Simulation and Testing of the Landing Period Designator (LPD) Helicopter Recovery Aid

Référence : OP11

Dr. Bernard de Ferrier
Engineering Manager, Dynamic Interface Program
Bombardier Services Corporation
Arlington, Virginia (USA)

Abstract

A synopsis is presented summarizing the development tasks, simulation projects, and testing program of the Landing Period Designator (LPD) helicopter recovery aid. The LPD, an empirical formulation, relates real-time ship motion to safe recovery times of a given aircraft-ship combination. It is designed to complete launch and recovery envelopes with a real-time dynamic assessment of shipmotion as a function of the helicopter limits. The "proof-of-concept" testing program required satisfaction of three criteria. The index must be sensitive to different aircraft and ship models for given sea conditions. Second, the energy index trace from a low to a high energy state must never violate a given motion time delay (termed rise-time). Third, for a given sea condition, the energy index response using simulated data must approximate recorded ship motion index response. Test program results supported all three test hypotheses. The next step employed the manned flight simulator in order to assess LPD utility. Recoveries in various sea conditions were conducted using the operational limits of several helicopter models. Results confirmed LPD utility in reducing pilot workload while improving pilot performance. In the final phase of the testing program, at-sea analysis was conducted. The results support the proof-of-concept hypothesis and the manned flight simulator test conclusions.

Introduction

The seaway is virtually universally accepted as unpredictable. Shipmotion is attributed to the energies transferred by surface waves with a contribution generated by atmospheric processes at the ocean surface (boundary layer). Using the ship as the platform provides insite into boundary layer processes, the zone used by the helicopter just before recovery. The landing period designator (LPD) is a system developed to aid helicopter pilots in launch and recovery from moving small ships. Recovery procedures and operational envelopes are heavily oriented to wind velocities and orientation while giving only scant attention to the orientation of the ship. The LPD is designed to provide the operator an evaluation of ship motion in terms of vehicle mechanical and dynamic limitations, identifying appropriate moments to initiate safe recoveries.

Dynamic Interface

The LPD is an application of the aircraft- ship dynamic interface (DI) program. Dynamic Interface is defined as the study of the relationship between air vehicles and a moving platform [1]. DI is performed to reduce operational risks and maximize tactical flexibility [2]. DI is institutionalized by the US Navy as the Dynamic Interface Department of the Rotary Wing Directorate at the Naval Air Warfare Center Aircraft Division at Patuxent River, Maryland. Study is primarily performed by experimentation. Analytic DI emphasizes mathematical modeling and simulation to support flight testing [3].

The LPD was derived from the Ship Motion Simulation (SMS) and the Aircraft/Ship Dynamic Interface Deck Safety Simulation programs. The SMS was developed by P.J.F.O'Reilly under contract to the USN in support of the V-22 competition [4]. Ship response spectrum is created as the product of transfer functions (Response Amplitude Operators) and the driving sea spectrum over the entire range of frequencies [5]. The product over all degrees-of-freedom are reduced to harmonic components. The sum of the harmonic components produce ship motion time histories. In mathematical terms, deterministic synthetic time histories are derived from probabilistic spectra (see figure 1).

The primary DI application of the SMS-DI programs is the development of aircraft/deck handling system/ship interface operational limits. Figure 2 illustrates a recent example of the operational limits of the AS-565 Dauphin Helicopter, SAMAHE helicopter handling system and the new French frigate La Fayette. In summary, the SMS-DI programs calculate system stability and indicates detection of static or dynamic on-deck turnover, pitchback, sliding or unintentional liftoff incidents.

---

de Ferrier received his Ph.D from the École Polytechnique de Montréal/ Presented at the American Helicopter Society 24th European Rotorcraft Forum for AAAF 15-17 September, 1998 Marseille

