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UAV Deck Recovery Stability Analysis

ABSTRACT

A manned or unmanned helicopter-ship qualification program (Dynamic Interface Testing) evaluates, improves, and/or develops all aspects of shipboard helicopter compatibility. Issues addressed during a test may include the adequacy, effectiveness, and safety of shipboard aviation support facilities and helicopter recovery procedures. Manned and unmanned aircraft share a number of common issues as those related to deck handling, repositioning, tie down, refueling and maintenance tasks. Procedures are further affected by the ability of an aircraft to land and remain on deck, in a controlled or restrained condition from the moment of touch-down to aircraft deck handling and tie down anchor regardless of the environmental conditions. These conditions are largely the product of the turbulent deck environment coupled by the ship's motion characteristics. The purpose of this Office of Naval Research sponsored Future Naval Capabilities and corresponding UK Ministry of Defence project is to demonstrate the feasibility to characterize the ship's environment to, amongst other objectives, automatically signal the initiation of UAV descent or to safely launch and recover manned air vehicles regardless of the seaway. A significant portion of shipboard helicopter compatibility testing involves pilot evaluations. Dynamic Interface (DI) testing of unmanned vehicles is not straight forward. The methodology of replacing piloted evaluations with operator estimates and the corresponding test criteria is established prior to actual testing. Focus on one aspect of the interface model to forecast from deck motion the encountered forces acting on a UAV with and without restraints, and corresponding deck motion limits, is discussed. Deck limits are computed from the load factors applied by various securing configurations based on the motion characterization of a platform in terms of, and as a function of, oleo compression and deflection, torque monitor along with indications of precise weight on wheels. Defining a limit, since there is no piloted variation or technique, scales normally used do not apply. The settled approach is to assess system performance using multiple launch and recovery cycles but only one recovery is required to justify an envelope expansion. 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 energy problems normally confronted by a helicopter during recovery in progressively difficult conditions.

ABBREVIATIONS

ASIST	Aircraft/Ship Integrated Secure and Traverse System also RSD
CD	Clear Deck Recovery
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
HARPOON	helicopter handling Sys (UK,USCG)
HCO	Helicopter Control Officer
HSL	Helicopter (Attack) Squadron Light
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
NVG	Night Vision Goggles
ONR	Office of Naval Research
RA	Recovery Assisted
RAO	Response Amplitude Operator
RAST	Recovery, Assist, Securing and Traversing
RN	Royal Navy (UK)
RNAS	Royal Navy Air Station (UK)
RSD	Rapid Securing Device (also ASIST)
SAMAHE	Helicopter Handling Sys (France)
SHOL	Ship-Helicopter Operational Limit
SMP	Ship Motion Program
SMS	Ship Motion Simulation composed of routines identified as NAV
TCS	Tactical Control Station
TD	Test Director

Report Documentation Page

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14. ABSTRACT
A manned or unmanned helicopter-ship qualification program (Dynamic Interface Testing) evaluates, improves, and/or develops all aspects of shipboard helicopter compatibility. Issues addressed during a test may include the adequacy,effectiveness, and safety of shipboard aviation support facilities and helicopter recovery procedures. Manned and unmanned aircraft share a number of common issues as those related to deck handling, repositioning, tie down, refueling and maintenance tasks. Procedures are further affected by the ability of an aircraft to land and remain on deck, in a controlled or restrained condition from the moment of touch-down to aircraft deck handling and tie down anchor regardless of the environmental conditions.

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TP	Test Pilot
UAV	Unmanned Air Vehicle
VLA	Visual Landing Aid
VMC	Visual Meteorological Conditions
VTUAV	Vertical take-off and landing Unmanned Air Vehicle
WOD	Wind-over-deck

INTRODUCTION

Dynamic Interface (DI) is divided into two broad categories: (1) experimental or at-sea measurement and analysis, and (2) computational analysis which is concerned with mathematical analysis and solution [1]. 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. The majority of DI experimentation investigates operational launch and recovery of vehicles, engaging and disengaging of rotors, vertical replenishment (VERTREP) and helicopter in-flight refueling (HIFR) envelopes. The purpose of DI testing is to safely expand existing day and night operational limits which are composed of wind speed and direction specifications. To a lesser degree, experimentation fixes corresponding static deck limits of ship roll and pitch.

A related task is shipboard suitability testing which assesses the adequacy, effectiveness, and safety of shipboard aviation facilities (such as UAV launch and recovery flight deck packages). Testing methodologies and procedures have been standardized by laboratories, such as, NAWCAD (Patuxent River) assisted by NSWC (Carderock), among other defense laboratories. Whilst envelope limits have some physical measures supporting its computation, it is predominantly composed of empirical constructs, such as, the Pilot Rating Scale (PRS). The operator measures workload resulting from: aircraft control margins, aircraft flying qualities and, performance in the shipboard environment [2].

Aviation facilities evaluation are evaluated with some physical measures, but is essentially assessed by empirical scales like the severity index. The index assesses facilities deficiencies as it affects day to day aviation operations. The distinguishing characteristic is the operability of the aircraft.

Level one is a deficiency affecting: airworthiness of the aircraft; the ability of the aircraft to accomplish its primary or secondary mission; the effectiveness of the air or ship crew; and/or the safety of the crew or the integrity of an essential subsystem.

Level two indicates a deficiency of lesser severity which does not substantially reduce the ability of the aircraft to accomplish its primary or secondary mission, but the correction of which will result in significant improvement in the effectiveness, reliability, maintainability, or safety of the aircraft.

Level three designation indicates a deficiency to be corrected for new aircraft and ship model but is too impractical or costly to correct on the studied model.

Experimental Dynamic Interface (DI) is complemented by computational DI which uses mathematical modeling and simulation to support flight testing. Simulation can be used to help define operational limits of any air vehicle/ship combination by:

1. Simulating any kind of ship motion and ship motion condition.
2. Simulating any kind of air vehicle over and on the deck.
3. Simulating any kind of retention (secured by nylon) or handling system
4. Simulating any kind of environment natural and artificial.

While computational methods may seem less taxing to the DI study process, it cannot replace experimentation. Envelope studies will always require physical verification. Simulation methods are used to initially compute the deck limits which are then compared to those recorded at sea. Whilst there are few simulations conducted ahead of the majority of current at-sea deck motion characterization analysis, it is still instructive to explain how deck motion limits are initially computed. 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 classic NIREUS (NATO Interopreability and RE-Use Study) and SAIF (Ship/Air Interface Framework) programmes 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 programme is focusing upon SHOL prediction where operations may involve recovery in high levels of turbulence about new naval vessels.

In this phase the existing flight simulator used for fleet training at RNAS Culdrose is being modified and external federate models 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 of NIREUS4 was to undertake a practical application of distributed simulations using the HLA methodology. With a view to demonstrate multi-national cooperation, simulation re-use and interoperability and to support the guidelines supplied by an Allied Naval Engineering Publication (ANEP) on the application of simulation based design and virtual prototyping in ship design. The VTOL-UAV application was chosen because of the NATO/PfP interest in MUAV operations [3]. 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 SAIF project, 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 (Ship-Helicopter Operational Limit) 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 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.

DI Simulation

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 imagined system was designed to operate at sea from small ship combatants. 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 data 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.

