacts on the proposed deck limits are discussed. Percent of improvement for operational availability is demonstrated. Details regarding the theory and derivation of the SH-60 and EH101 deck recovery calculations are developed. Preliminary discussions on how the results were validated at-sea complete the article.

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 maximise operational flexibility (Healey, 1982)[8]. 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)[7]. 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. Experimentation 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 activity is on launch and recovery envelope development and expansion. The difficulty of conducting launch and recovery operations are rated by the pilot based on an accepted scale, such as, the Deck Interface Pilot Effort Scale (DIPES). The pilot measures workload resulting from aircraft control margins, aircraft flying qualities, and performance in the shipboard environment (Ferrier, B., Applebee, T., James, CDR D., & Manning, A., 2000)[6]. Other experimental analysis are (but not limited to): aviation facility evaluation and deck handling.

Computational Dynamic Interface (DI) uses mathematical modelling and simulation to support flight testing. Simulation can be used to help support air vehicle/ship testing by:

- Simulating any kind of ship motion and ship motion condition;
- Simulating any kind of air vehicle over and on the deck;
- Simulating any kind of retention or handling system, viz: RAST, RAST/ASIST and SAMAHE;
- Simulating any kind of environment natural and artificial (degraded modes).

While analytics may seem less taxing to the DI study process, it cannot replace experimentation. Envelope studies will always require physical verification. Launch and recovery envelopes, typically developed empirically by experimentation, devote little attention to the dynamic factors imposed on recovery by the moving deck. The fundamental effort is expended in describing the dynamic area over the deck. Once defined, a static related value is imposed relative to the ship's motion. LPD was derived to fill the missing ship oriented parameters from the launch and recovery equation. The fundamental tools used early in the LPD development were the Ship Motion Program (SMP) series (Applebee, T., Baitis, E., Meyers, W. 1981)[1] coupled with the Ship Motion Simulation (SMS) program (O'Reilly, PJF., 1987)[9]. The program methodology uses essentially spectral probabilities in order to produce deterministic synthetic time histories.

Motion of an aircraft on the flight deck is calculated in terms of ship motion as a function of the aircraft model. The aircraft model is considered an extension of the ship. The model is defined by its landing gear footprint; deck location and orientation; aircraft weight and inertias, centre of gravity, lateral drag area and centre of pressure. The aircraft experiences ship transferred forces and moments that 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 (Blackwell, J. and Feik, R., 1988)[2]. In essence, the aircraft is displaced as the sum of all forces to which it is exposed. A wind force is added to the ship motion induced forces. In the Ship Motion Simulation, an unidirectional continuous wind model (simplistic model). Whose vector is in the same direction as the seaway, is applied. Deck conditions, e.g. dry or with substances, such as, water or oil, is a variable in the program. This parameter affects aircraft stability by changing the coefficient of friction between the aircraft landing gear and the deck. Aircraft handling systems are handled much in the same way. A maximum value of the encountered force load or geometric ship position is pre-programmed. When either force loading or ship angular position is greater than the manufacturer's design limits an aircraft incident is registered. The aircraft operational limit is produced due to the break-down of the aircraft handling system.

Scenarios are programmed for the "worst case" condition. For the greatest landing gear deflection, nose gears are modelled unlocked and free to castor for turnover. The model is lined up with the ship centreline and is rotated on the deck to find the least stable, but realistic, orientation.

Turnover incidents are static or dynamic in character. Static turnover is the same as on shore. The resolved weight vector migrates beyond either the friction forces causing the aircraft to displace or the reaction forces causing the aircraft to turnover.

The aircraft centre of gravity is in motion. In the sum of forces, the weight vector is continually modified in response to inertial forces applied by either the rotor disk or ship motion or both. At the point where the virtual centre of gravity becomes negative (over the aircraft stability line), the system is unstable and will seek to find a more stable, but usually undesirable geometric solution. In similar fashion, when the landing gear friction values are exceeded by the combination of aircraft apparent weight and induced inertial forces, slippage will occur. Aircraft slide will continue until the aircraft frictional forces are greater than the disturbing inertial forces. Finally, when the vertical inertial force equals and opposes the aircraft weight, the deck friction goes to zero and an unintentional lift-off is indicated. The sum of these incidents traces aircraft-ship envelopes for on-deck operations.

Full Motion Simulators

To house the dynamic interface programs, existing flight simulators are used (RNAS Culdrose in the UK and Manned Flight Simulator MFS in the US) 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.

The main aim was to undertake a practical application of disturbed simulations using the High Level Architecture (HLA) methodology. The tests were organised with a view to demonstrate simulation re-use and interoperability and to support the guidelines supplied in an Allied Naval Engineering Publication (ANEP) on the application of simulation based design and virtual prototyping in ship design. These tests have their origins in similar studies developed early in 2001. The milestone for NIREUS was to create a working demonstration of a UAV landing on a ship. HLA was chosen as the standard for building this simulation or Federation which consisted of component parts called Federates. The NIREUS concept federation pioneered a number of different approaches to the problem, including the successful de-coupling of the aircraft flight dynamics and ship air wake models into separate federate models.

Elements from NIREUS have been leveraged within the full motion simulator projects, with model re-use being a key principle behind the use of HLA and networked simulation. The system architecture has allowed replacement of a PC-based simulation of the UAV, by a full cockpit motion-based helicopter simulator. This demonstrates the scalability of the HLA architecture.

A key objective is to provide a system capable of conducting SHOL assessments during ship development and prior to sea trails. It is envisaged that a cost-effective combination of simulation and first-of-class flight trials at sea will maximise the operating envelope for the various new ship platforms from which a manned helicopter or UAV 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.

High Level Architecture Programming

Prior to testing the unmanned system, the system must be rigorously tested in a variety of conditions. The easiest is to evaluate the device in a closed and controlled environment. The testing platform used during this stage of the autoland system development, was a helicopter handling system equipped frigate. The primary elements of the imagined UAV system were: Unmanned Air Vehicle (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.

Once the decision was made to produce a networked federation, the system architecture was developed. This identified each of the individual federate elements within the simulation, and also defined the Federation Object Model (FOM), which listed the date items to be transmitted over the network. The design resulted in 6 separate federates being identified (FIG.1), connected via the HLA Run-time Infrastructure (RTI) software.

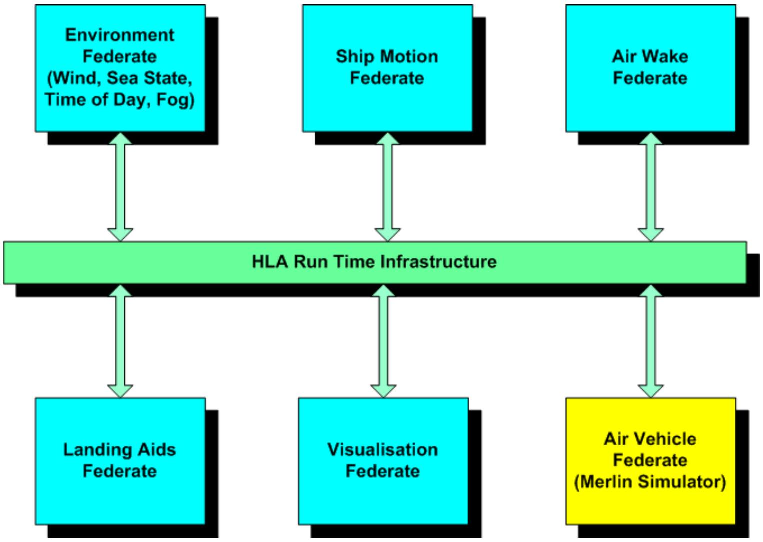

FIG.1 – TYPICAL FEDERATION ARCHITECTURE

Federates

The purpose of this initial analytic evaluation was to use the Simulator to determine the system effectiveness as a function of simulated ship motion, visual environment and synthetic operational systems, and to compare the results to related analytic data (Cox, I et al. 2005)[3].