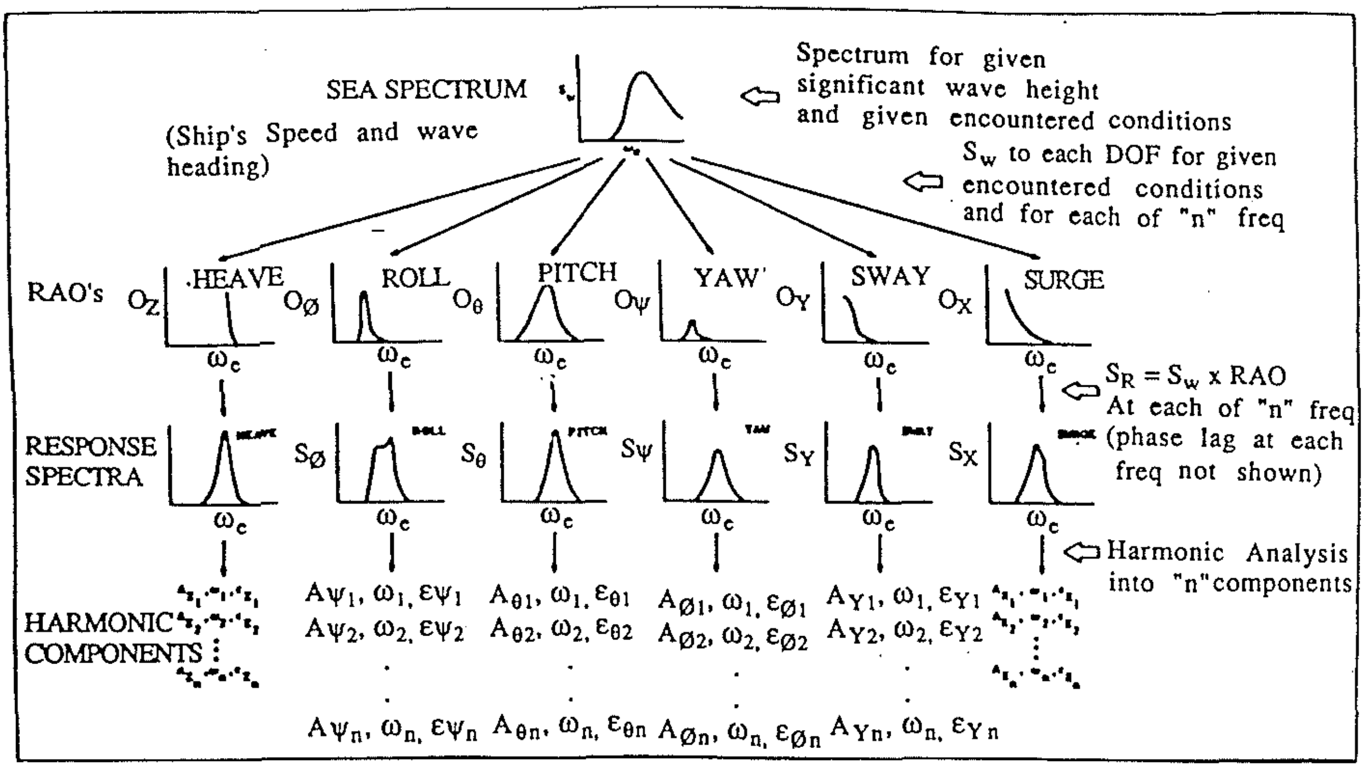


Figure 1 - Ship Motion Simulation Computational Summary

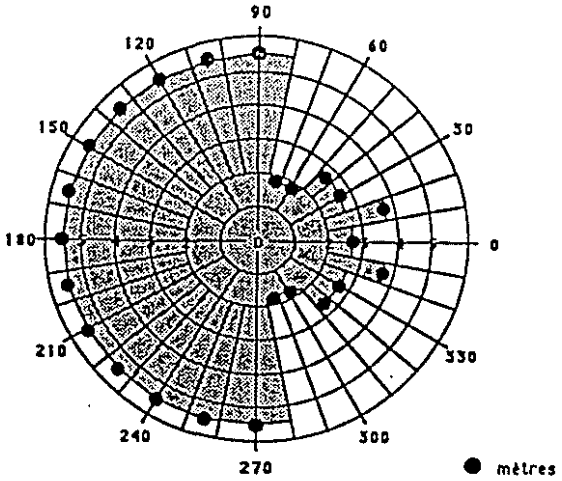


Figure 2 - Sample Deck Operational Limits

Evolution of the Energy Index

The LPD was derived from a specialized application of the SMS program. Identifiable ship motion delays (time lag from acceleration to displacement) were documented during many USN sponsored SMS applied activities. An index was considered as the best representation to discriminate in real-time, the periods when the ship deck platform was calm long enough for safe landings [6]. The formulation of the energy index (EI) hypothesis centered about the measured time lag experienced by large bodies at sea. The concept entails the reduction of 6 degree-of-freedom ship motion data, dynamic and mechanical aircraft limitations, and operator experience into a scalar value. The scalar value would represent deck availability to complete a given motion sensitive task.

Various algorithms were developed by O'Reilly (a founding engineer of the DI discipline) to measure ship motion in real-time in order to identify quiescent ship motion periods [7]. The algorithms were:

EQ.1- $EI=\sqrt{x^2+\dot{x}^2+y^2+\dot{y}^2+z^2+\dot{z}^2}$

EQ.2- EI=
$$\sqrt{x^2+\dot{x}^2+y^2+\dot{y}^2+z^2+\dot{z}^2+\phi^2+\dot{\phi}^2+\theta^2+\dot{\theta}^2+\psi^2+\dot{\psi}^2}$$

EQ.3- $EI=\sqrt{y^2+\dot{y}^2+\ddot{y}^2+z^2+\dot{z}^2+\ddot{z}^2+\phi^2+\theta^2}$

EQ.4- $EI=\sqrt{\dot{y}^2+\ddot{y}^2+\dot{z}^2+\ddot{z}^2+\phi^2+\dot{\phi}^2+\theta^2+\dot{\theta}^2}$

EQ.5- EI=
$$\sqrt{s_1\dot{y}^2+s_2\ddot{y}^2+s_3\dot{z}^2+s_4\ddot{z}^2+s_5\phi^2+s_6\dot{\phi}^2+s_7\theta^2+s_8\dot{\theta}^2}$$
(where s_1, s_n, are weighted static coefficients)
where;

ϕ- roll ship angle
θ- pitch ship angle
ψ- yaw ship angle
X- longitudinal motion @ landing spot
Y- lateral motion @ landing spot
Z- vertical motion @ landing spot

Equation 1 was tested at sea on board the USS Koelsch. Test results showed that it is possible to discriminate periods of low motion from periods of large amplitude motion using an index. As a result of that test, two critical observations for algorithm modification were made. An index should be created which contains appropriately weighted terms crucial to aircraft recovery. The second suggested that analysis be performed to determine the envelope of maximum motion amplitudes which might be expected at fixed time intervals (4,6,8 seconds) after the index drops below a suitably chosen threshold [8]. Equation 5 incorporated aircraft based coefficients connecting ship dynamics to motions critical to aircraft stability. Applying equation 5, analysis was made to identify motion phase lag or rise-time using weighted static aircraft based coefficients. In 1987, under the Technical Co-op Program (USA, Canada, Great Britain, Australia and New Zealand) memorandum of understanding, the USN transferred DI analytics through the Canadian Department of National Defence (DND) to Canadair for the expressed purpose of developing a LPD [9].

At Canadair, the DI programs were used in the DND New Shipborne Aircraft competition. The LPD developed as a Doctoral thesis and a Canadair special interest project. Weighted static coefficients were shown to be useless in changing seas and during operations entailing beam seas (numerous instantaneous rise-time violations). One attempt to resolve the issue by modifying 'Y' velocities unnecessarily restricted other relative wave angles [10]. The LPD Mk II was fitted with a sub-routine to allow coefficient calculation for changing seaway. Coefficients would still be applied to the index, statically. Coefficients in a changing seaway would be calculated, such that, values would converge on an optimal value. Converging coefficients required the LPD to indicate 'stand-by' while the computer calculated optimal values. This was done until the differences between interim values were below a threshold value (insignificant). A delay of about 2-3 seconds was measured when using simulation data. However, the LPD Mk II failed to exit the stand-by mode when real ship motion data was introduced. This occurred owing to vibrational noise in the recorded data. Even when heavy filters were applied, the sensitivity of the LPD caused numerous 'stand-by' delays. The LPD Mk II was abandoned as a dead-end. A new approach using dynamic coefficients was devised, the LPD Mk III.

Energy Index Theory Synopsis

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 capability of incorporating other parameters (eg: wind-over-deck module) to improve energy index significance and applicability. The index contains acceleration, velocity and displacement terms giving indications of the motion a ship must travel in the near-term future. This does not suggest that the index is predictive. Predictive typically means the use of historical data to extrapolate into the future. The energy index makes no attempt to extrapolate ship motion based on historical values. Rather, it capitalizes on the *rate at which a vessel can displace because of natural hydrodynamic forces against the structural and dynamic characteristics of the matching air vehicle.*

Energy Index Algorithm, LPD Mk III

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.

