The Use of Simulation Tools in the Calculation of Aircraft-Ship Interface Operational Limits

Bernard de FERRIER
Program Manager, Dynamic Interface Program
Bombardier Inc., Canadair Defence Systems Division (USA)
Arlington, Virginia U.S.A.

Olivier LE BIHAN
Responsable Interface Hélicoptère/Bâtiments de surface (Projet Horizon)
Délégation Générale pour l'Armement
Direction des Constructions Navales
London, U.K.

Abstract

An analytic approach to helicopter/ship dynamic interface testing is presented. A brief synopsis of the theory and calculation of the ship motion simulation program is presented. The application of ship motion simulation as a developmental operational tool is introduced. Sample helicopter/ship interface operational limits or envelopes are discussed. Spin-off projects into other fields of growth, such as visual aids, are discussed, as well.

Introduction

Helicopters operating from small ships are limited in the maritime environment by high winds and rough seas In addition, helicopters are limited by man-made obstacles, such as, hangar wall generated turbulence, ship stack hot gas motor ingestion, inappropriate deck lighting and markings. Dynamic Interface (DI) is defined as the study of the relationship between an air vehicle and a moving platform. It is performed to reduce risks and maximize operational flexibility [1]. Countries with a large number of platforms conduct DI testing as a matter of necessity. The American Navy matrix alone accounts for over a dozen VTOL/VSTOL manned and unmanned vehicles and more than 20 classes of aviation capable ships [2]. Recent and near future capital acquisitions by medium sized navies, such as in France, Britain and Germany, have increased interest in DI. The purpose of this paper is to present highlights of the analytic approach to dynamic interface testing and application.

Dynamic Interface Studies

Brief Overview

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 [3].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, engage and disengage of rotors, vertical replenishment and helicopter in-flight refueling envelopes. "Shipboard suitability testing" assesses the adequacy, effectiveness, and safety of shipboard aviation. Testing methodologies and procedures have been standardized by laboratories, such as, Naval Air Warfare Center (Patuxent River, USA), DCN Toulon (France), and DRA Bedford (UK). While experimental testing has numerous objectives, the primary activity is on launch and recovery envelope development and expansion. Launch and Recovery tests are rated by the pilot on an accepted scale, such as, the Pilot Rating Scale (PRS). The pilot assess workload resulting from aircraft control margins, aircraft flying qualities, and performance in the shipboard environment [4]. Other experimental analysis are (but not limited to): aviation facility evaluation and deck handling.

DI analytics use 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 or handling system, such as, RAST and SAMAHE.
4. simulating any kind of environment natural and artificial (degraded modes).

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While analytics may seem less taxing to the DI study process, it cannot replace experimentation. Envelope studies will always require physical verification.

Ship Motion Simulation

An important DI analytical tool is the Ship Motion Simulation (SMS) which was initially developed by Peter J.F. O'Reilly between 1973 to 1984 for the United States Navy. The program methodology uses spectral probabilities in order to produce deterministic synthetic time histories.

SMS Theoretical Synopsis

The Ship Motion Simulation (SMS) Model is derived from the relationship between the wave and ship motion spectrum [5]. It incorporates seakeeping philosophy and applies various definitions of seaway spectral formulation, such as, Bretschneider [6]. 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 it's structure.

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

$$Sr = S_w(w) \bullet RAO \bullet f(V, m) \qquad (1)$$

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

SMS can apply various definitions for the seaway. One of the most common is the definition called the Bretschneider, which is given by:

$$S_w(w) = \frac{483.5}{w^5 T_0^4} H_s^2 \, e^{\left(\frac{-1994.5}{w^4 T_0^4}\right)} \qquad (2)$$

where: T_0 : 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 in the SMS 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 [7].

The ship response spectrum is created as the product of the RAO and the driving sea spectrum (figure 1) 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:

$$A_z = \sum_{n=1}^{k}\left(A_{z_n}\cos\left(w_n - e_{z_n}\right)\right) \qquad (3)$$

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). Figure 2 displays a typical time history trace. In summary, the Ship Motion Simulation creates deterministic measures of ship motion from a probabilistic spectrum.