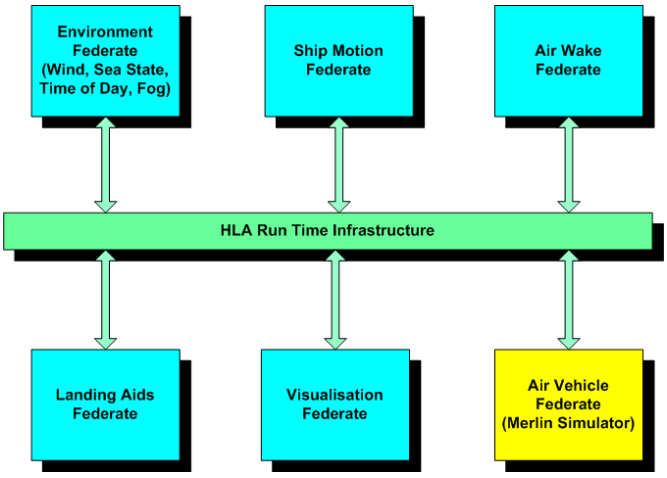


Figure 1 – Federation Architecture

FEDERATES

The purpose of this initial analytic evaluation was to use the Simulator and Tactical Control Station (TCS) 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 [4].

By discipline the Federation is reduced to figure 2.

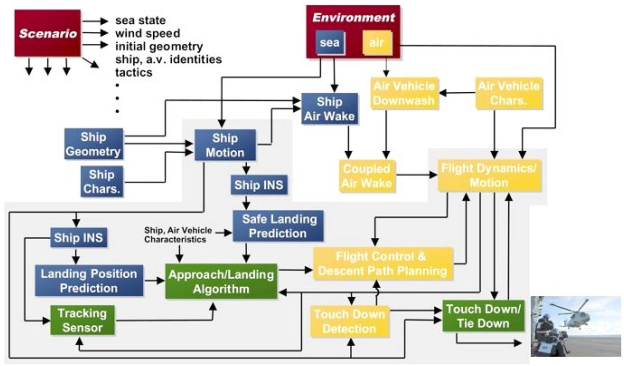


Figure 2 – HLA Federation by Discipline

Ship motion

Launch and recovery envelopes, typically developed empirically by experimental methods, devote little attention to the ship deck's dynamic factors encountered on recovery. The fundamental effort is expended in describing the atmospheric conditions over the deck. Once defined, a static related empirical value is imposed relative to the ship's roll and pitch 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 [5] coupled with the Ship Motion Simulation (SMS) program [6]. In the development of simulated ship motions, the computational methodology uses essentially spectral probabilities in order to produce deterministic synthetic time histories. The seaway is defined as the sum of a large number of regular sinusoidal waves each at different amplitudes, length and phase angles.

The SMS Model is derived from the relationship between the wave and ship motion spectrum [7]. It incorporates seakeeping (the ability of a vessel to withstand rough conditions at sea) philosophy and applies various definitions of seaway formulation, such as, the Bretschneider spectrum [8]. SMS defines a seaway, computes the hydrodynamic and hydrostatic forces imposed on a ship (defined as the product of its transfer function and the seaway) and calculates a resulting ship time history. The simulation is an extensive treatment of a floating object's response to the dynamic loads on its structure. The simulation has been validated periodically after every major program improvement [9]. Figure 3 defines the principal coordinate systems used in the simulations defining a study ship and air vehicle.

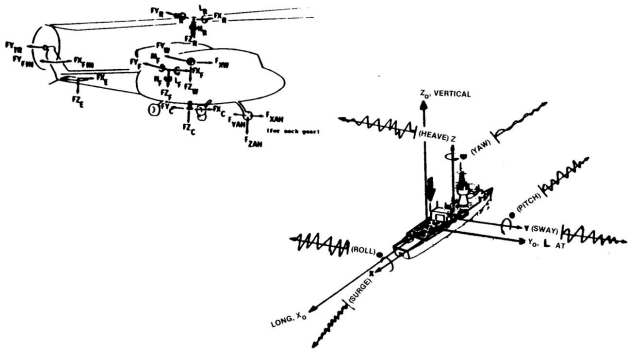
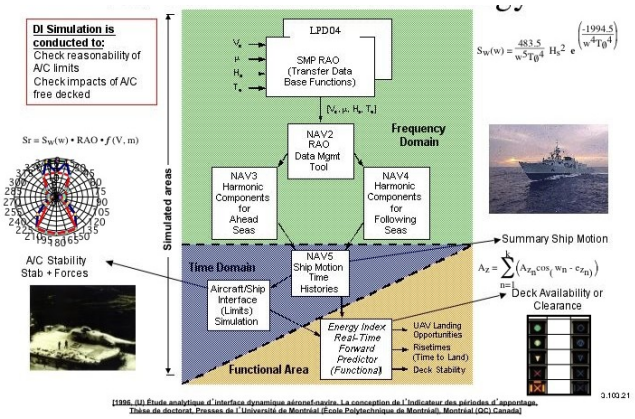


Figure 3 – Aircraft – Ship Interface Coordinate Systems

Figure 4 displays the simulation flow diagram along with the corresponding reports. The simulation strategy is divided

into eight (8) subject routines identified as NAV and then the series number. The simulation establishes in the frequency domain the description for the forcing function or seaway. It selects an appropriate definition of the ship transfer function, also called the response amplitude operator (RAO). The simulation then computes the ship response definition as a series of harmonic components. The transfer from the frequency domain to the time domain is next made by summing over time the series of harmonic components which produces ship motion time histories. The time histories are used to calculate aircraft deck limits, encountered deck forces and air vehicle motion limits. The transfer to the real-time is made by running the ship motion time histories through energy index algorithm called LPDLOOP, which calculates deck availability or clearance.



[1996, (U) Étude analytique d'interface dynamique aéronef-navire. La conception de l'indicateur des périodes d'appontage. Thèse de doctorat. Presses de l'Université de Montréal (École Polytechnique de Montréal). Montréal (QC) Canada]

Figure 4- DI Simulation Methodology

Referring to figure 4, the SMS portion of the program is divided into two basic themes, spectral analysis and the calculation of motion histories in the time domain. Figure 5 presents the calculation flow chart. The SMS fundamental relationship is:

$S_r = S_\omega(\omega) \bullet RAO \bullet \boldsymbol{f}(v, \mu)$ .....(1)

where: S_r:..... Ship response spectrum

$S_\omega(\omega)$:.....Seaway spectrum

RAO:..... Ship transfer functions

f(v,μ):.....Frequency mapping

v: .....Velocity

μ: Relative wave angle

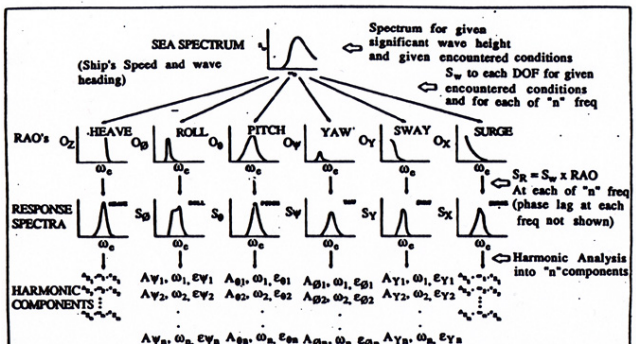


Figure 5 - SMS Calculation Methodology

The forcing function or Wave Spectrum is defined as a collection of a great number of simple, regular sinusoidal waves in summation. Relating this to the physical world, the seaway is composed of a great number of waves varying slightly in frequency.

The relative speed and direction of the ship and waves affect the transfer of energy and how the energy is expressed in ship motion. Likewise, the actual spectrum confronted by the ship will be different and based on these same parameters. The profile of energy transference is based on the angle between the ship's direction and speed with the dominant wave direction, wave height, period and speed. Figure 6 shows this mapping.