By discipline the Federation is reduced to (FIG.2).

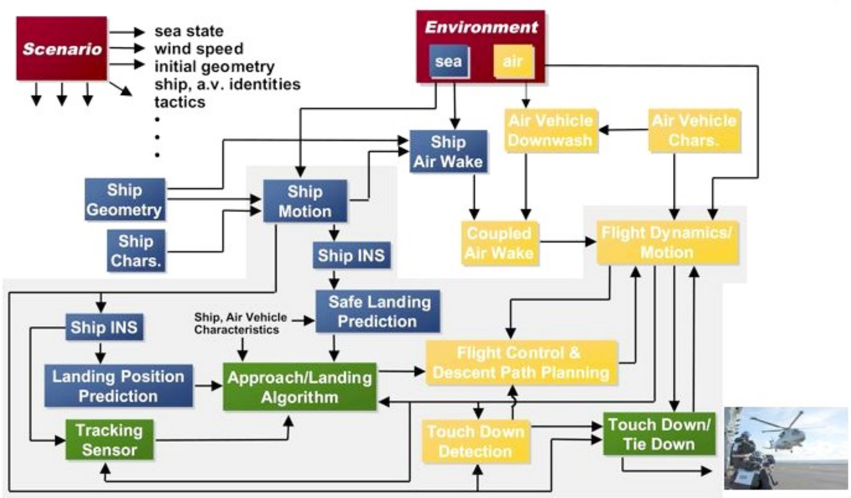

FIG.2 – HLA FEDERATION BY DISCIPLINE

Air Vehicle

The air vehicle simulation component developed for the US test was a SH-60B (FIG.3) which is a medium lift helicopter developed by Sikorsky, Inc in the 1970s.

FIG.3 – SH-60B HELICOPTER

The primary mission is anti-submarine and surface ship warfare, tracking and surveillance, littoral combat support and search and rescue operations. It has been operating from larger ships but also from decks as small as the FFG 8 but more recently from DDG. The first aircraft to enter USN service was in 1984. The bravo version is one of several Sea Hawk series employed by the USN. Merlin (FIG.4) is a medium lift helicopter developed by Agusta-Westland.

FIG.4 – EH101 MERLIN HELICOPTER

The primary mission is anti-submarine and surface ship warfare, tracking and surveillance, littoral combat support and search and rescue operations. It has been operating from larger ships but also from decks as small as the Type 23. The first aircraft to enter Royal Navy service was in December 1998. The first squadron and training facility is located at RNAS Culdrose.

Environmental Federate

The purpose of this federate is to supply all of the required environmental data to the rest of the federation. This consists of the following items:

- Sea State (in the range 0 to 6) and wave spectrum information (comprising amplitude, frequency, wavelength, phase and direction for each individual wave sinusoid). The sea surface is therefore described by the cumulative effects of each individual wave sinusoid;
- Free stream wind speed and direction;
- Fog level (i.e. a visibility range) and time of day;
- Scenario origin point (a reference datum for the geographical location of the simulation);
- Environment timestamp (a reference 'start time' of the simulation, used in wave height calculations).

Ship Motion Federate

The DDG-88 Destroyer ship was modelled. The DDG-88 replaces the FFG8 as the USN workhorse over the next few years. The first ship, USS Arleigh Burke DDG 51, represents one of the largest and most powerful sea dominance combatants ever commissioned by the US Navy. The monohull vessel is slightly larger than 150 metres in length, greater than 20 metres in width and a draft of just over 6 metres. It cruises at 18 knots with a maximum dash speed of 30 knots. It is fitted with a sophisticated stabilisation system. (FIG.5) displays a stern view of the vessel.

FIG.5 – DDG-88 DESTROYER (USS PREBLE)

The Type 45 Destroyer ship was modelled. The Type 45 replaces the Type 42 destroyer and is scheduled to enter service in 2007. The first ship, HMS Daring, is among the largest and most powerful air defence destroyers ever commissioned by the Royal Navy. The monohull vessel is slightly larger than 152 metres in length, greater than 21 metres in width and a draft of just over 6 metres. It cruises at 18 knots with a maximum dash speed of 29 knots. It is fitted with a sophisticated stabilisation system which promises to produce heavily dampened motion. (FIG.6) displays a forward view of the vessel.

FIG.6 – TYPE 45 DESTROYER

The flight deck movement is defined by time history (deterministic) motion derived stochastically from a probabilistic spectrum. Ship speed, relative wave heading, significant wave height and modal period are the primary ship motion parameters. The relative motions are calculated at the point of interest (bullseye or landing point).

The program methodology uses essentially stochastic spectral probabilities in order to produce deterministic synthetic time histories (Crossland, P et al (1995))[4].

The ship motion program is divided into two basic themes, spectral analysis and the calculation motion histories in the time domain. The SMS fundamental relationship is:

$$Sr = S_w(w) \bullet RAO \bullet \boldsymbol{f}(V,m) \quad (1)$$

where:

Sr:	Ship response spectrum
$S_w(w)$:	Seaway spectrum
RAO:	Ship transfer functions
f(V,m):	Frequency mapping
V:	Velocity
m:	Relative wave angle

The seaway most is defined by a forcing function called the Bretschneider, which is given by:

$$S_W(w) = \frac{483.5}{w^5 T_\emptyset^4} H_S^2 \; e^{\left(\frac{-1994.5}{w^4 T_\emptyset^4}\right)} \qquad (2)$$

where:

TØ:	period (sec)
w:	wave frequency (rad/sec)
$S_w(w)$:	seaway spectrum (m^2-sec)
H_s:	significant wave height (m)

The spectral characteristic of a vessel is defined by experimental or computational developed transfer functions termed Response Amplitude Operators (RAO). The response amplitude operators define the dynamic ship responses for a specified load/operating condition.

The ship response spectrum is created as the product of the RAO and the driving sea spectrum over the entire range of frequencies. The response spectrum is reduced to sets of harmonic components for each degree-of freedom. Synthetic time histories are created stochastically by summing the harmonic components over a given time period. A typical time history equation is given by:

$$A_Z = \sum_{n=1}^{k} \left(A_{Z_n} \cos\left(w_n - e_{Z_n} \right) \right) \quad (3)$$

where:

A_z:	DOF amplitude
w:	a circular frequency
e:	phase angle

Time histories are produced by the sum of 48 synthetic functions (k=48). In summary, the Ship Motion Simulation creates deterministic measures of ship motion from a probabilistic spectrum.

Ship Air Wake Federate

The airflow around the superstructure of a ship generates a disturbed airwake containing both steady and unsteady perturbations relative to the freestream flow. Operation of helicopters through airwake can cause handling and performance difficulties and will ultimately limit the safe envelope for various combinations of relative wind speed and direction over the flight deck.