Aircraft/Ship Interface Simulation

The primary application of the SMS is in operational simulation such as aircraft launch and recovery; deck handling; and flight readiness or availability. The Aircraft/Ship Interface Simulation (DI) is a mathematical description of conditions limiting the availability of an air vehicle. Factors affecting an air vehicle on a moving platform are primarily ship motion; Wind Over Deck; Ship Airwake Turbulence; and deck conditions (eg: wet, dry, oily, obstructed).

An example of DI analysis involves deck handling. In DI the 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. Deck handling studies determine turnover limits, sliding freedom, tiedown forces, traversing factors, and pitch back limitations.

DI Theoretical Synopsis

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 intertias, center of gravity, lateral drag area and center of pressure. 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 [8]. In essence, the aircraft is displaced as the sum of all forces. to which it is exposed

The inertial loads at the helicopter center of gravity induced by ship motion is given by;

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

where,

$\begin{pmatrix} Fix \\ Fiy \\ Fiz \end{pmatrix}$ = inertial forces due to ship motion

W = aircraft weight

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

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

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} T_{11}T_{12}T_{13} \\ T_{21}T_{22}T_{23} \\ T_{31}T_{32}T_{33} \end{pmatrix} \begin{pmatrix} Fix \\ Fiy \\ Fiz+W \end{pmatrix} \qquad (5)$$

where: Tij = T (ϕ,θ,ψ) (transformation matrix from ship's axis system to horizontal level/vertical axis system).

and

ϕ= roll
θ= pitch
ψ= yaw

Next, a wind force is added to the ship motion induced forces In the Ship Motion Simulation, an unidirectional continuous wind model, whos vector is in the same direction as the seaway, is applied. The wind vector is defined by its magnitude (Vwod) and its direction (ψwod). To compute the lateral force applied at the aircraft Center of Pressure due to the wind, the Vwod 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, as follows:

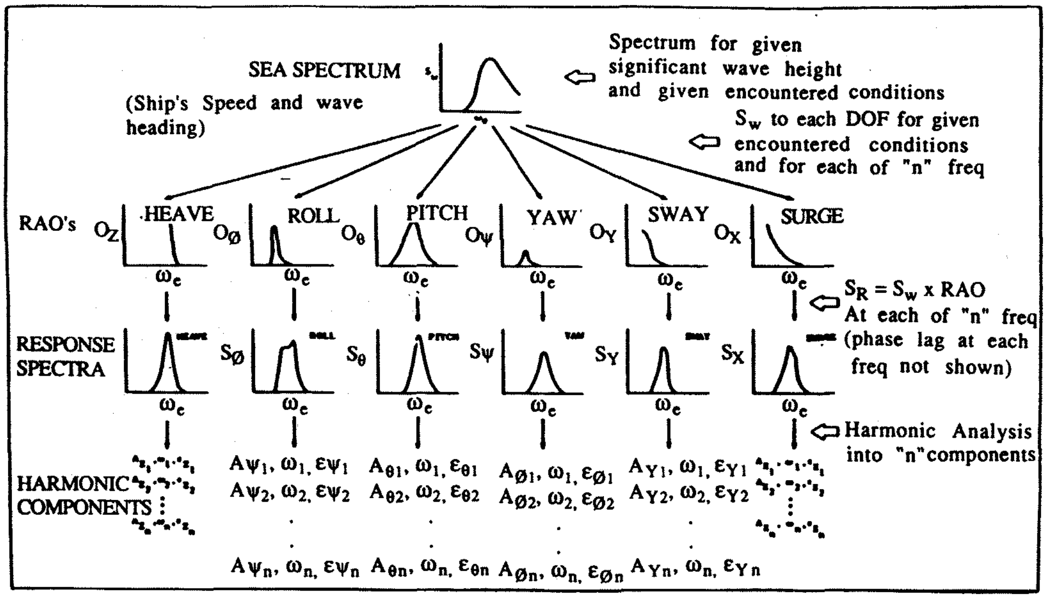


Figure 1 - Ship Motion Simulation Flow Diagram

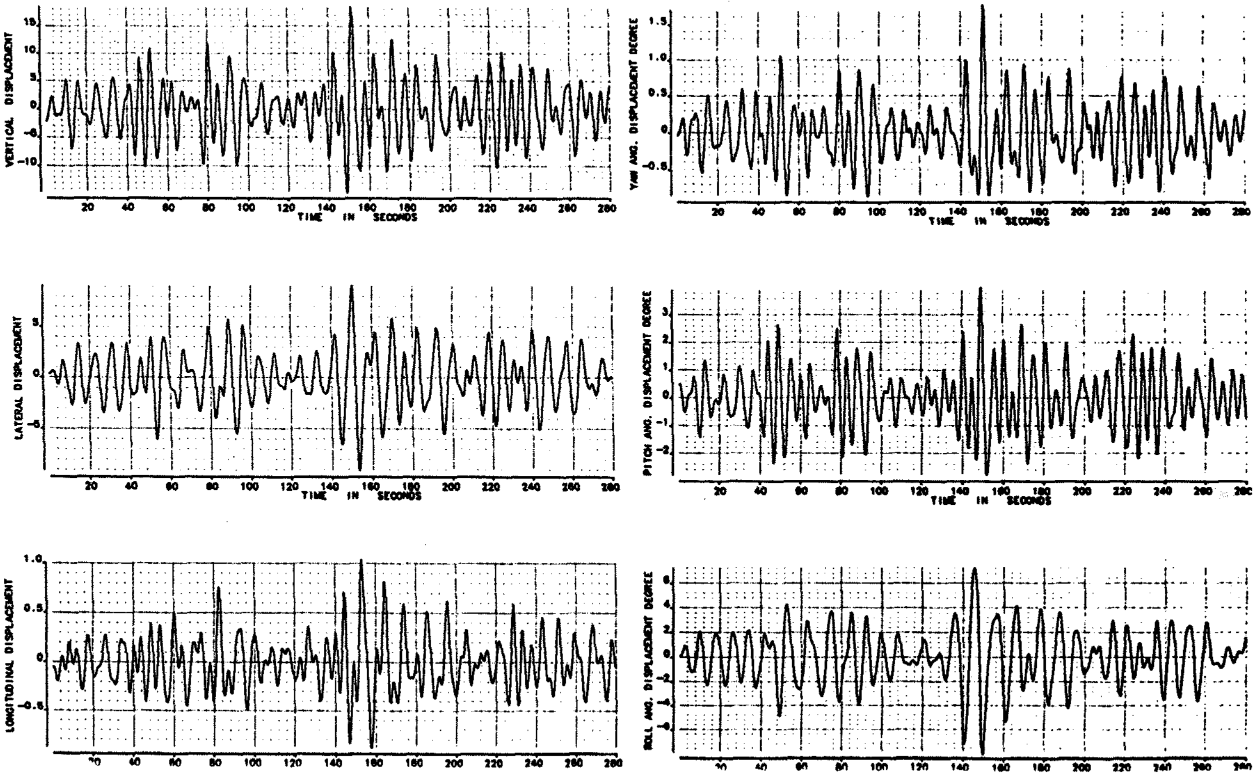


Figure 2 - Typical Time History Trace

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

where: A_y =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

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

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

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:

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

where: K = spring constant

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

$$F_{RMG_{(Inertie)}} = Y\left(\frac{WL_{CG} - WL_G}{L_{BL} + R_{BL}}\right) \qquad (9)$$

where:

WL_G =Center of gravity waterline

$F_{RMG_{(Inertie)}}$ =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:

$$F_{LMG_{(Inertie)}} = -F_{RMG_{(Inertie)}} \qquad (10)$$

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

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

$$\Delta\phi(\text{Inertie}) \quad = \tan^{-1}\left(\frac{F_{RMG_{(Inertie)}}}{(K)(L_{BL})}\right) \qquad (11)$$

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

$$\Delta\phi(\text{total}) \quad = \Delta\phi(\text{vent}) + \Delta\phi(\text{inertie}) \qquad (12)$$

Deck conditions, eg: 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 preprogrammed. 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 owing 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 castored for turnover. The model is lined up with the ship centerline and is rotated on the deck to find the least stable, but realistic, orientation (figure 3).

Referring to figure 3, the 'worst case' hinge line on the flight deck about which the aircraft will turnover are defined by Rto and Lto (right turnover and left turnover). Each line is computed from its main gear position to the nose gear swivelled for turnover. The azimuth of these two lines are then determined with respect to the ship's longitudinal axis, AZrto and AZlto.