EQ.6 EI=

$$a_1\dot{y}^2+a_2\ddot{y}^2+a_3\dot{z}^2+a_4\ddot{z}^2+a_5\phi^2+a_6\dot{\phi}^2+a_7\theta^2+a_8\dot{\theta}^2$$

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

As indicated in equation 6, the index contains acceleration, velocity and displacement terms giving indications of the motion a ship vessel must travel in the near-term future. The LPD code calculates the rate at which a vessel can displace due to natural hydrodynamic forces against the structural and dynamic characteristics of the matching air vehicle. The energy index uses eight parameters and eight terms to represent ship motion and interface implications based on four degrees of freedom. 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 selected are the most important to complete 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 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.

Eq. 7

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

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-liberty 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 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.7) produce the energy index coefficients in real-time. The energy index is then calculated and compared to the deck availability scale the results of which are communicated to the user. A summary of the energy index calculation is provided on figure 3.

Evaluation of Landing Deck Motion

Interpretation of the energy index scalar quantity is the object of intense investigation. To be a meaningful value, the scalar quantity must reflect a physical state of being for a given 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' [11]. The definition of each deck security zone will be determined during initial LPD sea trials. The initial color coded criteria is shown on table 1.

Table 1 - Deck Security Zones

COLOUR	DEFINITION
RED	DANGER •high energy level •a/c limits exceeded
YELLOW	CAUTION •elevated energy •limited deck motion
GREEN	SAFE •slight accel. in deck
FLASHING GREEN	WINDOW ASSURED •energy very low

The energy index value is correlated 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 dangerous 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 ΔEImax. For the mass of a FFG-7 class ship, during normal operating conditions, this measure is about 5 seconds.

Development of Threshold Criteria

The threshold of the various deck availabilities are directly based on the combination of ship characteristics (measured), aircraft limitations (defined), and pilot-in-loop factors (see figure 4). . Deck motion security limits must be established for each combination. These limits may be measured experimentally or calculated analytically (see table 2). 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. 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. A recovery when index values are greater than than the danger limit means 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.

The time required to raise the deck from minimal motion to unacceptable motion is called the rise-time. The rise-time may be analytically or experimentally determined. In

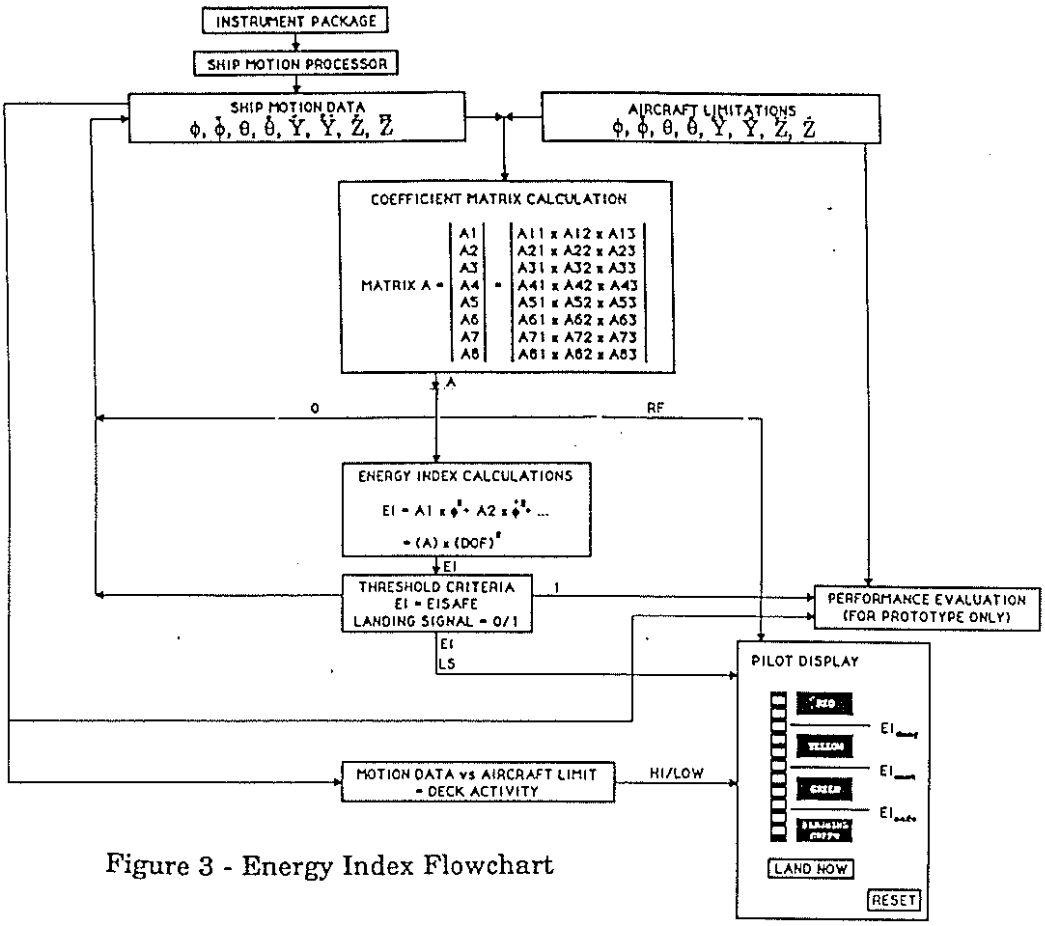


Figure 3 - Energy Index Flowchart

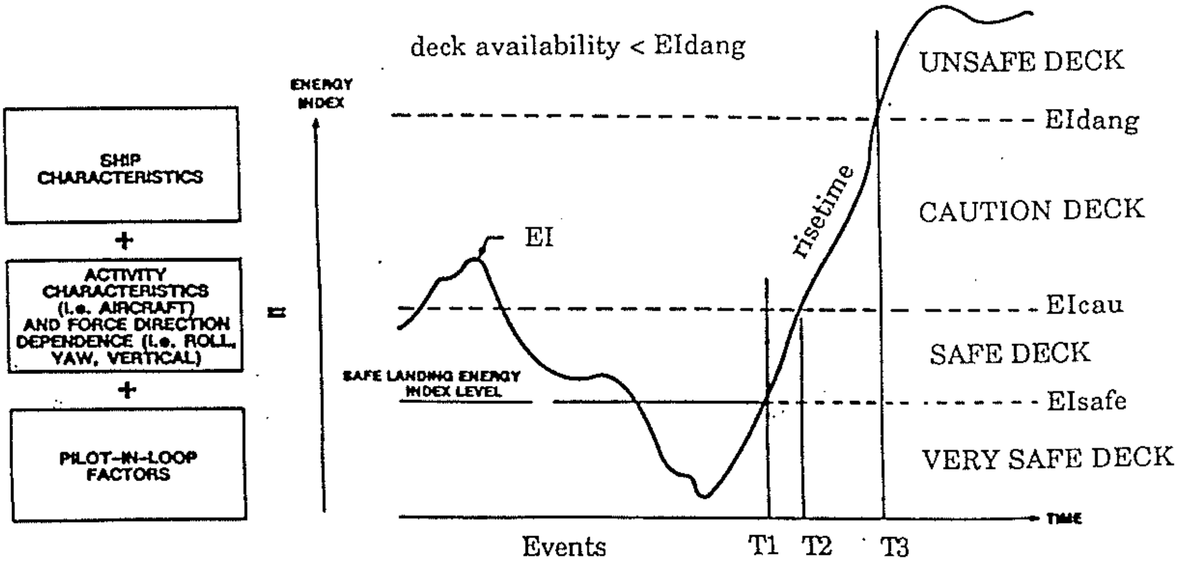


Figure 4 - Threshold Criteria (Risetime = $t_3 - t_1$)