The airwake federate allows a representation of the spatial variation of both the steady and unsteady effects by use of lookup tables populated with data prepared using non-real time modelling tools such as Computational Fluid Dynamics (CFD). The federate receives as input the co-ordinates (x, y and z) of all the points where air flow information is required and produces as output the instantaneous flow velocities at these points taking account of both steady and unsteady effects. In its current configuration the co-ordinate list comprises 67 locations over the airframe, main rotor disc and tail rotor hub, where aerodynamic calculations are to be made. The federate is capable of computing airwake at up to 100 different locations for each frame of the simulation (Woodrow, I et al. 2002)[11].

Ship Motion Forward Prediction

One of the key factors relating to the operation of Maritime Aircraft is the ability to land it safely on the deck of a ship moving in response to the waves. Currently, the procedure for landing manned aircraft on the deck of a ship varies from navy to navy. In most cases the aircraft is piloted to a position of hovering over the moving deck, then when the Landing Safety Officer (LSO), who is standing on the ship's flight deck, perceives that the ship is suitably quiescent, he will instruct the aircraft to begin its final decent.

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 is designed to predict or designate quiescent periods of ship motion suitable for the recovery of the helicopter.

Ship motion forward prediction (SMFP) uses information on what the ship is doing right now and/or what it has been doing in the recent past to forecast what it may be doing in the very near future. In essence this is akin to the experience LSO standing on the ship's flight deck and 'guessing' the ship motion.

The standard Landing Period Designator unit was implemented into the Federation by utilising a wrapper. This wrapper enable the LPD unit to exchange data with the other federates. The aircraft limits, which form part of the initialization data used during federation start up, are expressed as the ship's energy index, which is a scalar empirical formulation.

The energy index 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), 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 (FIG.7).

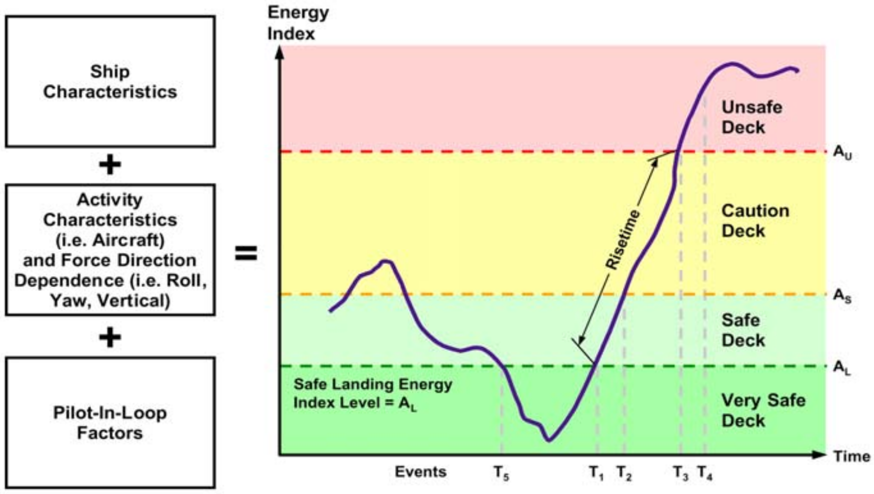

FIG.7 – DECK AVAILABILITY AND RISETIME

The time required to raise the deck 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 as (T_3 – T_1) as shown in (FIG.3). The risetime is a thumb print characteristic of the ship's response and rarely changes.

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 energy index (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 on-board SH-60 computer to descend. Using the data developed, motion histories containing the energy index outside of the deck limits calculated, were evaluated. Each green deck point was analyzed.

Theoretically, any green deck point would permit a signal to the top of recovery. Assuming that the rise time for a given vessel is not violated, the aircraft descends within the rise time value, the aircraft is assured a within limit deck on recovery. Essentially, the methodology summarized above is a formulation to quantify operating beyond the static deck limits. (FIG.8) displays graphically beyond the static limit operations. The base envelope is taken from 10 knots of ship's speed. As before, any points within the hourglass 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.

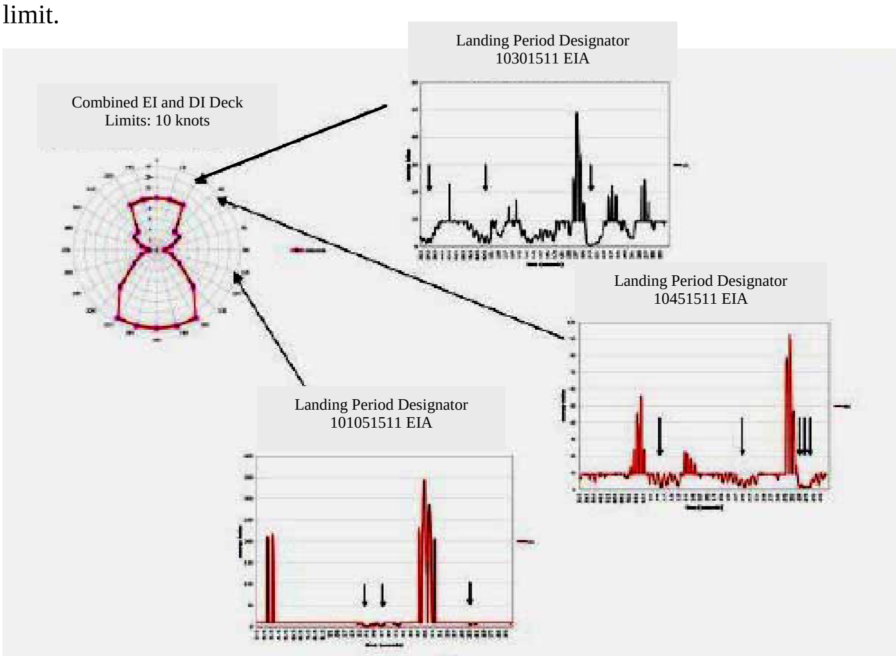

FIG.8 – EXAMPLES OF SAFE MOTION OPERATIONS

Using the Energy Index to calculate dynamically the deck clearances, five minute motion histories were studied. Five minutes was chosen as a metric which represents a preferred SH-60 hover time over the deck. Three randomly chosen out-of-limit motion traces may be seen on the figure. In all cases, quiescent points appear permitting a signal to the top of recovery to be sent. The number and frequency of the appearance of these quiescent points are directly related to the ship motions and the characteristics of the air vehicle under study.

Test Bed Simulators

The test bed at RNAS Culdrose (which mirrors that of the US MFS) is essentially a simulator composed of modular programs which represent the various parts of the air vehicle, modules representing the various emerging technologies selected for development by MoD Defence Procurement Agency (DPA) and the corresponding monitors, hard-drives and support network. The Merlin Simulator Facility is incorporated in a purpose built, m^3 building at Royal Naval Air Station

Culdrose. The facility comprises a Cockpit Dynamic Simulator (CDS), 3 Rear Crew Trainers (RDT), 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 aircrew. (FIG.9) displays the external view of the simulator.

FIG.9 – CULDROSE MERLIN SIMULATOR

The Pilot's view from within the simulator is shown in (FIG.10).

FIG.10 – PILOTS VIEW

The Simulator Control Station is presented in (FIG.11). All functions are within easy reach of the Simulator Operator.