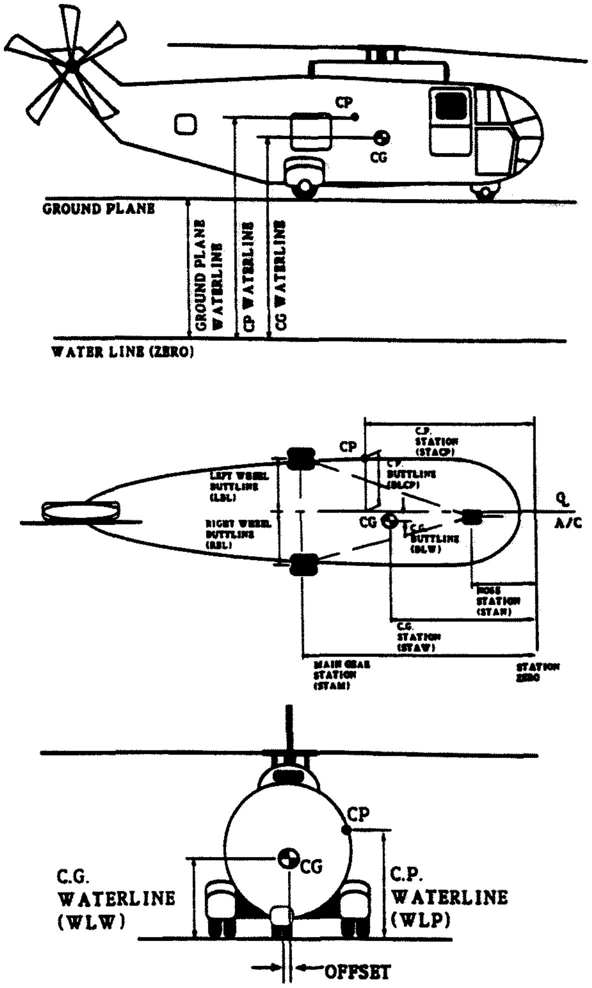
The distance from the aircraft center of gravity (CG) to each line is computed as TODR and TODL (right and left). They define the distance that the CG should move for a turnover to occur (right or left). These lines describe an angle TOR (right) or TOL (left). They are expressed as:

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

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

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:



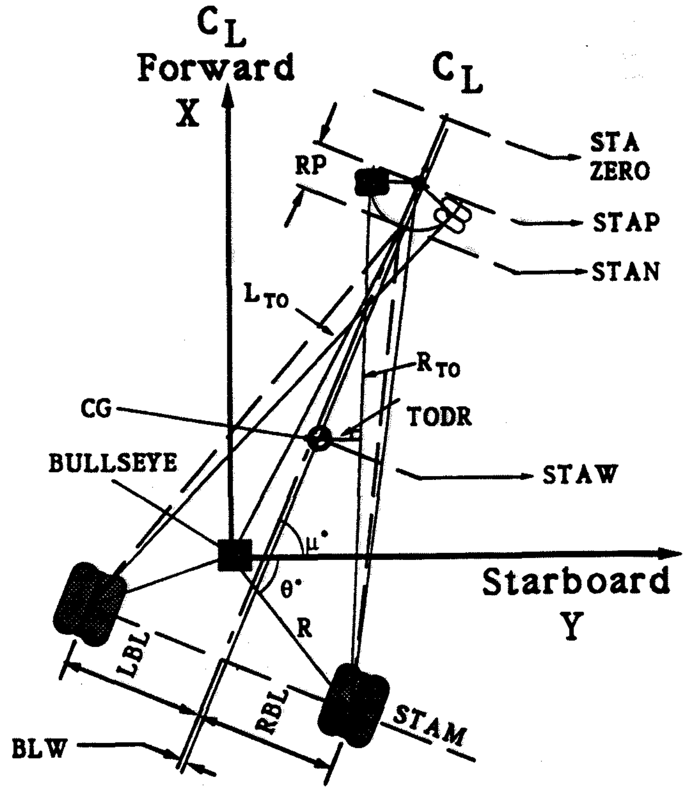


Figure 3 - Aircraft Model Definitions

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

where,
PBD= pitchback distance
CGx= aircraft CG station
MGx= aircraft main gear station

The associated pitchback angle or PBA is given by:

$$\measuredangle PBA = \tan^{-1}\left(\frac{MGx-CGx}{WL_W-WL_G}\right) \qquad (16)$$

where,
WL_w = Waterline to the aircraft CG
WL_g = 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. Dynamic turnover caused by the rotor disk (uneven loading of the rotor) or by ship motion, the same phenomena occurs. 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.