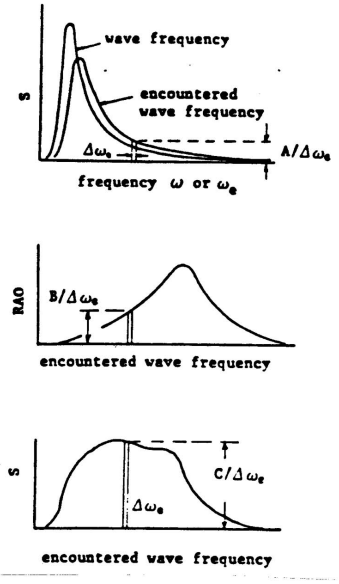


Figure 6 – Response Spectrum Calculation

The mapping of the seaway spectrum into the encountered spectrum is given by:

$$\omega_e = \omega - [(\omega^2)/g] \bullet V \cos \mu \qquad (2)$$

where

ω_e = encountered frequency (rad/sec)
ω =regular oceanic frequency (rad/sec)
V =ship's speed (knots)
μ =relative wave angle (degrees)
g =gravitational constant (ft/sec^2)

As developed in figure 7, the ship response spectrum is created as the product of the RAO and the driving sea spectrum over the entire range of encountered frequencies.

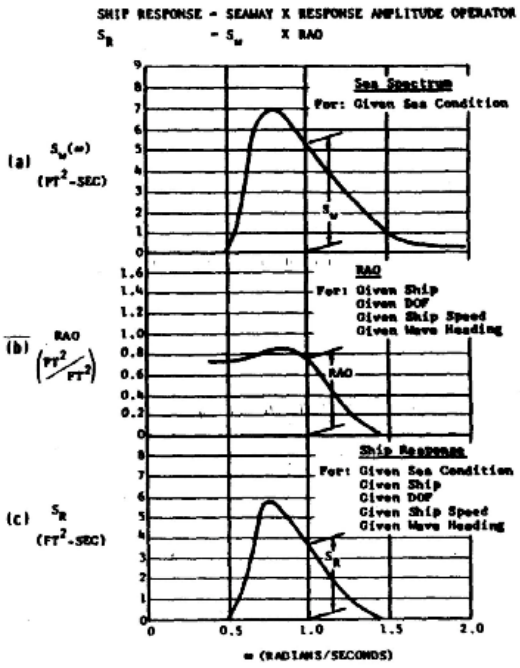


Figure 7 – Response Spectrum Calculation Sequence

The response spectrum is reduced to sets of harmonic components for each degree-of freedom. Typically, this means selecting response spectrum components, which represent the vast majority of the energies in the system. Harmonic components are used to create non-repetitive time histories. The relationship between the frequency and time domains is graphically displayed in figure 8.

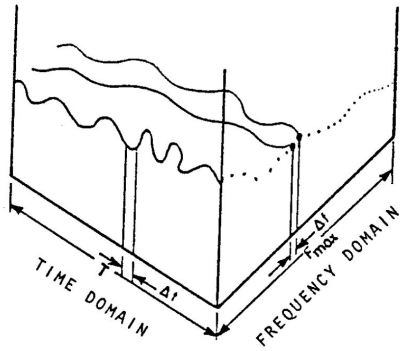


Figure 8 – Relationship Between Time and Frequency Domains (after Ouellet, Y.1985)

From figure 8, it is possible to describe recorded time histories in terms of its frequency content. The frequency spectrum is created representing the passage of a wave in real-time. Consequently, there exists in the frequency domain an irregular unique profile of real-time wave motion. The converse is not true. There are a large number of real-time solutions for a given spectral density. Synthetic time histories are created stochastically by summing the harmonic components over a given time period. A typical time history equation is given by:

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

where

A_Z: DOF amplitude

ω: a circular frequency

e: phase angle

Time histories are produced by the sum of 48 synthetic functions (k=48). This is a stochastic process. A stochastic process is defined by a random family of variables dependent on space and time. A typical synthetic time history trace is shown in figure 9.

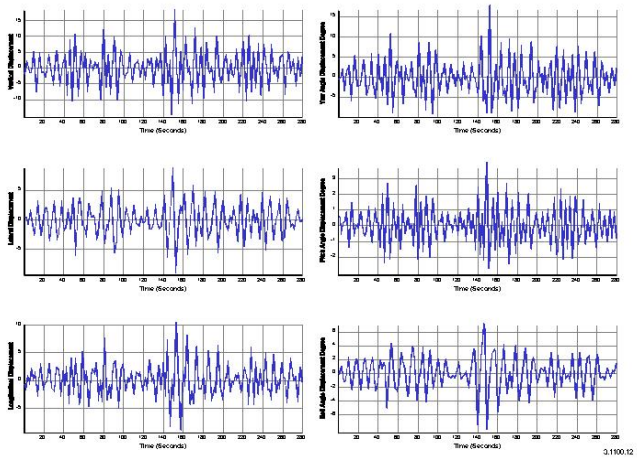


Figure 9- Stochastic Time History Trace

The relationship between time histories traces by degree-of-freedom are displayed in figure 10 a,b.

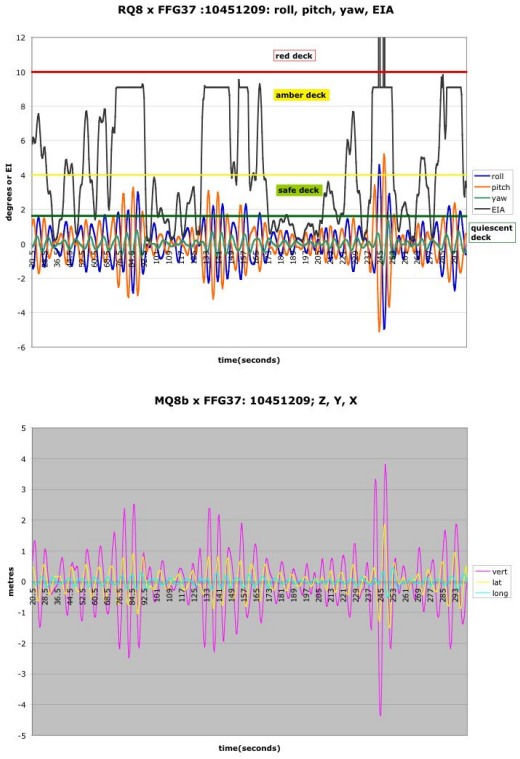


Figure 10a- Typical Stochastic Time History by superposition

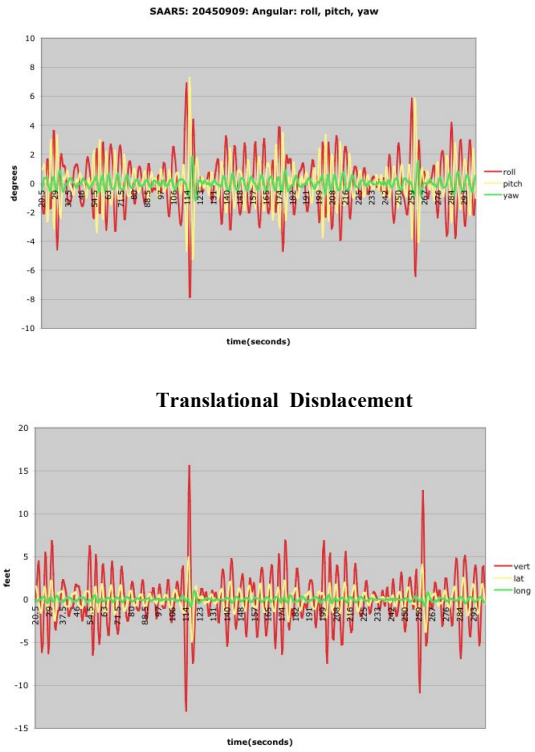


Figure 10b – Time Histories Superimposed

Here angular and translational degrees-of-freedom are superimposed. From this figure, it becomes evident when motion sensitive tasks, such as aircraft recovery, ought to take place. In summary, the ship motion simulation creates deterministic measures of ship motion from a probabilistic spectrum.