FIG.11 – OPERATOR'S STATION

(FIG.12) displays the CAE FLIGHT SIMULATOR graphical users interface (GUI) which displays the Energy Index visual information. The GUI is based on the Empire Test Pilot School symbology developed in the late 1990s. That original symbology is redisplayed in (FIG.13). The hypothesis in the development of the deck energy symbols is that one builds towards red deck. The same symbology is used for both day and NVG only. The NVG version is replaced with blue lights. The same symbology was programmed for the simulation test.

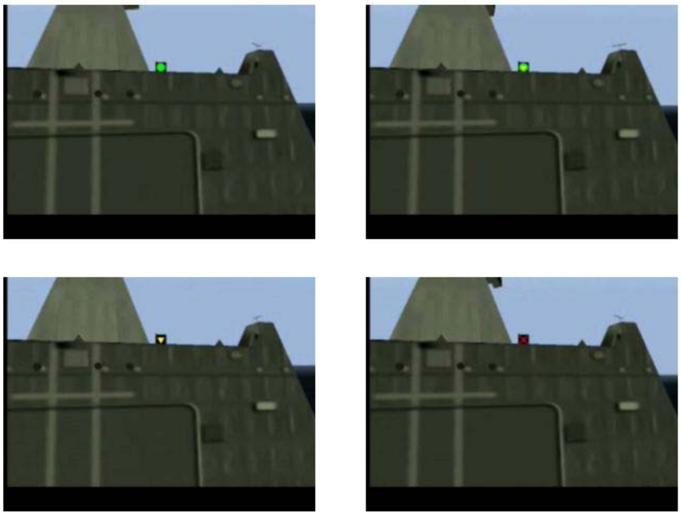

FIG.12 – CURRENT LPD DECK MONITOR GUI CONFIGURATION

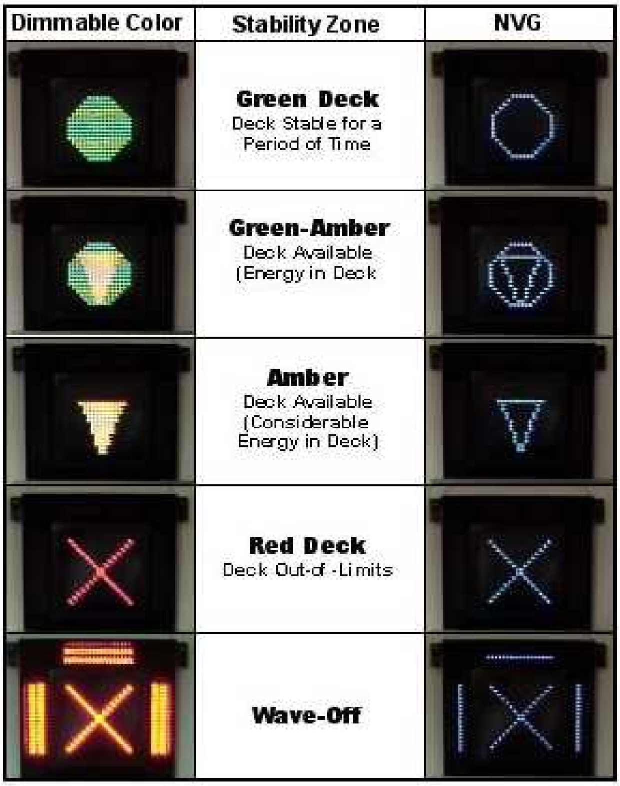

FIG.13 – CURRENT LPD SYMBOLOGY CONFIGURATION

Test Objectives

- The simulated flight test has 5 (five) essential global objectives: assess the capabilities of the Landing Period Designator to support or conduct SHOL deck limits; demonstrate simulator utility as a platform to test aircraft-ship interface issues; and evaluate recovery safety improvements offered by LPD.
  Global trial scope was limited to the conduct of critical azimuth tests establishing the fidelity of the simulated model with recorded observations. Air wake native to the simulator system, was used. Environmental issues impacting aircraft handling and performance, and the improvements caused by the use of the LPD, were studied. Issues related to the known "wet-deck" phenomena, were not reviewed. The Simulation test was based on US/UK DI at-sea formats.

- Standard LPD Test Plan component; Operator General Course and Ship Brief.
  Mission Task Elements were formulated during a LPD training course. The course takes the user through the development and design of the empirical formulation which converted ship motion characteristics, aircraft structural dynamic limits, and user experience into a meaningful value. Experience with the LPD using simulation and real-time conditions were discussed. Discussions related to manned applications. This leads to flight profile planning and LPD use during the final part of the approach to the ship and flight deck. A "pre-sail" brief was conducted for all concerned participants. The LPD was demonstrated. Final comments by operators and air crew were made, the equipment adjusted accordingly. The LPD Test Log was opened. In a real test at sea, an operator's course would be performed.

- User Evaluation
  Test objectives and scope included evaluation of the LPD display and format, LPD contribution to recovery operations, helicopter quality ratings, vertical velocity abatement and pilot perceived workload. Owing to the restrictions imposed on the LPD, the LPD Flight Test Program was conducted only with the DDG-88 Simulation. Evaluations were not restricted to any script, but was initially based on helicopter pilot PRS.

- Test Event Markers
  Shipboard aspects were discussed with test personnel. These focused on data recovery of aircraft operational parameters (point at which the LPD light is illuminated and its intensity), safety and environmental conditions monitoring. The concept is designed to ensure maximum safe deck availability. Test crew enthusiastically participated in all discussions. In addition, the DI was accommodated for viewing of manned simulated flight operations on all occasions.

- Data Recovery and Analysis
  This objective started well before the simulator was used. Traditionally, ship interface analysis had been limited to relating ship-motion measurements and sea conditions to the degree of difficulty experienced in

performing helicopter operations (recovery precisions) with and without LPD. In this program, the LPD and ship-motion data were recorded on the MFS computers, along with instrumented aircraft parameters and pilot comments.

- Other LPD related Studies
  Not a formal component of the Flight Test Document, several utilities were engaged during the simulation analysis. These included:

    - Energy Index Filter programs (styled Fort Victoria and Marlborough);
    - Ship List suppression program (styled Fort Victoria);
    - Analysis of deficiencies and/or compatibility of light indicator with other devices;
    - Development of operational procedures that were compatible with other devices.

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 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 enveloped limits.

Primary Testing Objectives and Conditions:

- Indicator of success was the pilot's ability to safely and repeatedly recover to the deck;
- Day and night and under progressively difficult deck conditions;
- Programmed deck SHOL by aircraft;
- Standard Circuit: First Circuit LPD off. There after: LPD ON, LPD OFF first day then night, same order. The pilot rated workload and describe task cue.

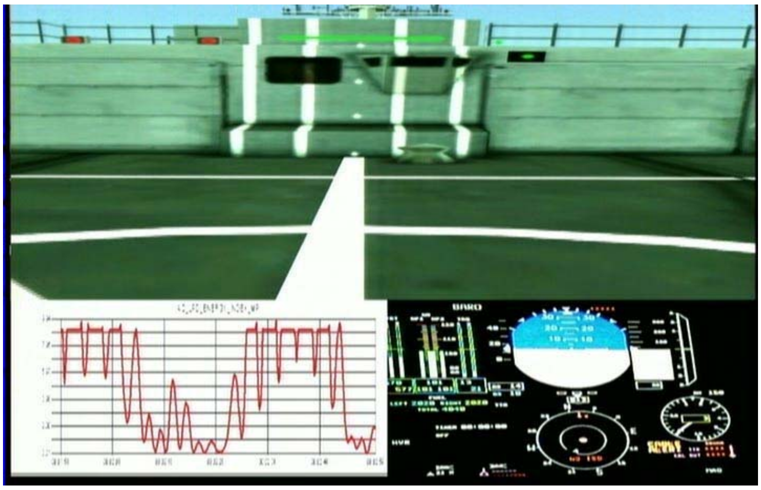

FIG.14 – USN MFS DESTROYER W LPD DISPLAY

Test Results

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 on-board USS PREBLE which followed the last US simulated DI test. Between the two programs, hundreds of evolutions were conducted in conditions, which varied in 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's speed was maintained essentially at 10 knots. The visibility was either day or night with several scenarios computed 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 (FIGs.15-17).