Calculation of Aircraft/Ship Operational Limits

The objective of analytic DI is to identify operational envelopes for launch and recovery, deck handling and general flight readiness or availability. The intention of analytical DI is not to replace experimental DI but to compliment tne activity. Once operational envelopes are calculated, DI test engineers would randomly verify selected data points in and out of the envelope. Ship speed, relative wave heading, significant wave height and modal period are the primary ship motion markers. A typical test matrix is furnished in table (1).

Ship Velocities:	05, 10, 15, 20 knots
Wave Angles:	0 - 180°, every 15 degrees
Sig.Wave Height: (Equivalent Sea State ~	1, 3, 6, 9 metres 3, 5, 6, 7)
Modal Period:	5, 9, 11, 15 seconds
additional matrix attributes	
Deck Condition: (Coefficients)	DRY and WET (water) 0.8 0.5
Wind-Over-Deck:	0 - 50 knots

Table 1 - Typical Test Matrix

Several studies have been achieved by the Bombardier, Inc Canadair Defense Systems Division's Dynamic Interface Office for the Direction des Constructions Navales (DGA France). Several aircraft were modelled with high center of gravities and corresponding minimum mission weights. The air vehicles were modelled both secured and unsecured on the deck with rotors spread and free to rotate and fuselages unfolded and locked. The helicopters are modelled centered at the bullseye. The landing gear deflection and forward gears are modelled unlocked and castored for turnover. The aircraft are set on the ship's centerline and rotated to -20 degrees to provide the least stable orientation.

In the examples which follow, envelopes are based on limitations defined by the point at which an aircraft/ship incident occurs. Incident means occurrence of aircraft turnover, pitchback, ondeck slide or uncontrolled liftoff. At any point during a simulation analysis an incident is identified, the entire data point is declared out-of-limit. Interface testing is performed according to the test matrix indicated in table (1). Deck safety rondelles are created as a function of ship velocity and deck condition deck condition (figure 4). Areas within the shaded areas are inside operational limits. The bow of the ship is along the principal axis to the right out to 0 degrees relative wave angle. Each concentric ring relates a relative wave height and significant wave height. All cases are tested in seas ranging from 1 to 9 meters, 180 degrees in bearing (by symmetry 360 degrees) and a maximum of 50 knots wind-over-deck.

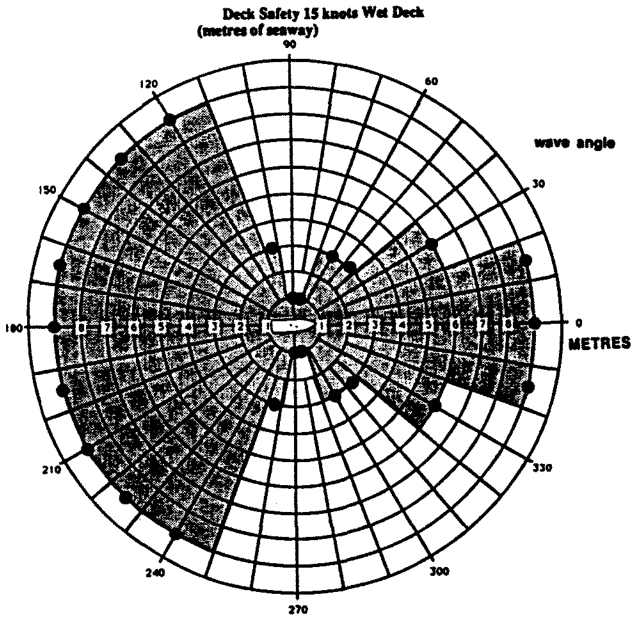


Figure 4 - Sample Deck Envelope

A comparative operational limit sample between various aircraft on the same ship is presented in figure (5). Here the models A and B show better limits than helicopter C for the same ship conditions.

Rondelles maybe used to indicate encountered loads as presented in figure (6). Here the shaded zone indicates air vehicle exposed force loads as a function of a given ship's velocity, and significant wave height. For example, the rondelle shows increased encountered loads at 75 degrees relative wave angle. In the following seas conditions, as one would expect, encountered loads are minimal.