DOF Limit	SEAKING Canada*	SEAKING USA**
roll	10 deg	15 deg
pitch	02 deg	03 deg
Y velocity	01 ft/sec	> 1 ft/sec
Z velocity	08 ft/sec	08 ft/sec

*-DMAEM6-2-2 Létourneau **- RW04

(the energy index is capabile of accomodating other limits as they are definded)

Table 2 - Definition of Seaking motion limits

terms of the energy index scale, it is defined as the period of time that is measured from the end of a flashing green signal to the positive side of the red line. The rise-time is mirrored by a drop-time which is the time period measured from the negative side of the red line to the negative side of the flashing green line.

Simulation Testing Program

A development and testing plan, comprising three phases, was proposed in early 1992. Phase I, the Proof of Concept: The goal was to program, assemble and test a pre-prototype LPD system. A demonstration project was proposed to show the feasibility of a functioning real-time LPD at sea. This article concentrates on this phase.

Phase II, the Development of a LPD Prototype: Two Canadair prototype LPD testbed systems would be developed and assembled; one for sea trials of the LPD and one for use as a reference system at Canadair. Each system would comprise a PC, a ship motion measurement unit, and peripherals such as a LED communication system. Phase III, is the incorporation of an LPD prototype with a full-scale visualization system for mounting on, for example, the hangar face.

Phase One, Triple Hypothesis Test

The primary achievement in phase 1 was the calibration of the LPD using real and simulated ship motion data. The simulation test program may be reduced to three hypotheses:

i EI sensitive to differing ships and aircraft

ii EI risetime (or droptime) > to an approximately Δt delay

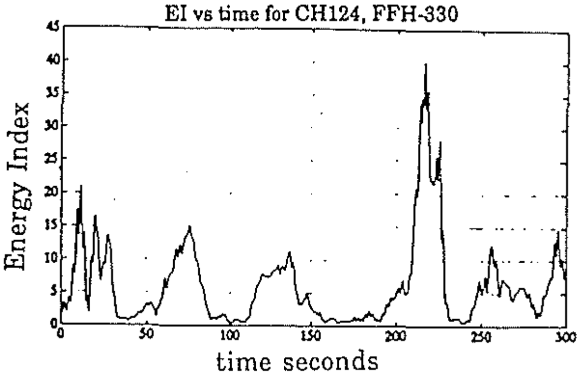
iii. EI results using simulated ~ EI using real data

The testing matrix for the calibration program produced 600 executions of the LPD-SMSimulation programs (this added to earlier analysis numbered well over 2000 runs). Taking the LPD through five ship speeds, 180 (by 15 degree intervals) degrees relative wave angles, eight significant wave heights (3 to 20 feet) and corresponding wave periods.

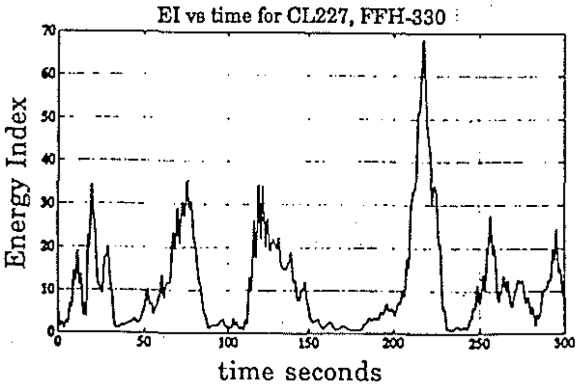
As a result of the calibration effort, 600 different scenarios were formulated [12], the conclusions drawn, were:

a. Test (i), hypothesis supported. The Energy Index is sensitive to changes of aircraft, ship and sea conditions (figure 5).

Figure 5 - Energy Index Sensitivity Test



Sample of test 1 - sensitivity to different air vehicles



b. Test (ii), hypothesis supported. The Energy Index peak never occurred AFTER a degree-of-freedom peak (figure 6) or (after calibration) did not respect an approximate t-lag rise (or drop) time (figure 7). Table 3 displays the average length of rise-time between flashing green deck, red deck and average overall percent of green deck availability by significant wave height.