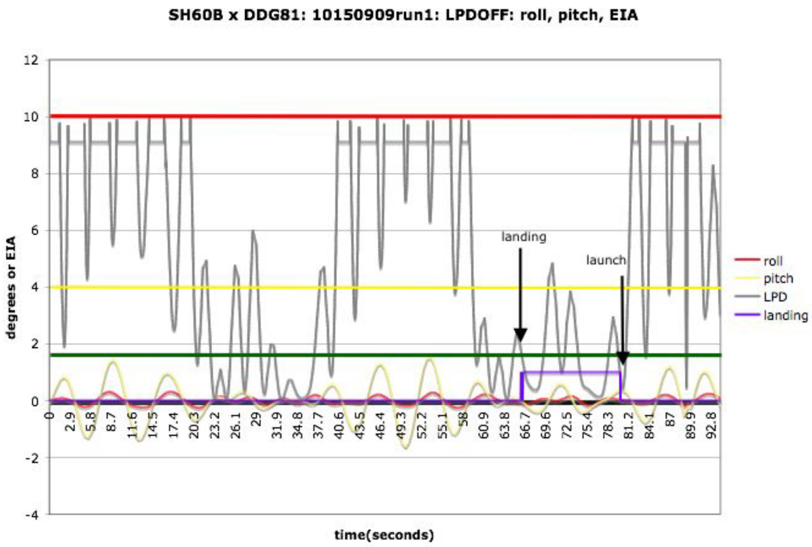

FIG.15 – DAY WITH LAUNCH AND RECOVERY POINTS

(FIG.15) time history, with LPD off, the recovery event occurred on a green-amber or safe deck, and the launch happened from quiescent deck. The corresponding translational traces showed similar displacements at launch. Oleo compression (FIG.16) appeared normal with the tail wheel striking firmly first, but the, engine torque was measured greater than 100% at several points through the evolution (FIG.17). This might be attributed to adjustment to simulator flight operations.

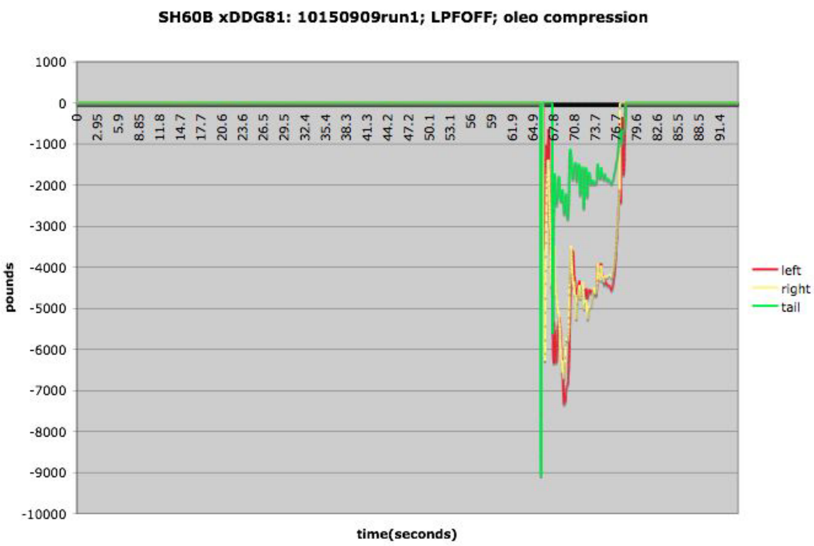

FIG.16 – FORCE ON WHEELS (-Z POSITIVE FORCE)

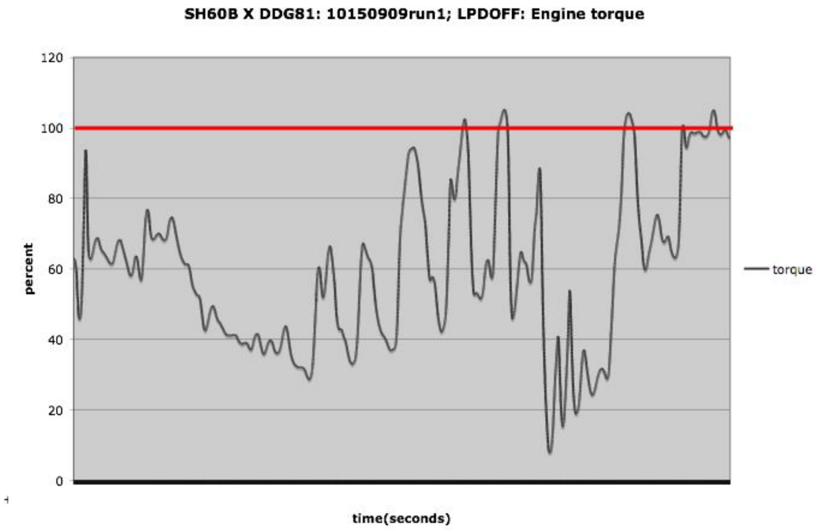

FIG.17 – ENGINE TORQUE

(FIG.18) (UK example) LPD on, is composed of the launch and recovery events, energy index, ship's roll, pitch and yaw traces along with the deck energy levels.

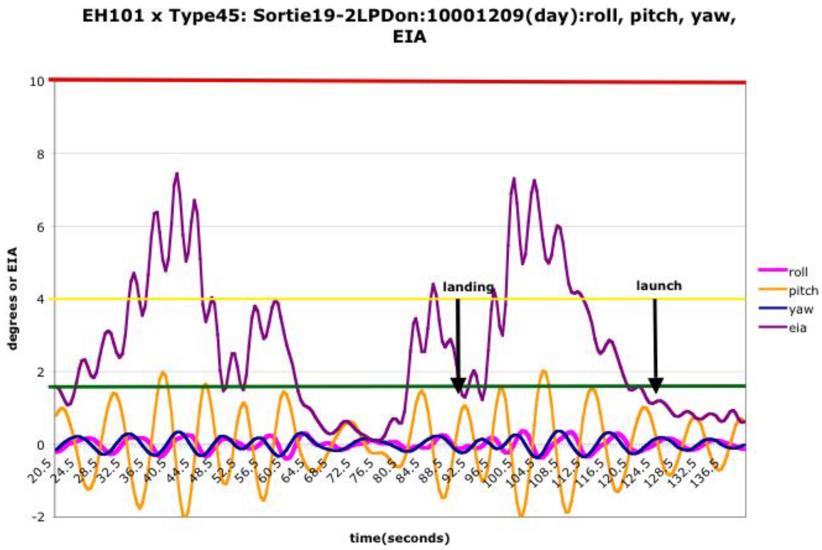

FIG.18 – DAY WITH LAUNCH AND RECOVERY POINTS

Oleo compression trace appeared to show a peak compression on the nose gear (FIG.19).