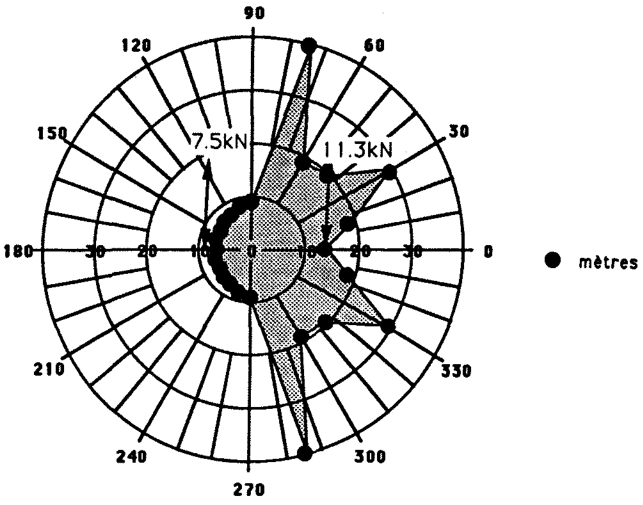


Figure 6 - Encountered force loads

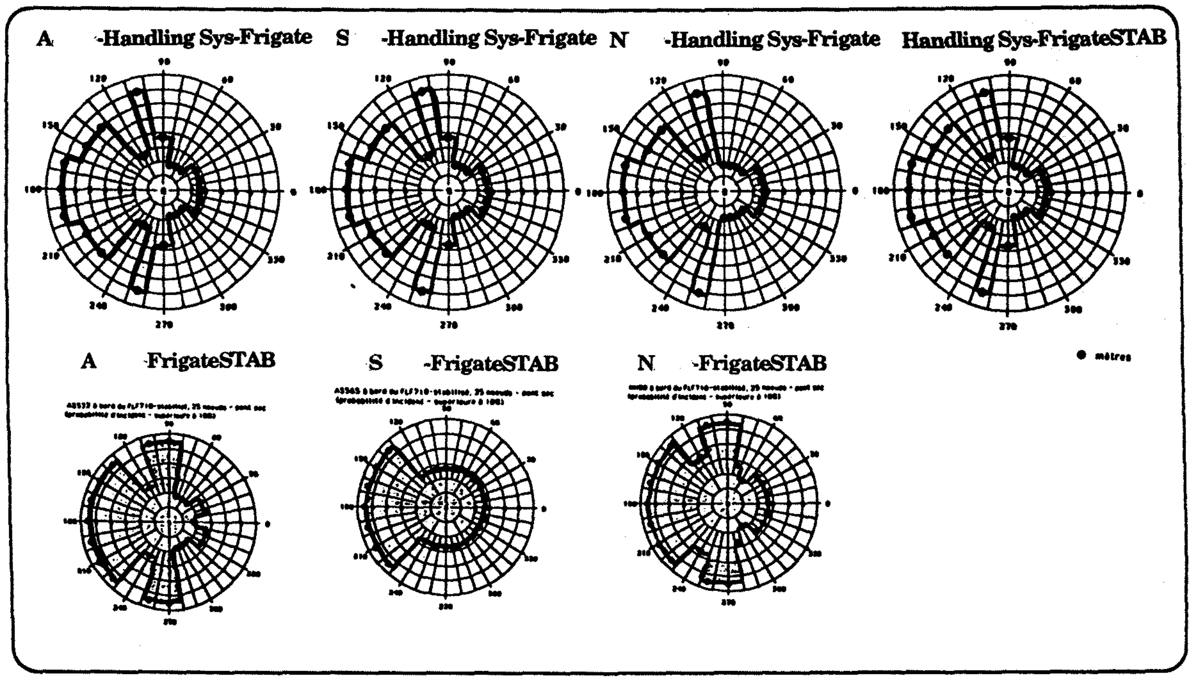


Figure 5 - Comparative Operational Limits

Real-Time DI Applications, Visual Aids

Application of DI tools to the operational environment has produced numerous real-time improvements. One such improvement is the **CL352 Landing Period Designator (LPD)** helicopter landing aid. The LPD supplies real-time information about the motion of any vessel as a function of helicopter operational limits. The system furnishes this information about any kind of aircraft in any sort of sea condition on any sea vessel. LPD is designed to reduce pilot workload in completing ship interface activities by improving operational security in the reduction of helicopter hover time.