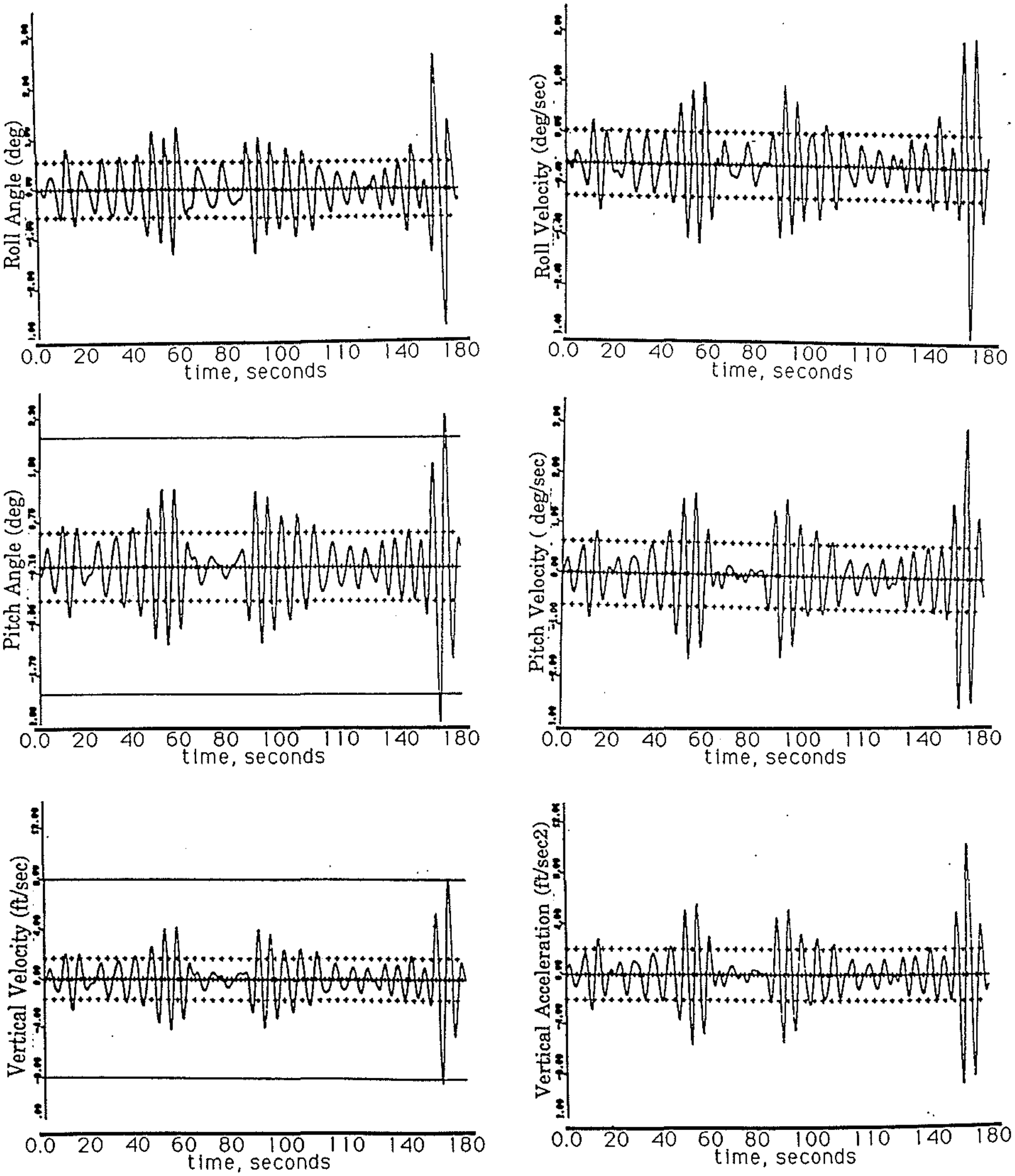


Figure 6- Sample Energy Index Simulation
Seaking x FFG37 (USA):
Ship Vel.=10 knots, Wave Heading= 75°
Wave Height= 06 feet; Period= 07 seconds

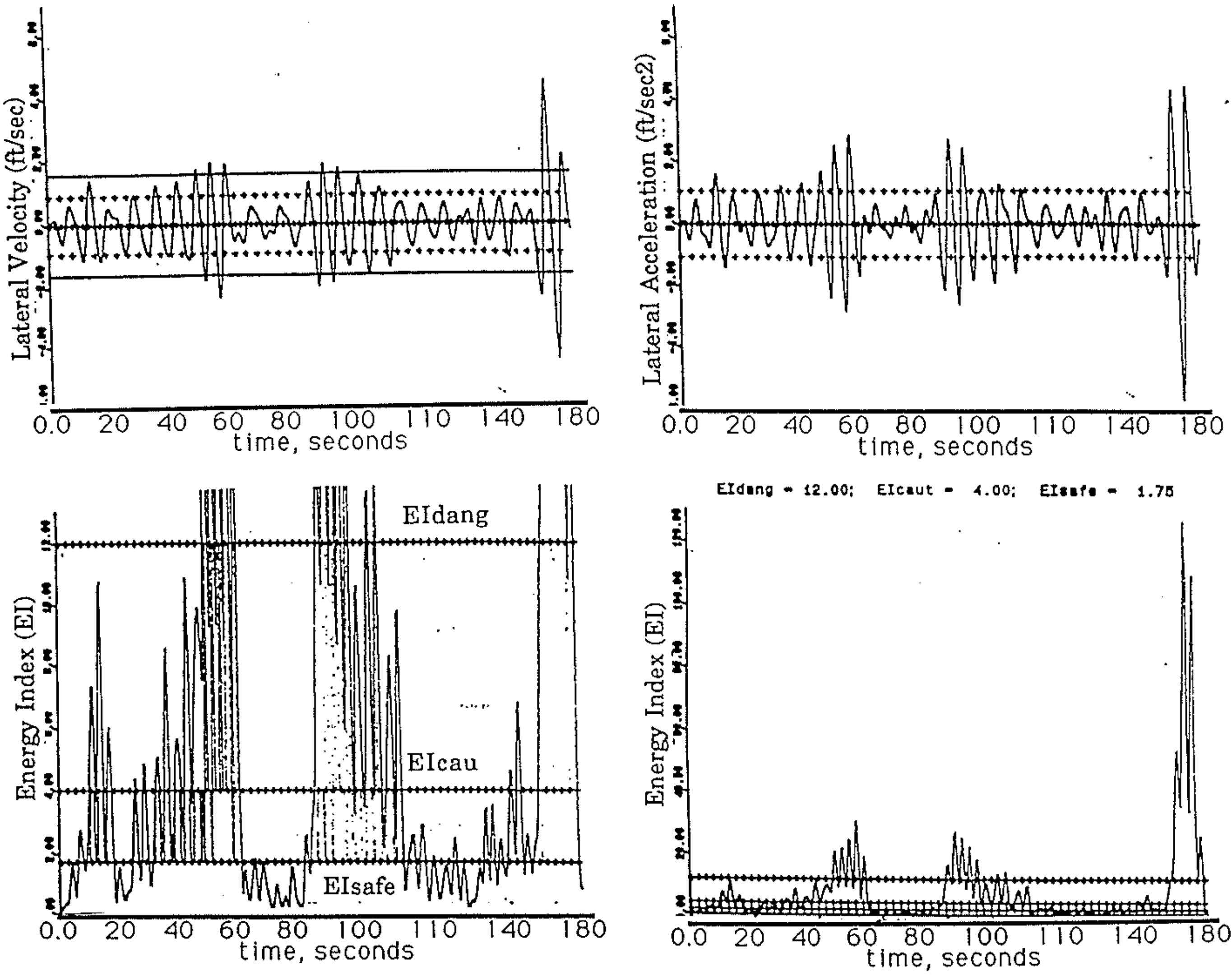


Figure 6- Sample Energy Index Simulation Seaking x FFG37 (USA):
Ship Vel.=10 knots, Wave Heading= 75°
Wave Height= 06 feet; Period= 07 seconds

Continued

c. Test (iii), hypothesis supported. A simplified matrix of at sea recorded data was used and compared with synthetic time history driven energy index results. Trace results show the energy index response to be consistently stable . Energy index response using at-sea recorded data and simulation data in the frequency domain proved to be nearly identical (figure 8).