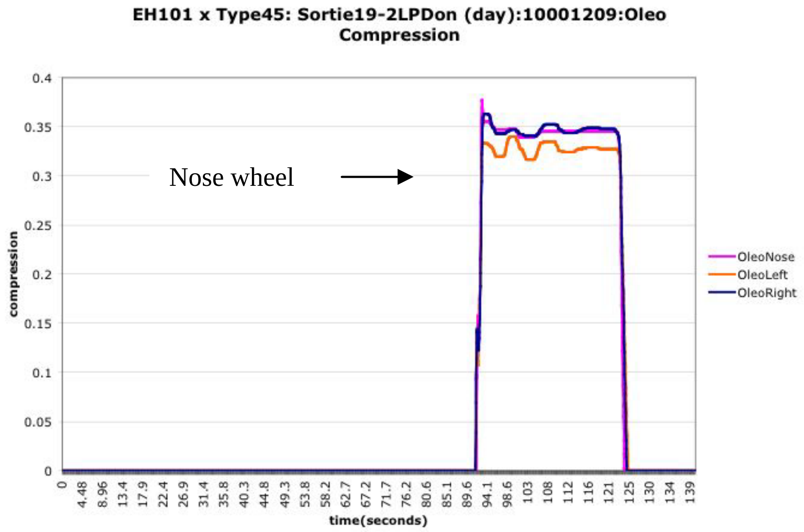

FIG.19 – OLEO COMPRESSION TRACE

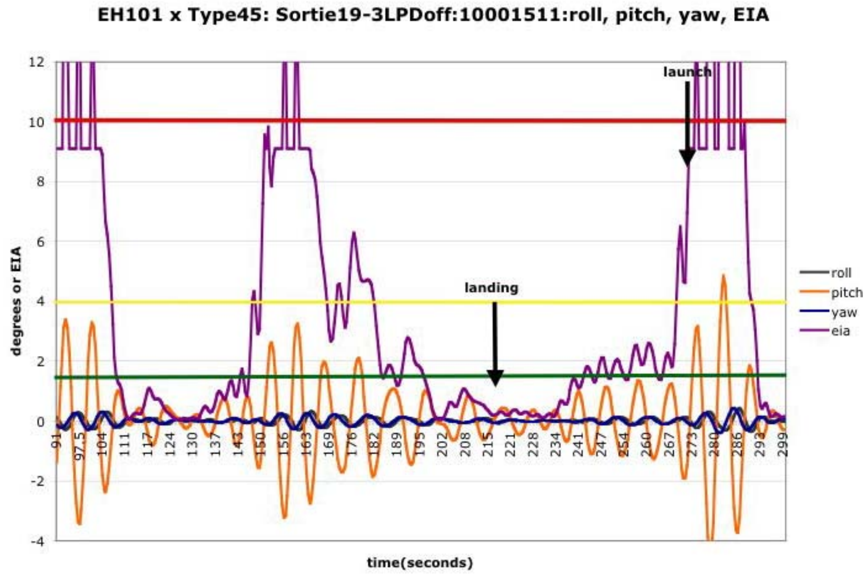

FIG.20 – DAY WITH LAUNCH AND RECOVERY POINTS

(FIG.20) 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 the, engine torque was measured greater than 10% at launch (FIG.21).

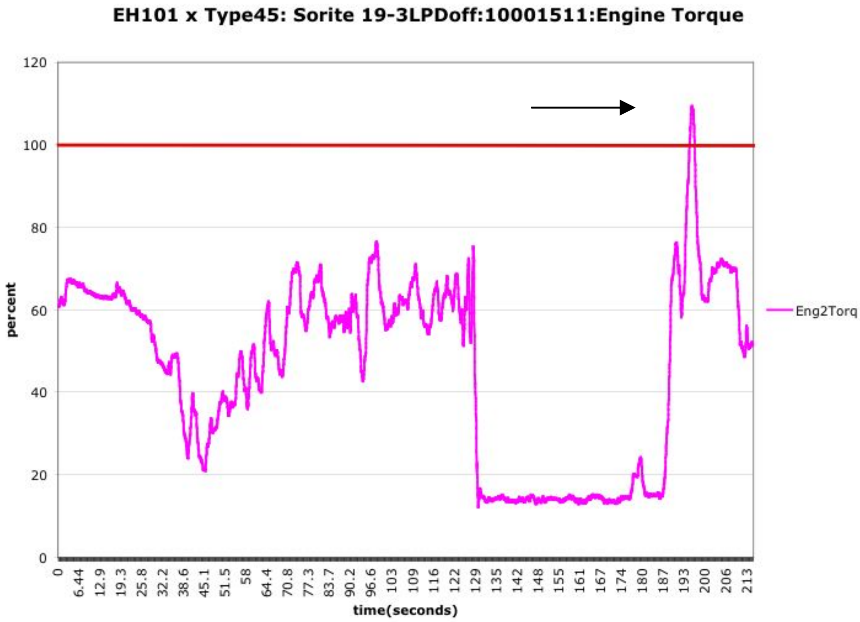

FIG.21 – ENGINE TORQUE

Deck Recovery Test

As mentioned earlier, one of the key factors 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. 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. Test one assessed the condition of the deck at launch and recovery, with and without LPD. The metric of success was the choice of recovery with LPD ON quiescent or near quiescent deck. The data for this metric was recorded and displayed.

Evaluating by Sortie (flight), (FIG.22) displays the deck condition at launch and recovery during UK Sortie 19. The chart is divided into day and night evolutions. The evolutions are divided into with and without LPD. The day, launch and recovery attempts without LPD indicated a 58% rate of choosing a quiescent (or green) deck. A little over 30% of the deck evolutions occurred whilst the deck was green-amber (or safe). There were no Sortie 19 Day LPD OFF launch and recoveries occurred whilst the deck was out-of-limit or red. With LPD on, all launch and recovery events in Sortie 19 Day occurred to and from a quiescent deck.

Night launch and recovery attempts without LPD indicated about 40% rate of choosing a quiescent (or green) deck. A little over 20% of the deck evolutions occurred whilst the deck was green-amber (or safe). There were an equal percentage of launch and recovery events from an amber (caution deck). Greater than 10% of the launch and recoveries occurred whilst the deck was out-of-limits or red. With LPD on, all launch and recovery events in Sortie 19 Night occurred to and from a quiescent deck.