The LPD may show improved recovery opportunity from its ability to identify the onset of quiescent ship motion periods. This ability is based on ship motion as a function of the mechanical and dynamic limits of the helicopter. These limits are expressed by a scalar empirical formulation, termed, the energy index. The index identifies ship quiescence using displacement, velocity and acceleration terms. In short, the index furnishes information of the motion a ship must travel in the near-term future. This does not suggest that the index is predictive (using historical information to extrapolate into the future). Rather, it capitalizes on the rate at which a vessel can displace due to natural hydrodynamic forces as a function of the structural and dynamic characteristics of the approaching air vehicle.

The energy index is an empirical formulation designed to convert ship motion characteristics, aircraft structural dynamic limits, and user experience into a meaningful value. The index is modular in design with the capacity of incorporating other parameters (e.g.: wind-over-deck module) to improve energy index significance and applicability. The Energy Index equation of LPD Mk III measures lateral, vertical velocities and accelerations as well as roll and pitch angular displacements and velocities weighted by dynamic coefficients. The equation in the Mk III is the sum of the squares of the various parameters and terms representing real-time ship/aircraft interface motion.

$$EI = a_1\dot{y}^2 + a_2\ddot{y}^2 + a_3\dot{z}^2 + a_4\ddot{z}^2 + a_5 f^2 + a_6\dot{f}^2 + a_7 q^2 + a_8\dot{q}^2 \quad (17)$$

(where a_1, a_2,... are weighted dynamic coefficients)

As indicated in equation 17, the index contains acceleration, velocity and displacement terms which determine the motion of the ship in the near future. The LPD code calculates the rate at which a vessel can displace due to natural hydrodynamic forces against the structural and dynamic operating limits of the matching air vehicle. The energy index uses eight parameters roll and pitch, their rates, lateral and vertical velocities and accelerations. All of the parameters are weighted by dynamic coefficients which are weighted according to the individual degree-of-freedom, the coupled degrees of freedom and normalized according to aircraft characteristics. The remaining two degrees of freedom (yaw and surge) are monitored for motion within certain limits and may be incorporated more actively later if warranted. The degrees of freedom, viz: roll, pitch, lateral, and vertical, are considered the most important for motion sensitive tasks (in particular launch and recovery of air vehicles).

Methodology for Coefficient Calculation

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 following 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.

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

The degrees-of-freedom that are considered highly coupled are roll and lateral motion and pitch and vertical motion. Coupled means that the 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. A maximum 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 degree-of-freedom. The product of the element coefficients A_{11}, A_{23}, (see eq.18) produces the energy index coefficients in real-time. The energy index is then calculated and compared to the established threshold (green, yellow, red) scale the results of which are communicated to the user.

The flow-chart of the energy index is presented on figure 7.

Methodology for Energy Index 'Motion Zone' Calculation

The meaning of the index value has been the object of much investigation. To be applicable, the quantity must reflect a physical state of the aircraft/ship combination in a given sea condition. For expedience, the scale is initially divided into four 'deck security' or 'availability' zones similar to the 'Pilot Rating Scale' (PRS) [9]. The definition of each deck security zone is normally refined during initial LPD sea trials.

The energy index value is analogous to the level of kinetic and potential energy contained in the ship. When the index is low the ship is stable and the ship motion is small. When the index value is below the danger threshold the landing deck motion is acceptable for aircraft activity. The ship can only displace from a stable to a high risk condition by the introduction of certain quantity of energy from the sea. For a given condition, time necessary to raise the deck from a stable to an unavailable condition can be derived experimentally from the calculation of the maximum EImax. For the mass of a Destroyer class of ship, this measure is about 5 seconds. For a FFG-7 or Type 23 class ship, during normal environmental conditions, this minimum measure is about 4.5 to 5.0 seconds. Exceptions to this rule occur when encountering longitudinal propagating, high energy intensity wave fronts such as those created by an earthquake or weapon explosion.