Further, as a result of the simulation portion of Phase 1 Testing Program, other tendencies were identified:

1. The LPD algorithm can respect a 5 second rise-time (or drop time) regardless of the significant wave height. In the worst cases, flashing green deck never occurs. Thus, recovery must be made in green and yellow deck with no lag-time assurance of deck stability. The algorithm becomes a real-time deck motion indicator only.

2. The index as currently defined, is very conservative. Aircraft limits are currently defined using static values regardless of the coupling or stabilizing dynamic factors that several degrees-of-freedom impose on the equation. Thus, when a degree-of-freedom

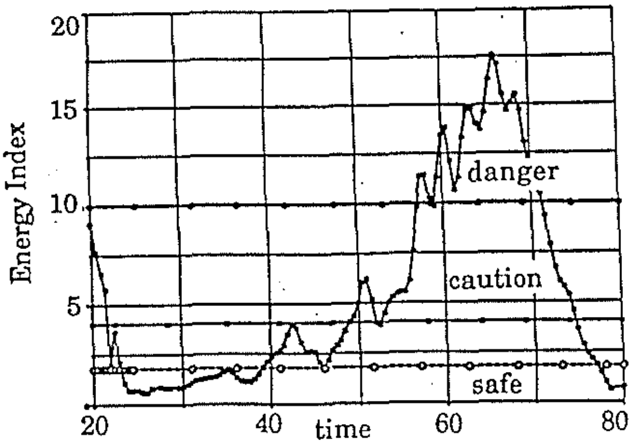
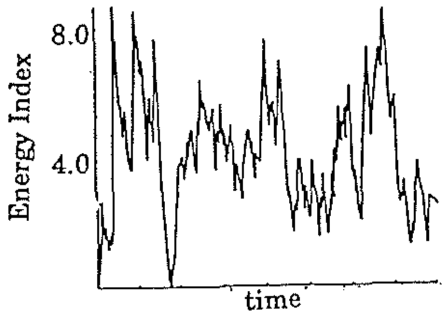
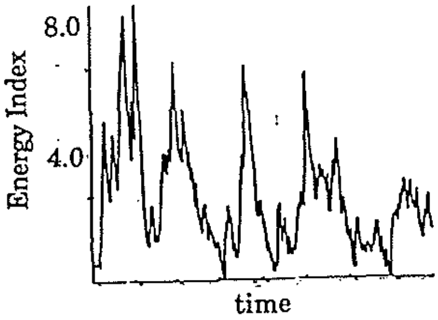


Figure 7- Sample Simulation Risetime
Seaking x FFG37 (USA):
Ship Vel.=10 knots, Wave Heading= 00^0
Wave Height= 09 feet; Period= 09 seconds



Recorded Data



Simulated Data

Figure 8- Sample Real vs Simulated EI Case
Seaking x FFG37 (USA):
Ship Vel.=11 knots, Wave Heading= 39^0
Wave Height= 12 feet; Period= 09 seconds

exceeds a limit value, the equation issues a red signal, regardless if the aircraft is actually in dynamic stress. Improved definition of aircraft limits will increase the number of deck availability periods identified by the algorithm. As an aside, conservatism is worse in following seas than in ahead seas.

LPD Pre-prototype Assembly

The LPD was assembled as a pre-prototype system during the course of phase 1. Software modules were written to acquire, treat and pass ship motion data from a sensor package through to the energy index program (see figure 9). Specifically, the sensor input module receives ship motion data from a sensor package as analog voltages. The sensor compensation module is designed to reduce sensor biases and correct any scale-factor errors. The data transformation module converts analog information to digital signals, performs axis rotation and calculates velocities from acceleration values. This module also contains various filters to reduce vibrational and transmission biases in the converted data. Finally, the treated data are directed to the LPD module for *energy index calculation* to the LPD output module. The output module contains various switches including a conversion of the energy index values back to analog voltages for study purposes.

Table 3- Sample risetime length,
% Green deck during run by
randomly selected interface
Seaking x FFG37 (USA)

Case	Avg rise(t) (sec)	% green deck
100300507	11.3	39.8
101050305	40.0	43.0**
050150909	05.0	11.0
100150607	----*	84.2
100150305	----*	100.0
200000607	28.0	70.5
100301511	x	0.0
200150909	5.3	14.2
150150909	5.25	19.5
251651209	5.9	25.0**

where:
ex: 100300507 = Ship vel. 10 kts
Wave heading= 030 degs
Wave height= 05 feet
Wave period= 07 seconds

* - no risetime detected (never reached red)
x - no flashing green detected
**- not typically used for launch/recovery

The LPD hardware assembly (pre-prototype) is composed of three devices: Ship Motion Sensor Package (SMP); Signal Conditioning Package; and Portable IBM Compatible PC (see figure 10). The current compatible sensor package contains two angular pendulums, three-axis rate gyro, and three linear accelerometers. The SMP analog signals are received by the Signal Conditioning