Air Vehicle

The air vehicle simulation component developed for the NIREUS programme was based upon the Helistab model developed at QinetiQ for use in flight control, handling qualities and piloted simulation studies. It resembled essentially a traditional helicopter with tri-cycle landing gear. This model was recently reengineered and extended to form a Simulink-based helicopter library, Helilink, from which modular, moderate complexity rotorcraft simulations can be created.

The MUAV simulated in NIREUS was assumed to be a conventional helicopter configuration, and was constructed from Helilink rotor, aerodynamics, engine and undercarriage components, combined with standard flight dynamics elements such as the rigid body equations of motion, Euler angle attitude equations and ISA standard atmospheric model.

The Aircraft/Ship Interface Simulation (DI) used since NIREUS, is a mathematical description of the stability of an air vehicle confronted by a defined environmental condition. Factors affecting an air vehicle on a moving platform are primarily ship motion; Wind Over Deck; Ship Airwake Turbulence; and deck surface conditions (e.g.: wet, dry, oily, obstructed).

In DI, deck handling limitations can be defined as the point at which an aircraft/ship incident occurs. Incident means an occurrence of aircraft turnover, pitchback or on-deck slide at any point from touch-down to hangar stowage and back to launch position. Deck handling studies determine turnover limits, sliding freedom, tiedown forces, traversing factors, and pitch back limitations.

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: aircraft landing gear footprint; on-deck location and orientation; aircraft weight, inertias, center of gravity, lateral drag area and center 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 aircraft relative to the ship as function of time, for various ship motions [10]. Figure 11 displays a résumé of the moments acting on a generalized aircraft at sea.

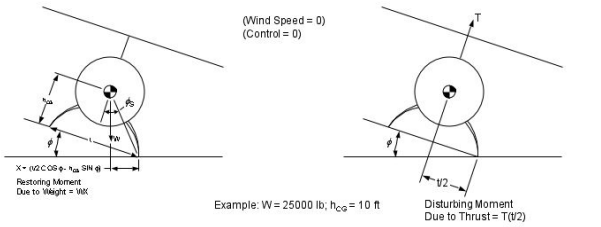


Figure 11- Moments Acting on a basic air vehicle on the deck at Sea

The inertial loads at the aircraft center of gravity induced by ship motion are given by;

$$Fi_x = W * AXcg$$
$$Fi_y = W * AYcg \quad (4)$$
$$Fi_z = W * AZcg$$

where,

$\begin{pmatrix} F_{ix} \\ F_{iy} \\ F_{iz} \end{pmatrix}$ = inertial forces due to ship motion

W = aircraft weight

$\begin{pmatrix} A_{xcg} \\ A_{ycg} \\ A_{zcg} \end{pmatrix}$ = acceleration

In the longitudinal, lateral and vertical directions, these inertial loads become:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} T_{11}T_{12}T_{13} \\ T_{21}T_{22}T_{23} \\ T_{31}T_{32}T_{33} \end{pmatrix} \begin{pmatrix} F_{ix} \\ F_{iy} \\ F_{iz}+W \end{pmatrix} \quad (5)$$

where: Tij = T (f, q, y) (transformation matrix from ship's axis system to horizontal level/vertical axis system).

and

f = roll

q = pitch

y = yaw

A wind force is added to the ship motion induced forces. In SMS, a unidirectional continuous wind model (simplistic model), with its vector in the same direction as the seaway, is applied. Figure 12 displays the inertial components associated with the introduction of wind on the computation of the sum of forces at the center of gravity of the air vehicle. The wind vector is defined by its magnitude, V_{wind} and its direction, Df_{wind}. To compute the lateral force applied at the aircraft Center of Pressure due to the wind, the V_{wind} is resolved along the normal to the aircraft center line ($V_{W_{long}}$ and $V_{W_{lat}}$). The lateral component is used to compute the lateral force with a proportionality constant, as follows:

$$F_{W_y} = 3.5\ Ay \left(\frac{V_{W_{lat}}}{100}\right)^2 \quad (6)$$

where: Ay =Aircraft projected area normal to the $V_{W_{lat}}$ component

F_{W_y} =Lateral force applied at the aircraft center of pressure due to wind

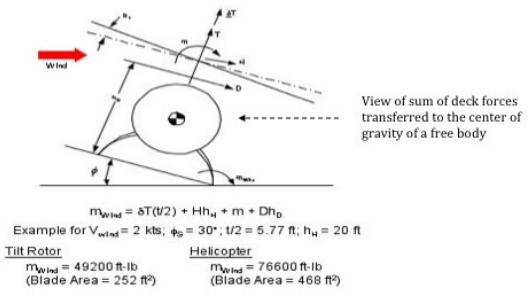


Figure 12- Wind Acting on an Air Vehicle on the Deck

The standard coordinate system used to develop the stability of air vehicle on the deck of a moving vessel is displayed in Figure 13.

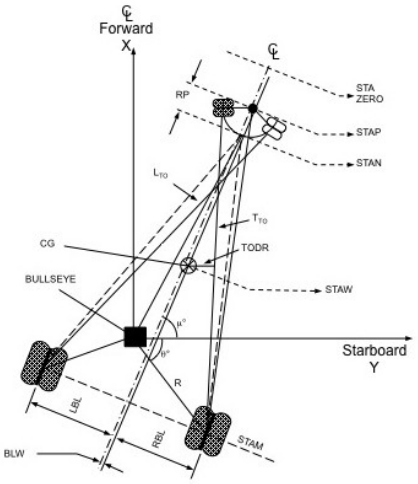


Figure 13- Undercarriage Air Vehicle Freebody Diagram

The axial forces on the main landing gear due to the wind force F_{W_y} is given by:

$$F_{RMG_{WIND}} = (F_{W_y}) \frac{(WL_{CP} - WL_G)}{(L_{BL} - R_{BL})} \quad (7)$$

where:

$F_{RMG_{WIND}}$ = Main Gear (right) axial force

F_{W_y} = Wind lateral force component

WL_{CP} = Center of pressure waterline

WL_G = Ground waterline

L_{BL} = Left wheel butteline

R_{BL} = Right wheel butteline

The incremental aircraft roll due to the wind is given by:

$$Df_{(WIND)} = \tan^{-1}\left(\frac{F_{RMG_{WIND}}}{(K)(L_{BL})}\right) \quad (8)$$

where: K = common spring constant

Axial forces on the main landing gear due to aircraft inertial forces in the plane of the main gear, is given by:

$F_{RMG_{(Iner}$ View of sum of deck forces transferred to the center of gravity of a free body (9)

where:

WL_G =Center of gravity waterline

$F_{RMG_{(Inertia)}}$ =Right main gear axial force due to the lateral inertial force Y defined in equation (5).

Assuming perfect rocking, the axial force on the left main gear is vectorially opposite to the force acting on the right main gear:

$$F_{LMG_{(Inertia)}} = -F_{RMG_{(Inertia)}} \quad (10)$$

where: $F_{LMG_{(Inertia)}}$ = Left main gear axial force

The incremental aircraft roll due to inertial loads is determined by:

$$Df_{(Inertia)} = \tan^{-1}\left(\frac{F_{RMG(_{Inertie})}}{(K)(L_{BL})}\right) \quad (11)$$

The simulation model assumes a constant wind, therefore, $Df_{(wind)}$ is constant throughout the simulation run. However, $Df_{(Inertia)}$ is continuously changing with ship motion. The total incremental change in the aircraft roll with respect to the ship is given by:

$$Df_{(total)} = Df_{(wind)} + Df_{(Inertia)} \quad (12)$$

The distance from the aircraft center of gravity (CG) to each line is computed as TODR and TODL (right and left). They define the distance that the CG should move for a turnover to occur (right or left). These lines describe an angle TOR (right) or TOL (left). They are expressed as:

$$\sphericalangle\ TOR = \tan^{-1}\left(\frac{TODR}{WL_W - WL_G}\right) \quad (13)$$

$$\sphericalangle\ TOL = \tan^{-1}\left(\frac{TODL}{WL_W - WL_G}\right) \quad (14)$$

They describe the angle between a vector from the CG normal to the Rto and the Lto and the vertical.