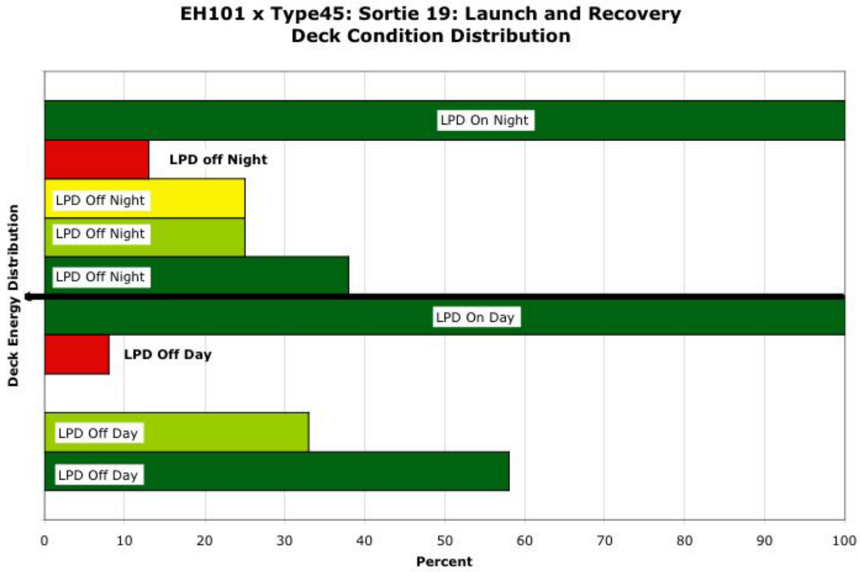

FIG.22 – DECK CONDITION AT LAUNCH AND RECOVERY DURING SORTIE 19

(FIG.23) displays the deck condition at launch and recovery for an equivalent USN Sortie. The chart is divided into day and night evolutions. The evolutions are divided into with and without LPD. Referring to the day, launch and recovery attempts with LPD on indicate around 50% rate of choosing a quiescent (or green) deck. A little over 20% of the deck evolutions occurred whilst the deck was green-amber (or safe). About 25% of the launch and recoveries occurred on an Amber desk. There were no red (out-of-limit deck) LPD-ON launch and recoveries. Compare this with the launch and recoveries without LPD. Events occurred in quiescent conditions at 23%. Green-amber rose to around 20% of the time while + 30% of the time the event occurred in Amber conditions. Almost 30% of the launch and recoveries occurred whilst the deck was out-or-limit or red.

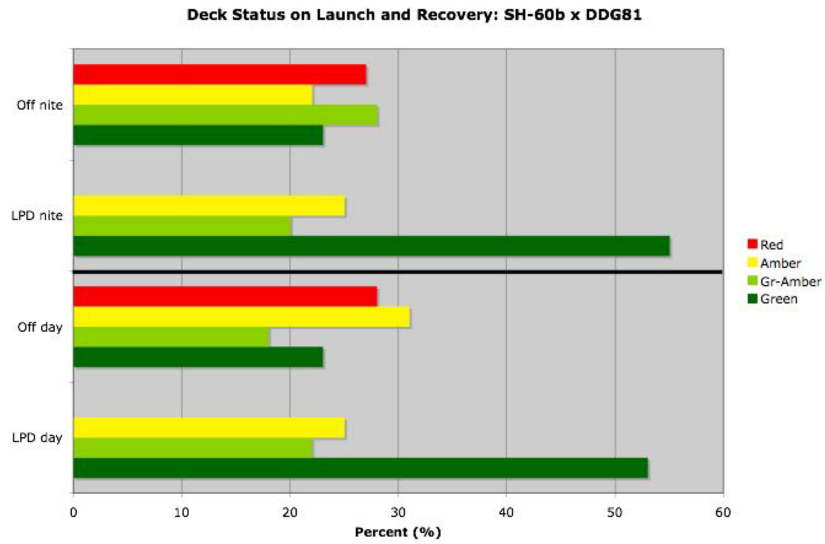

FIG.23 – PERCENT DISTRIBUTION BY LPD ENERGY STATE

Still referring to (FIG.23), night launch and recovery attempts with LPD indicated 50% rate of successfully choosing a quiescent (or green) deck. A little over 20% of the deck evolutions occurred whilst the deck was green-amber (or safe). About 25% of the events occurred from an amber deck. Here again, there were no events to or from a red deck. With LPD OFF, LPD deck status appears to be almost equally distributed, or about 20%.

Another key factor related to increased operational capability in landing helicopters onboard ship, is the ability to repeatedly launch and recover safely and *quickly* 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 (FIG.24).

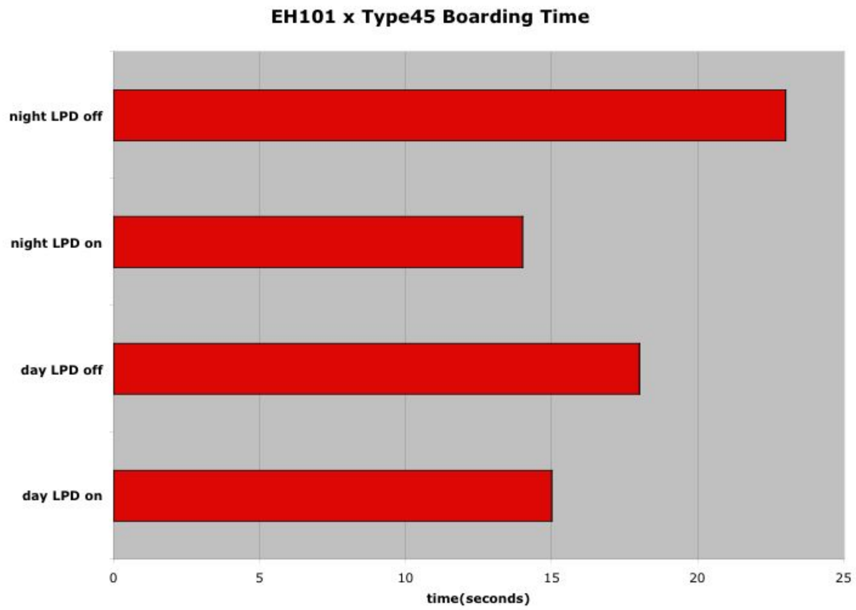

FIG.24 – BOARDING TIMES PORT-WAIT TO THE DECK

(FIG.24) is divided into Day and Night operations, with and without LPD. Referring to the Day portion of the graphic, with LPD OFF, it took on average about 18 seconds to manoeuvre the aircraft from the port-wait to the deck. With LPD ON, the boarding time average decreased to 15 seconds. Referring to the night portion of the graphic, with LPD OFF, it took about 23 seconds to recover from the port-wait station to the deck. With LPD ON, the same evolution took about 14 seconds, shaving off nearly 10 seconds. The improved recovery times is attributed to improved confidence on the part of the pilots making the landing decision.

The metric for test two is the time required to recover from the port-wait (glide slope down to a hover off of the port side) to the deck. LPD achieved completing test two by providing the necessary deck motion data to the pilot in order to more efficiently assist the pilot's decisions making functions. The equivalent USN test result is shown in (FIG.25).

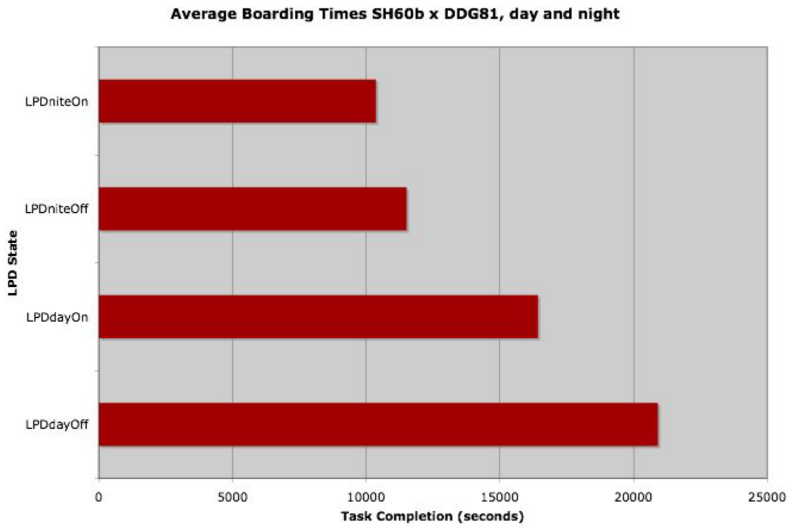

FIG.25 – OVERALL BOARDING TIMES FROM SIMULATION UNFREEZE TO THE DECK

(FIG.25) is divided into Day and Night operations, with and without LPD. The axis is measured divided by 100. 1000, for example is actually 10 seconds. Referring to the Day portion of the graphic, with ***LPD off***, longer to manoeuvre the aircraft from the simulator un-freeze point (several hundred metres from the simulator un-freeze point (several hundred metres aft of the ship) to the deck. With ***LPD on***, the boarding time average decreased. Referring to the night portion of the graphic, with LPD off, the same tendencies are demonstrated. 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 on average to the availability of fewer cues.