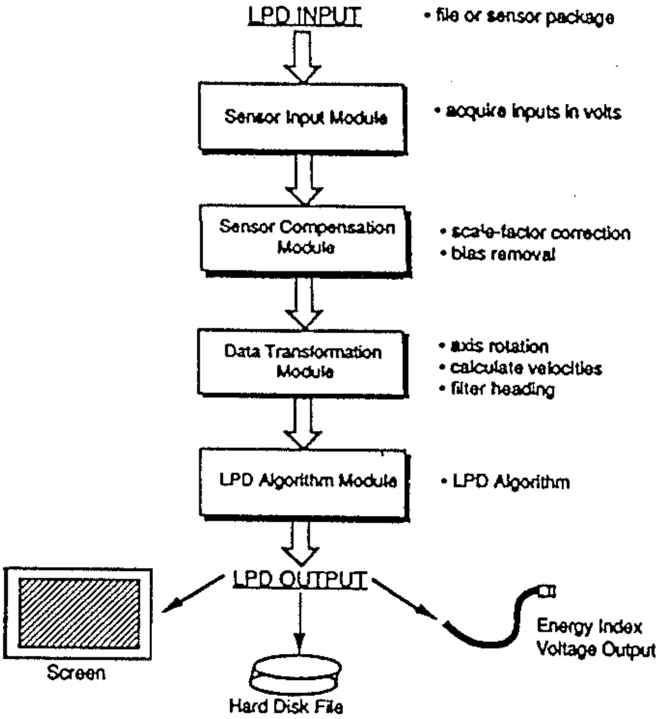


Figure 9- Software Functional Flowchart

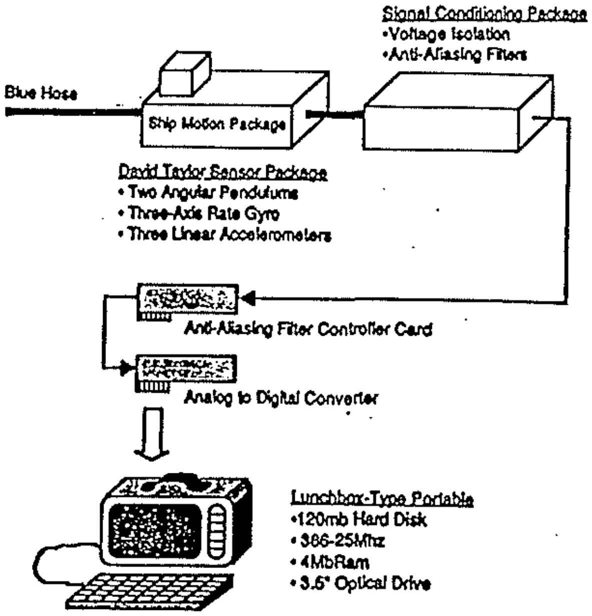


Figure 10- Hardware Functional Flowchart

Package (SCP). The package contains voltage isolation and anti-aliasing filter systems. The SCP is controlled by the IBM PC compatible computer by an anti-aliasing filter controller card. The computer also contains the analog to digital converter card. The LPD software is contained by the PC. Data is maintained either in MATLAB or binary format for easy transfer to diskette. At this stage there are no peripherals attached (little study has yet been conducted).

Figure 11 presents the experimental program display. Energy index results may be viewed in real-time on the screen of the LPD PC. The experimental LPD program screen contains various data studies (*not all yet connected*). The first line of the LPD screen is for documentation (options, flight information, run time) Below and to the left are the sensor package parameters. The voltage values recorded from the ship motion package are compared to the equivalent compensated digital values. The ship synchrometer (if available) parameters are recorded below the SMP. Below the synchrometer data are the bullseye motion parameters. Here aircraft limits are indicated in the ship coordinate system. These are measured against actual real-time recorded values. To the right of the sensor package portion of the screen is the landing light. Here the energy index is converted to a deck availability energy signal. The performance summary *is not currently an option* (additional programming is required). Finally the energy index status is a double check of the landing light.

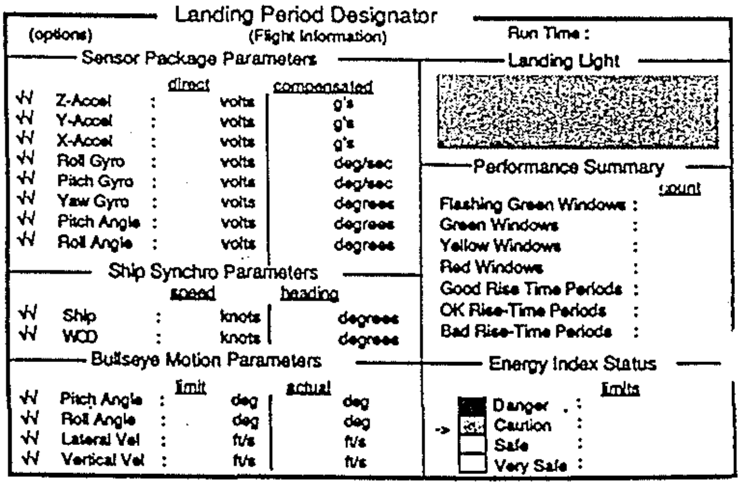


Figure 11- Proof-of-concept Display Panel

Pre-Prototype Initial Testing

A matrix of recorded ship motion data has been passed through the pre-prototype assembly. Energy index performance has consistently respected the triple hypothesis test discussed earlier. Figure 12 displays a sample of energy index calculation using at sea data. The LPD responded to the at-sea matrix in the same manner as it responded during the phase 1 simulation program.

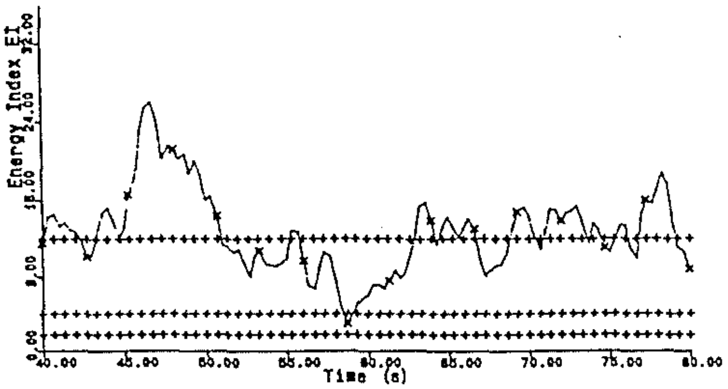


Figure 12- Sample EI At-Sea Recorded Data
FFG22 x Seaking Interface
Ship Vel.- 11 kts, Wave Heading.- 39 deg
Wave Ht.- 12 feet (est.), Period- 9 sec. (est.)

Hardware Assembly Testing

On three occasions, the full assembly, has been tested in the laboratory using the SMP. The most important test occurred in August 1993. The LPD-SMPkg rate table test measured the response of the assembly through a matrix of decoupled and coupled degrees-of-freedom. The conclusions from the report were [13]:

i. Whenever the angular displacement was greater than a danger limit, the LPD signaled red. Marginal conditions allowed analysis of the LPD through various deck availability conditions (safe, warning, etc). At the appropriate moment, the LPD consistently changed signal color.

ii. Connection between actual motion and the LPD responses relative to helicopter operations must be further investigated.

iii. The LPD showed sufficient operability to warrant USN at-sea testing.

Manned Flight Simulator

While initial programming of the Manned Flight Simulator (NAWC-Patuxent River) occured sometime prior to that in the UK, pressing Royal Navy needs favoured accelertated LPD investigation in the UK. The LPD was programmed into the Advanced Flight Simulator at the Defence Research Agency's Bedford Laboratory. The LPD is used visually to identify windows of quiescences from ship motion data using a colour indicator representing a deck security condition. The definition of each deck security zone is as follows. Red is defined as a condition in which there exists high energy in the aircraft-ship system. Aircraft limits will be exceeded if landing is attempted. Yellow is defined as having elevated energy in the system with limited deck motion. However the deck is still within aircraft limits. Solid green (later changed to be green-amber) is considered safe, however, there is some acceleration detected that could translate very rapidly into unacceptable motion. Flashing Green (later converted to solid green) is a special condition in which there is insufficient energy in the aircraft-ship system to raise the deck out of limit in under some defined time period. For the size of a USN FFG x Seaking, this time lag is 5 seconds. For the Type 23 this time lag is greater than 4 seconds. This time lag from flashing green to red is termed 'rise-time', In this project, rise time is defined as the time lag that the accumulated energies in a vessel produce a ship displacement from quiesence to a high risk condition (outside the normal aircraft operating limits), as a function of a specific helicopter.