Similar boundaries are computed for the pitchback condition. The hinge line about which the aircraft is likely to pitchback is the line which joins the right to left main gear. The distance from the CG to the hinge line is defined as PBD (pitchback distance) and expressed as:

$$PBD = (CGx - MGx) \quad (15)$$

where,

PBD= pitchback distance

CGx= aircraft CG station

MGx= aircraft main gear station

The associated pitchback angle or PBA is given by:

$$\measuredangle \text{ PBA} = \tan^{-1}\left(\frac{\text{MGx-CGx}}{\text{WL}_W\text{-WL}_G}\right) \qquad (16)$$

where,

WLw = Waterline to the aircraft CG

WLg = Waterline to the ship deck

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. Figure 14 develops dynamic turnover caused by uneven loading of the rotor or by ship motion, the same phenomena occur.

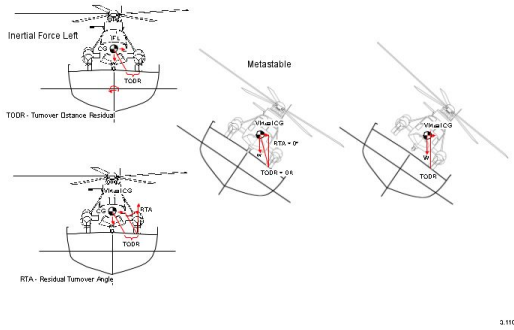


Figure 14 – Ship motion caused Dynamic Rollover

The aircraft center 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. The distances TODR, TODL, and PBD essentially reflect system stability. At the point where a distance becomes negative, 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 liftoff is indicated. The sum of these incidents trace aircraft-ship operational envelopes [11].

Deck Characterization [Landing Period Designator]

The energy index is an empirical formulation designed to convert ship motion characteristics and aircraft structural definitions into deck limits. It is correlated to the level of kinetic and potential energy contained in the ship. This index provides information on the motion that the ship could exhibit in the near future using real-time motion measurements of angular displacements and velocities, and linear velocities and accelerations. It capitalizes on the rate at which a vessel can displace fluid due to natural hydrodynamic forces imparted by the sea as a function of the operating limits of an approaching air vehicle rather than predicting using historical data to extrapolate into the future. 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 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 [12].

The energy index equation measures lateral and vertical velocities and accelerations as well as roll and pitch angular displacements and velocities weighted by dynamic coefficients. The equation is the sum of the squares of the various parameters and terms representing real-time ship - aircraft interface motion.

$$EI = a_1\dot{y}^2 + a_2\ddot{y}^2 + a_3\dot{z}^2 + a_4\ddot{z}^2 + a_5\phi^2 + a_6\dot{\phi}^2 + a_7\theta^2 + a_8\dot{\theta}^2 \qquad \text{(eq 17)}$$

where a_1 to a_8, are weighted dynamic coefficients.

The calculation of dynamic coefficients is performed in three distinct steps executed simultaneously. In the first step, relative coefficients are established between each of the four degrees of freedom and their derivatives. A relationship is derived for roll angle and roll rate, pitch angle and pitch rate, lateral velocity and lateral acceleration, and vertical velocity and vertical acceleration. These relationships are directly related to the ship's velocity, the relative wave angle, the significant wave height and the modal period.

$$A = \begin{bmatrix} A1 \\ A2 \\ A3 \\ A4 \\ A5 \\ A6 \\ A7 \\ A8 \end{bmatrix} = \left\{ \begin{matrix} A11 \bullet A12 \bullet A13 \\ A21 \bullet A22 \bullet A23 \\ A31 \bullet A32 \bullet A33 \\ A41 \bullet A42 \bullet A43 \\ A51 \bullet A52 \bullet A53 \\ A61 \bullet A62 \bullet A63 \\ A71 \bullet A72 \bullet A73 \\ A81 \bullet A82 \bullet A83 \end{matrix} \right\} \qquad \text{(eq 18)}$$

The degrees-of-freedom that are considered highly coupled are roll and lateral motion and pitch and vertical motion. Coupled degrees-of-freedom are directly related and can only occur independently in very special cases. Pitch and vertical motion usually occur together though rarely in phase. The phase lag between coupled degrees-of-freedom contribute to the stability of the energy index. As discovered in earlier studies, a maximum value in pitch will often occur some time, t, BEFORE the coupled peak in vertical displacement.

The third step compares the aircraft limitations scale completing the calculation of the appropriate weights of each degrees-of-freedom. The product of the element coefficients A_{11}, A_{23}, (see eq.18) produce the energy index coefficients in real-time. The energy index is then calculated and filtered (Queen-Victoria and DOFmax filters). It is then compared to the deck availability scale which are communicated to the user. A summary of the energy index calculation is provided on Figure 15.

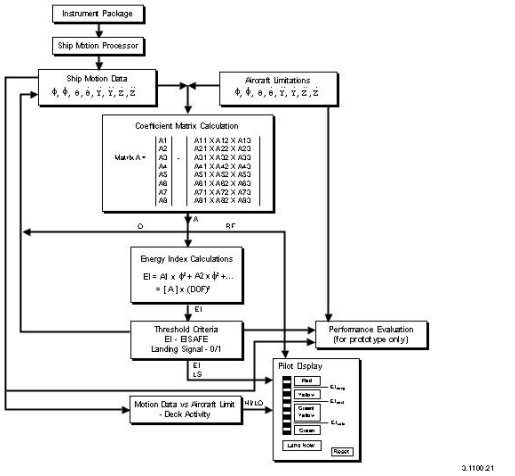


Figure 15 – Energy Index Calculation Flow Diagram

The deck availability, as defined by the energy index, is directly based on the ship characteristics (measured) and aircraft limitations (defined) (see figure 16). Deck motion security limits must be established for each combination of aircraft and ship. These limits may be measured experimentally or calculated analytically. A limit is defined by the impact that a certain ship motion condition may have on the structural integrity or dynamic response of a given air vehicle. If the condition exceeds an operational specification, a limit condition is identified. The sum of these limits produces a red line that is drawn on the energy index scale for a given ship.

The red line is absolute. In a red light means one or more DOFs have exceeded acceptable aircraft limits. Therefore, deliberately assigning DOF limits several points under the calculated absolute limit is a prudent if not conservative measure. Nonetheless, the deck is available for aircraft activity under the red line. However, in order to capitalize on ship physical motion constraints, the operator must await a green signal. The energy defined for a green condition infers that the potential energy being transferred from the sea into the ship's structure is not sufficient to displace the ship into a red line condition in under some specified period of time.