At Sea Preliminary Test

The purpose of these at-sea is two fold. In the first instance, the DI team was engaged to apply the LPD VLA using NATOPS/SHOL limits during standard deck landing qualification (DLQ) trials. The second, using aircraft/ship dynamic interface expertise and analysis demonstrate operational enhancement, safety and the feasibility of envelope improvement by applying the Energy Index Algorithm (the operative element in the Landing Period Designator Launch and Recovery Aid). The objective is to recover the aircraft on-board a moving vessel within reasonable safety margins regardless of the seaway. As demonstrated in during the Simulated DLQ experiment, simulator analysis indicated a marked improvement in launch and recovery from quiescent decks. In the course of these tests, a methodology has been developed to use the Manned Flight Simulator in advance of the sea trials in which the selected test pilots may practice the LPD application for their launch and recovery tasks. The by-product is a means of complementing DI experimentation with computational methods.

Within the confines of VLA/Auto-recovery project, the purpose of the manned and unmanned shipboard test is to qualitatively and quantitatively evaluate the effectiveness of the LPD tool as a visual landing aid to fill an operational or environmental gap on US and UK surface combatant ships in high motion conditions and/or low visibility conditions. The related articles details the technical results of measured aircraft interface launch and recoveries with recorded deck motions using the Landing Period Designator on-board USS PREBLE and HMS Sutherland. It is also estimated that this test is a required precursor of other LPD manned and unmanned aircraft deployment tests at sea. The articles assesses aircraft and deck availability improvements by using the Energy Index to signal the top of recovery (manned or unmanned). Energy Index quiescent recovery opportunities are presented outside the boundaries of current operating limits, though none of the launch or recoveries were made physically outside of published deck limits. Impacts on the proposed deck limits are discussed. Percent of improvement for operational availability is demonstrated. Details regarding the theory and derivation of the SH-60B and Scan Eagle deck recovery calculations are discussed. One of the most striking outcome from the VLA DLQ exercise is the apparent validation of the simulated results. The implication is the NAVAIR MFS or the RN MERLIN full-motion simulators may be used as a platform to advance calculate dynamic interface limits with considerable accuracy. This may furnish the naval aviation community with a potentially powerful tool, which may help in defining and possibly identify probable solutions to many of the problems affecting ship-aircraft operations. Beyond the basic problem of data verification and validation, the analytic procedure demonstrated above is sound and could be used to cross-correlate between proposed aircraft-ship deck limits and the vehicle expected physical responses.

In the shorter run, pilot comments observed that LPD rate tendency cannot by communicated from the display as it presently exists. That is, there is no way of knowing whether it is approaching green or red. Pilot D presented an interesting approach to this problem:

The relatively large "amber" zone that accounts for a wide range of deck motion states results in long periods of amber status. With no rate or trend information available, the pilot does not know whether the deck is trending towards green or red. This may result in a tendency to fixate on the LPD display, waiting for the status to change prior to takeoff or landing. It may be worth exploring a method of displaying "where" in the amber zone the deck energy exists. One possible way to display this would be seen on (FIG.26).

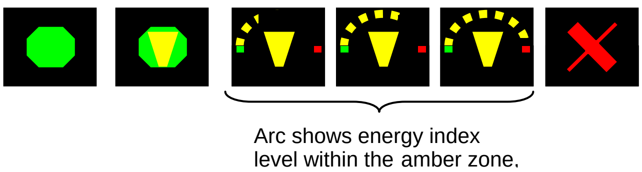

FIG.26 – PROPOSED LPD EXTERNAL LIGHT UP-GRADE OR MODIFICATION

Another potential problem occurs when the LPD displays a Red X and the deck status light shows Green. All wave-off lights should be coordinated and should display the same colour.

Conclusions

The primary goal for conducting dynamic interface analysis is to expend 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. Analytic study 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.

This report assesses aircraft and deck availability improvements by using the Energy Index to signal the top of recovery. Energy Index quiescent recovery opportunities are presented outside of current operating limits. A brief synopsis of the theory and calculation of the ship motion simulation and Energy Index programs, were discussed. The study conducted in real-time space, analyzed the interface of the SH-60B and DDG-88. Permitting a certain level of aircraft incident risk, it may be generally stated that SH-60 x DDG-88 deck clearance for the briefly unsecured SH-60B, while lightly restricted ahead and unusually unrestricted in beam sea, should not limit SH-60B availability or impact directly on the performance of the air vehicle under normal operating conditions. Air vehicle and deck availability are enhanced well beyond the indicated envelope when the operator uses the energy index to signal the top of recovery. As developed in the report, green deck points are identified even in the worst of sea conditions. The periods may be rapid, but owing to the rise time, the deck is constrained to pass from green to red by a latency period. This approach to deck limits is based on dynamic factors rather than static. It should be apparent that the envelopes calculated above are combination specific and dependent on the mathematical definitions programmed. If any dynamic or static parameters are modified, the envelope limitations may be modified, as well. Dynamic issues continue to be present throughout this period. The deck needs to be sufficiently stable for some time after recovery. Once their rotor is stopped, the deck crew would use the LPD as a deck monitor. The limits would be those at which a person would stumble owing to boundary layer conditions. This is particularly important if the crew is refuelling, rearming or traversing the aircraft.

While the report 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 service.

In the development of this study, an overview of the ship motion and dynamic interface simulations and modelling had 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 limit to be programmed for air vehicle automatic recovery. Beyond the basic problem of data verification and validation, the analytic procedure demonstrated above is sound and could be used to cross-correlate between proposed aircraft-ship deck limits and the vehicle expected physical responses.

On completing the aircraft-ship interface envelope study, the sum of the probability of incident produces deck limits by degree of freedom. These limits could be used in the first instance of air vehicle at-sea flight tests using the Energy Index to signal the onset of recovery. While angular and translational rate limits are used, the purpose of the energy index is to recover the vehicle in quiescence or flat deck. This is particularly important given the air vehicle configuration and the need to reduce to a minimum the grid recovery dispersions. A separate article summarises SH-60B / DDG-88 and ScanEagle / HMS Sutherland deck availability using Landing Period Designator (LPD) data recorded on-board Feb and March 2006. The tests were used to validate deck limit results obtained during simulated DLQ experiments described in this article (Ferrier, B., Carico, D. 2007)[5].

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Biographies

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Dr. Bernard Ferrier is Technical Director of BMT Syntek Tech. Aircraft/Ship Dynamic Interface Office. 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 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 Montreal, Quebec Canada and Arlington, Verginia. Prior to joining Bombadier, 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 Ecole Polytechnique de Montreal (Quebec) Canada.

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 analysing 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 September 2003.