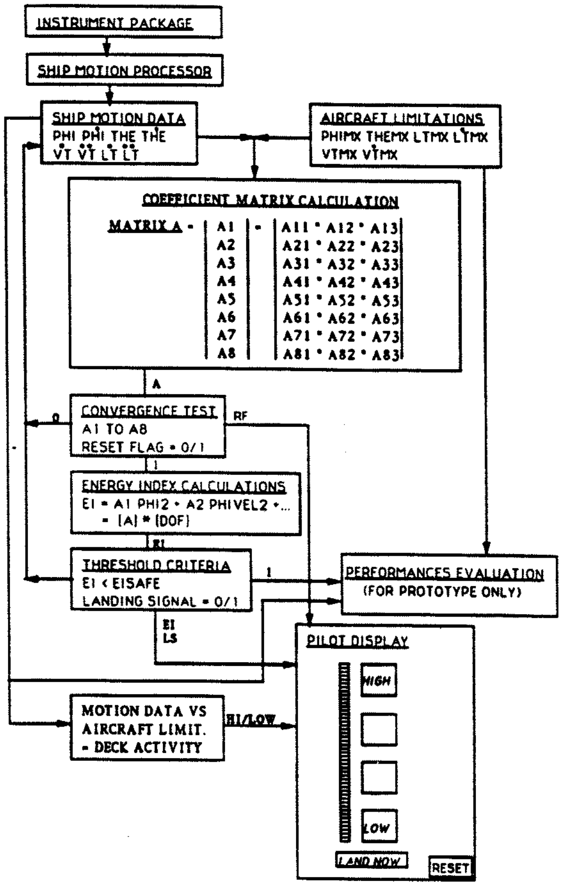


Figure 7 - Landing Period Designator Components

The deck availability, as defined by the deck security zone criteria, is directly based on the ship characteristics (measured), aircraft limitations (defined), and pilot-in-loop factors (see figure 8). Deck motion security limits must be established for each combination of helicopter and ship. These limits may be measured

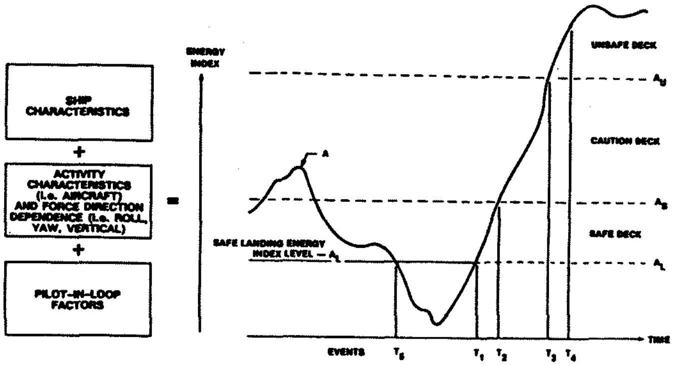


Figure 8 - Threshold Criteria

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 helicopter. 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.

All energy index values under the red line infer acceptable deck motions. The red line is absolute. In a red light helicopter recovery, one or more DOFs have exceeded acceptable aircraft limits. Therefore, deliberately assigning the red line several scalar points under the calculated absolute limit is a prudent if not conservative measure. 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 flashing green signal. The energy defined for a flashing 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.

Simulator and at-sea testing have been conducted by the US, British and German navies. The primary analysis after concluding that the LPD performed as per specification was to compare recoveries with and without the LPD. Figure 9 displays this result for both day and night, with and without the LPD.

Differences were detected between LPD day and night, and again between no LPD day and night calculated from a common way-point to the ship deck. Height over the deck and energy index traces were used (see Figure 4.3 for an example). From the data, night recoveries take on average about 50 seconds longer than day landings (other parameters held constant). During the day without the LPD, flights lasted on average almost as long as night recoveries with LPD. Night landings without the LPD took more than 25 seconds longer to complete than the same mission with the LPD.

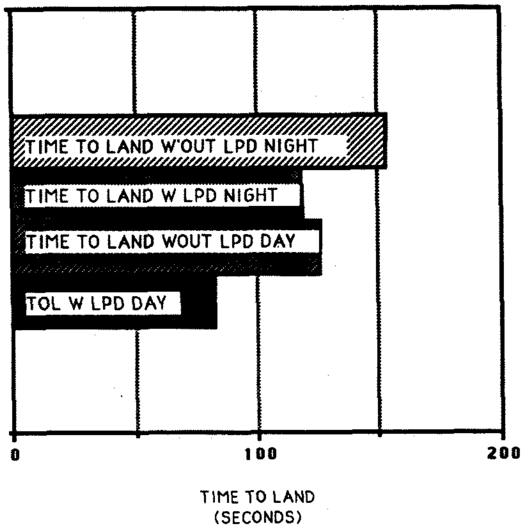


Figure 9 - Time to Land from Common Way-point

CONCLUSION

The overall 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.

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