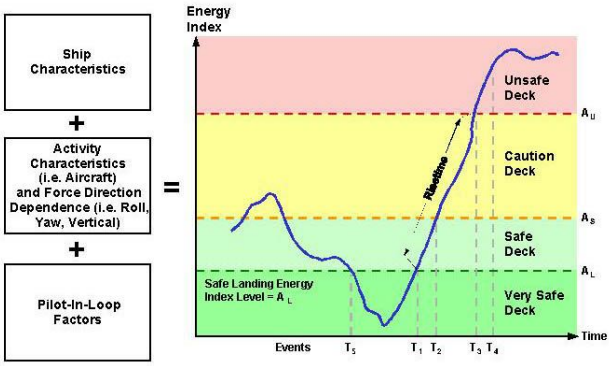


Figure 16- Deck Availability and Risetime

The time required to raise the deck from minimal motion to unacceptable motion is called the risetime. The risetime may be analytically or experimentally determined. The risetime is a characteristic of the ship's response and rarely changes. In terms of the energy index scale, it 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. The risetime is mirrored by a falltime, which is the time period measured from the negative side of the red line to the negative side of the green line. A typical recorded trace is displayed in figure (17).

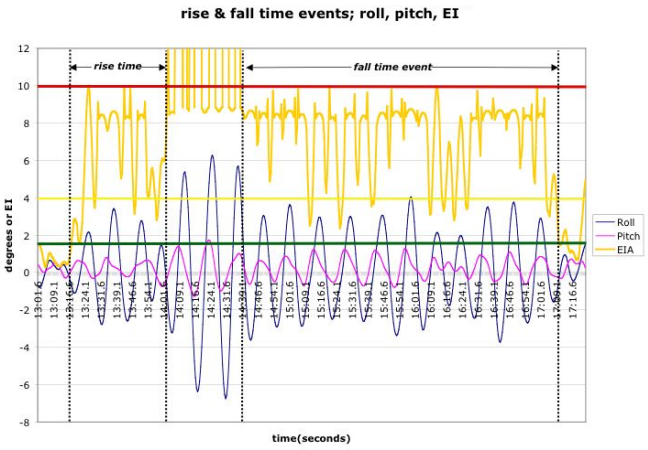


Figure 17- Typical Rise and Fall time Event and Trace

AT SEA TESTS WITH SAMPLE RESULTS

Motion of the aircraft on or near the flight deck 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.

The system used to measure the ship's motions, consists of a Kongsberg (Seatex) Motion Reference Unit (MRU). Both the ONR LPD and MORIAH units used the same measurement device. The MRU was zip-tied fast to an upright beam behind the LPD rack on the port side of the hangar near a fire hatch. The energy index was calculated based on the MRU's evaluation of the deck's motion.

Figure 18 – Motion Reference Unit (MRU) on LCS-2

The CPU is housed in a rack encased standard PC hard disk (Figure 19). Other components not used but are normally associated with the LPD include an external light for manned operations and a peanut light box used for manual launch and recovery of UAVs. It also contains a wave-off feature for manned operations

The entire test kit was assembled and secured in the hangar near the hangar door (located at the flight deck level). As described above, the MRU was attached behind a bulk-head attached steel plate protecting the instrument from accidental disturbances. Owing to the temporary nature of the MRU deployment, the device was secured with no-play zip-ties. It was levelled and calibrated to the ship's integrated MORIAH environmental kit (located in the flight tower) and confirmed. A MORIAH CPU was Velcro-wed to the top of ONR LPD rack encased standard PC hard disk (Figure 19).

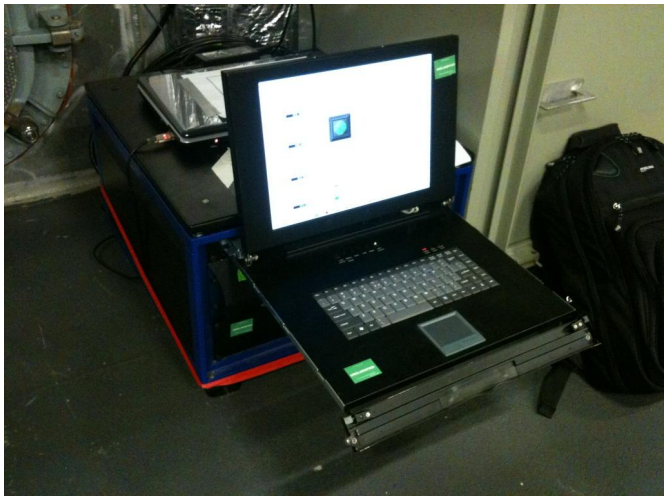


Figure 19 – ONR LPD unit secured for sea

During the trial LPD data was continuously recorded in files of one-hour segments. Each file contained a time stamp, the calculated energy index value and the engineering units representing the various six degrees of freedom, and their rates and accelerations. In addition, a channel was reserved for ship true heading, but not used on this trial. The LPD energy index calculations are made at a rate of up to 20 Hz but normally at 10 Hz. The data files were run though a utility program (NAV11 or LPDLOOP) in order to identify each green to red rise and the corresponding ship motion parameters that caused the red indication. This green to red change is what was defined earlier as the 'rise-time'. A NAV11C evaluation file was created for all the runs containing information on any rise-times and the statistics regarding deck availability with the entered limits.

An example follows of the recorded test results with

corresponding study graphics. Three basic graphics are shown. The first graphics displays a one-hour trace (figure 20) containing roll and pitch along with the corresponding energy index. The second graphics (figure 21) displays a rise and fall time event (time from rest to out of limit) along with a third graphics (figure 22) displaying the corresponding rate displacement for the period.

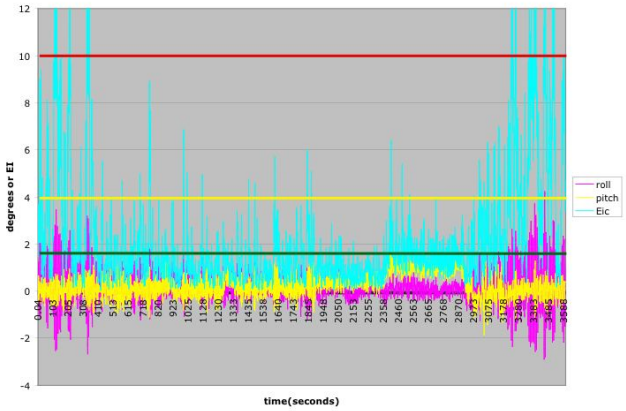


Figure 20 – Sample Recorded trial data

Figure 20 time history displays the full one-hour recorded roll and pitch traces along with the corresponding energy index trace. The orange trace is the energy index calculation. Any trace above the red EI = 10 line indicates out-of-limit or unsatisfactory conditions. Anything between the yellow and red lines refer to high energy but in-limit deck conditions. Traces within the green and yellow bounded area refer to safe deck conditions while the area between zero (0) and the green line is the zone called green or quiescent deck conditions. Also shown are the corresponding roll and pitch measured values.

Figures 21 and 22 displays one of the recorded rise and fall time events contained within this file. In each case, note the response of the energy index trace to changing roll, pitch, Z', Y, or X'. Here red deck was caused by excessive roll and Y' (lateral rate) motions.

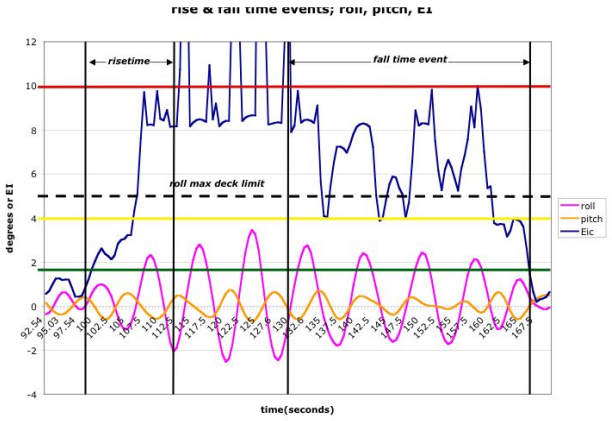


Figure 21 – Rise time event in time history

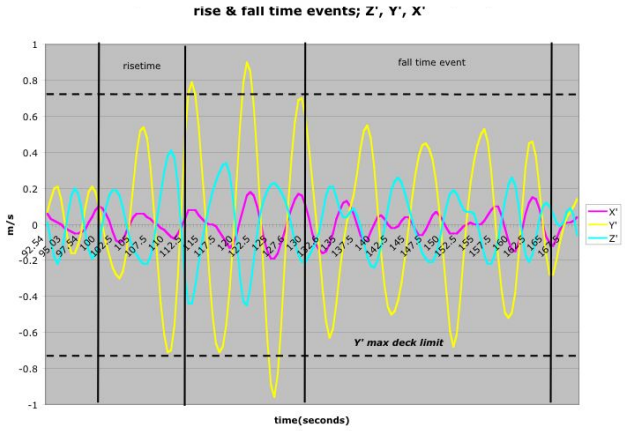


Figure 22 – Corresponding rate motions

Table 1 displays the file summary of rise time events, time length by rise time, and the distribution of LPD deck status.

Table 1 – Corresponding Abridged Analysis

****NAV11C EVALUATION FILE****
DIAGNOSTICS on data file: .csv
This file is type: 2.00 where 0 2 3=recorded 1=simulated

Data Playback time step= '0.50' seconds'

RISETIME EVENT BEGINNING @ TIME '99.54' EIA '1.66' ENDING TIME '113.04' EIA '10.74'
Risetime event = '13.50' seconds
ROLL= '-1.32' PITCH= '0.47' ROLLVEL= '1.53' PITCHVEL= '-0.17' ZVEL= '-0.44' m/s YVEL= '0.73 m/s'
RISETIME EVENT BEGINNING @ TIME '198.05' EIA '1.68' ENDING TIME '215.54' EIA '18.37'
Risetime event = '17.49' seconds

There are '7200.00' points in run
Green Deck in run= '2281.50' seconds which is= '63.38' percent of run
Green-Amber Deck in run= '840.00' seconds which is= '23.33' percent of run
Amber Deck in run= '438.00' seconds which is= '12.17' percent of run
Red Deck in run= '40.50' seconds which is= '1.12' percent of run

Total deck availability in run = '3559.50' seconds which is = '98.88' percent of run

Good risetimes in run + 5.0 seconds = '7.00'
OK risetimes in run + 4.0 - 4.9 seconds= '0.00'
Error risetimes in run < 4.0 seconds= '0.00'
Total number of risetimes in run= '7.00'

The data file is a recording composed of 3600 seconds (60 minutes). Referring to the example, the ship experienced 2281.5 seconds of quiescent deck or 63.4% of the run. 840 seconds of safe deck or 23.3 % of the run. Amber deck measured 438 seconds or 12.2%, and 40.5 seconds were measured as danger or red deck amounting to a bit greater than 1% of this run. The UAV model could have operated through 98.9% of the run. There were 8 rise time events measuring greater than 7 seconds.

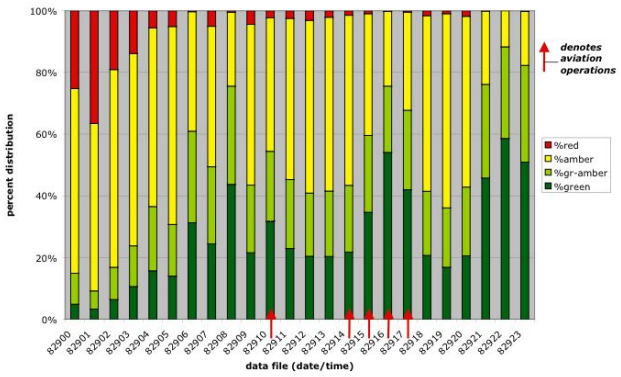


Figure 23 – Overall Percent Deck Stability

Figure 23 displays the percent distribution of deck energy recorded. The LPD was active all 24 hours. There were 5 files with Aviation Operations containing launch and a recovery events. The data indicates the ship experienced significant agitation early in the day. The seaway began to subside along with strategic ship maneuvering greatly reduced the extreme motions on the deck. The largest deck motion displacements coincided with night sailing. The majority of the recordings indicate the deck was available for operations but with less than a half of the time measured in quiescent and safe deck conditions. There were 23 files exhibiting excessive motion measuring from a few seconds to several minutes. The files contained both excessive Y' and roll motions. A sample hour is shown in figure 24.

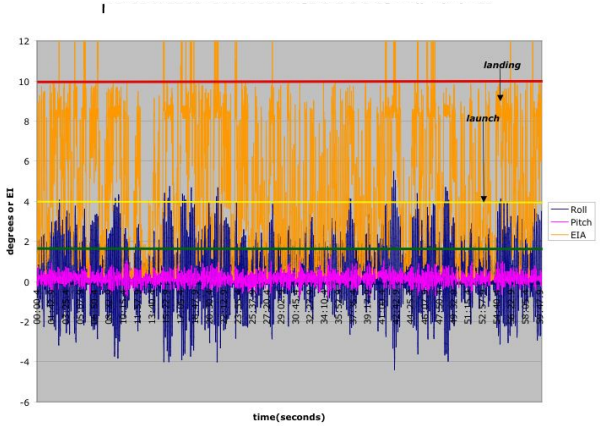


Figure 24 – Time History File Flt Operations

Figure 24 shows the ship was essentially in trim. In the course of analyzing the ship's motion, other characteristics which may impact the launch, recovery and deck handling, were identified. As introduced earlier, the time necessary to raise the deck from a stable to an unavailable condition can be derived experimentally from the calculation of the maximum EImax. As described earlier, the time required to raise the deck from minimal motion to unacceptable motion is called the risetime. The risetime is a thumb print characteristic of the ship's response and rarely changes. In terms of the energy index scale, it 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. The risetime is mirrored by a droptime, which is the time period measured from the negative side of the red line to the negative side of the green line. A typical trace is displayed in figure 25.

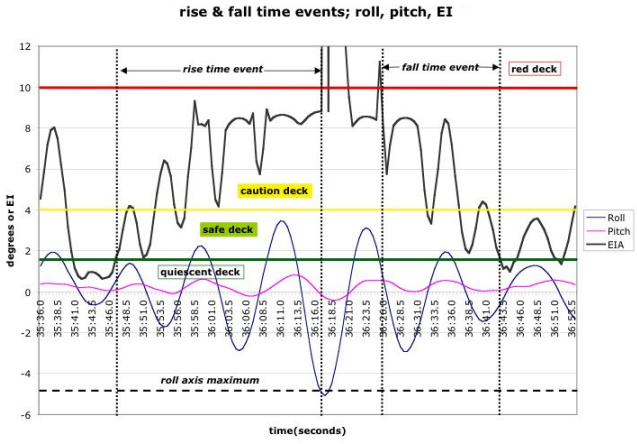


Figure 25 - Rise and Fall time events

The example shows a roll axis divergence exceeding

the deck roll limit. In this case the time it took for the deck to rise from quiescence was 26.5 seconds. The amount of time it took the ship to expend the excess energy to achieve quiescence was 23 seconds. There appears to be a 1° roll list to port and 0.5° +pitch trim condition.

In the course of these trials, there were 2, 423 rise time events recorded. Of the total sum, there were 113 slam events. As mentioned earlier in the report, slam is a ship motion response to a strong yaw axis stimulus causing the ship to rise swiftly, in many cases, out of the water. Slam depresses the normal rise time measurement artificially. It is not unusual to record rise times under 1 second. Discounting slam induced rise times leaves 2, 423 events. The computational minimum of the test vessel is 5.0 seconds. The number and duration of the minimum rise time events is shown in figure 26.

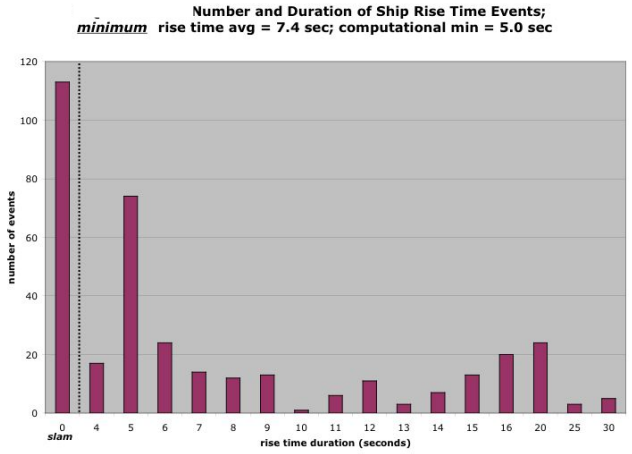


Figure 26 – Minimum Rise time distribution

The figure displays the distribution of events by time period indicating that events occurred at very long periods but was particularly weighted around 5 – 6 seconds. The implication is that a modal response zone exists between 4.9 – 6.5 seconds vis-à-vis the deck limits of the vehicle. Another modal area appears further down the risetime scale around 15 seconds.

Normally, ship motion variations occurs as a function of ship speed and direction and wave heading and sea state. The LPD test points vary according to ship conditions and wind-over-deck speed and direction combinations that result in different levels of ship motion. The choices offered to the UAV are set by a truth matrix testing various conditions simultaneously. Given a descent time less than the risetime characteristic of the host vessel, deck motion conditions must physically be within air vehicle deck limits on recovery. Of the several test cases attempted, none had the air vehicle recovered on a deck other than within limits.

The preliminary analysis indicates favourable proof-of-concept solution. The impact for the UAV program includes improved program safety and reduced risk in the launch and recovery operation. Other impacts for landing and launching within deck limits include: reduced ole - skid compression; lower engine torque; lighter gear deflection and improved aircraft stability. Finally, given the preliminary data results, the ONR LPD program appears to favourably support the fundamental ONR Future Naval Capabilities mission for UAV autonomous operations, in general, and towards UAV autorecovery in particular.

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. 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.

The focus of this evaluation applied a well established computational methodology to analyze and characterize the ship's motion as a function of the UAV deck limits. There were 453 hours of recorded motions representing sea states calm – 4/5. As a fundamental, the recorded motion data indicates that the platform configuration to be stable even in significant seas. The motions were smooth with the various axis of motion computed without any unusual displacements or discontinuities in the data. Red deck incidents appeared very early into the test. Excessive motions were initially caused by ship's maneuvers but also rising and falling seaway. In order of importance to the system, excessive roll, Y' and pitch (in that order) were the principal causes for the development of red deck. In much of the red deck time histories, excessive Y' did occur either alone or in association with excessive roll with excessive Y' developing first. Based on early simulations, the free decked aircraft has a tendency to slide on the deck in seaways containing in excess of Y'. Neither Y'max or Z'max are presently tracked for not-to-exceed measures. Interesting enough, excessive Z'max was not recorded in any of the time history files. This is consistent with the recordings in its coupled angular axis, pitch. Excessive pitch was rarely recorded during the testing program and never during flight operations.

In the development of the report topic, an overview of the ship motion and dynamic interface simulations and modeling has been described with

the emphasis on forces induced to the undercarriage 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 is sound and could be used to cross-correlate between proposed aircraft-ship deck limits and the air vehicle's expected physical responses.

Evaluating the launch and recovery event time histories in terms of the energy index value, launch events appear to have a lower energy index value average than the corresponding recovery events. In addition, in a related observation, there doesn't seem to be a relationship between the ship's motion and the moment choice of deck landing. To avoid making the UAV system deck interface portion too complicated while addressing aircraft-deck critical motion parameters, it may be possible to apply a deck motion monitoring system, like the energy index, to automatically signal excessive motion warnings to the operator and/or the tactical control station. The software fix in place, all the aircraft limits could be applied without altering appreciably the present recovery concept.

The other physical attribute of the platform concerned its risetime behavior. There were over 2,400 risetime events recorded throughout the testing program. The shortest rise time events averaged out to 7.4 seconds with an overall average inertial delay of 18.6 seconds. The computational minimum risetime is 5.0 seconds. The report described the application of a monitor device to amongst other objectives, automatically recover unmanned air vehicles from the final hover position to the recovery grid irrespective the sea condition. To achieve this autonomous operations goal, knowledge and use of the risetime phenomena would be necessary. Application of the risetime may require analysis of current UAV latencies which may lead to an adjustment of the perch position and corresponding low hover altitude along with corresponding descent rates.

REFERENCES

[1] Ferrier, B & Semenza, J (1990). NATC Manned Flight Simulator VTOL Ship Motion Simulation and Application. *Proceedings of the American Helicopter Society*. Washington.

[2] Ferrier, B., Applebee, T., Manning, A., James, CDR D(RN). (2000). Landing Period Designator Visual Helicopter Recovery Aid. *Proceedings of the American Helicopter Society*. Washington.

[3] S. White, R. Reading (2001). NATO/PfP HLA Federation of VTOL Operations Supporting Simulation Based Acquisition. 01E-SIW-032. Brussels

[4] I. Cox, G. Turner, J. Duncan (2005). Applying a Networked Architecture to the Merlin Helicopter Simulator. Royal Aeronautical Society Conference. London.

[5] Applebee, T., Baitis, E., Meyers, W. (1981). "User's Manual for the Standard Ship Motion Program, SMP". David W. Taylor Naval Ship R&D Center Report. DTNSRDC/SPD-0936-01. Washington.

[6] O'Reilly, PJF. (1987). Aircraft/Deck Interface Dynamics for Destroyers. *Marine Technology*. Volume 24, Number 1. Society of Naval Architects and Marine Engineers. New York.

[7] St. Denis & Pierson, W (1953). On the Motions of Ships in Confused Seas. Transactions of SNAME. Vol 61. New York.

[8] Bretschneider, C. L (1959). "Wave Variability and Wave Spectra for Wind-Generated Gravity Waves". Beach Erosion Board. U.S. Army Corps of Engineers. Technical Memo No: 118. Washington.

[9] O'Reilly, PJF. (1978). "Ship Motion Analysis". (BHTI 699-099-087). Bell Helicopter Textron. Ft. Worth.

[10] Blackwell, J and Feik, R. A (1988). "A Mathematical Model of the On-Deck Helicopter/Ship Dynamic Interface (U)". Aerodynamics Technical Memorandum 405. Aeronautical Research Laboratory. Melbourne.

[11] P. Crossland, B. Ferrier, T R. Applebee (2004). Providing Decision Making Support to Reduce Opeator Workload for Shipboard Air Operations. Royal Institute of Naval Architects. London.

[12] W.C. Sandberg, R. Ramamurti, J. Kellogg, and F.E. Camelli, Computational Challenges for Launch and Recovery Analyses for Novel Unmanned Air and Underwater Vehicles, ASNE Launch and Recovery Meeting, Annapolis MD 2005.

[13] Ferrier, B (2006). "Safe Expanded Ship Operations by Quiescent Deck Recognition". Scan Eagle x Type 23 Deck Availability. UK060417-1. Bristol.

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Dr. Bernard Ferrier *is Head of the Dynamic Interface Lab at Hoffman Engineering Corp.'s Arlington Office and contract SETA engineering in PMA 266. The DI Lab 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 Engineering, the DI Program was at BMT Syntek Technologies. Earlier, 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*