The participating pilots were asked to follow test techniques developed during handling qualities work on battlefield helicopters [14]. Mission components were evaluated by element (Mission Task Elements or MTE). Each element included desirable and adequate task performance parameters against which the pilot could assess success in completing each task [15]. Pilots flew the final approach segment of the recovery task. The pilot techniques are standard in the Royal Navy. The objective was to assess the visual cues on the ship as an aid for landing rather than the benefits to aircraft instrumentation or the improvements for the flight deck officer.

The initial aircraft conditions for each run were:

Distance from the stern	150 m
Height	15 m
Offset from stern	10 m
Airspeed (indicated)	15 knots

Other aircraft environmental conditions included:

Approach "glide" slope	3°
Radial angle from the bow of the ship	165°
Visibility	0.4 nm day
Visibility	1.0 nm night
Wind (based on beaufort)	no airwake

The Royal Navy standard appoach for Merlin consists of flying to the 'port wait' position (along side the landing deck and parallel with the bullseye). The pilot generally hold at this position until a quiescent period is detected. The aircraft is then manoeuvered over the flight deck to a hover position directly over the bullseye. The pilot then holds while assessing ship motion until an appropriate ship motion condition is achieved. At this point, the pilot recovers. For small aircraft like Lynx, UK standard procedure is for one manoeuvre from port wait to landing.

The aircraft and LPD models were configured with EH101 (Merlin) data. The model was representative of an aircraft of the same class. The ship model was a Type 23 using synthetic time histories based at a ship velocity of 12 knots with a relative wave angle of 45 degrees. The seaway was altered from 3 to 6 on the sea state scale with analysis limited to 3 - 5 on the sea state scale.

Pilot performance was based on individual pilot's assessment and the analysis of recorded flight parameters. Debriefing occurred immediately after touch-down. The pilot performance made use of the Cooper-Harper handling qualities rating (HQR) scale. Pilots were informed of their actual performance based on aircraft final location on the deck and recorded parameters, such as, descent velocity.

After a period of familiarization the trial took place with various visiual cues (including the Landing Period Designator).

The sortie definition legend is given, as follows:

Mission		Qualifier
A-	Day/ SS0	1- Horizon bar
B-	Day/ SS3	2- Hover Position Display
C-	Day/ SS4	3- Horizon bar with LPD
D-	Day/ SS5	4- Hover Position Display + LPD
E-	Night/ SS0	5- Helmet-mounted display
F-	Night/ SS3	
G-	Night/ SS4	
H-	Night/ SS5.	

SS= Sea State

Sorties with LPD were, therefore, combinations involving the qualifier 3 and 4.

RESULTS

To establish early a relationship between environmental conditions and the evaluations of the test pilots, an assessment was made comparing performance parameters between day and night as a function of increasing sea state and the HQR rating scale. Note the clear separation between night and day activities. The figure suggests that the seaway has a more profound effect on pilot performance during night than during the day. This confirms the primary assumption that visual cues are of paramount importance during night.

Pilot verbal comments strongly supported the LPD concept and presentation. During two sorties, the comments most often used under the task cues were: "LPD gives enough time to position the helicopter and land"; it confirms what the pilot thinks"; "without LPD I would have waited much longer to land"; "improved confidence"; "reduces pilot workload". Under system characteristics: "LPD gives confidence on ship activity"; "LPD helps reduce workload". Negative comments included; "set too conservative"; "it can draw you in".

The next logical step was to compare recoveries with and without the LPD. Only SS0 and SS4 were flown without LPD. SS0 was used only to standardize the test and was flown without the LPD only. Thus, only SS4 could be compared. Figure 13 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. 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. This information was compiled for SS4 from three sorties.

From the traces, with few exceptions, the recovery occurred during low energy index indications which reflected actual ship motion conditions. On several occasions, pilots chose to land in the green or yellow which are acceptable for aircraft limitations but offer no guarantee on near-future ship motion. On one occasion an inadvertent landing occurred during a "red" condition while the pilot was hovering at too low a height, when the deck was out of limits and experienced a positive heave.

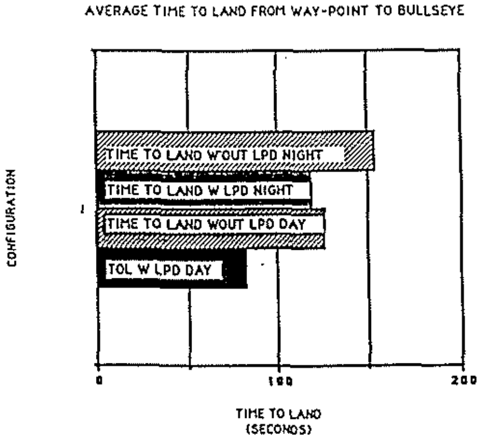


Figure 13- Average Time to Land

CL-352 LPD Assembly

As Bombardier, Inc Canadair Defence Systems Division does not manufacture ship motion reference units or LED light indicators, a competition was conducted. Members of the evaluation panel of more than 15 responses to the RFP included the USNaval Surface Warefare Center, Carderock Division and USNaval Air Warefare Center, Patuxent River. The resulting assembly is displayed in figure 14. It loosely resembles the NSWC Ship Motion Reference Unit used by NAWC early in the LPD program. The principle components attached to a portable computer are: Motion Reference Unit (MRU) and LPD LED light indicator. The MRU is manufactured by Seatex (Norway) and the light indicator is manufactured by ETW (Germany). The revised LPD screen is shown in figure 15. This assembly has successfuly operated through Sea State 8.

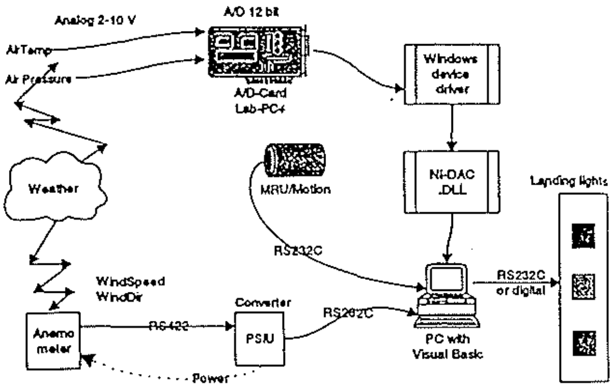


Figure 14- CL352 LPD

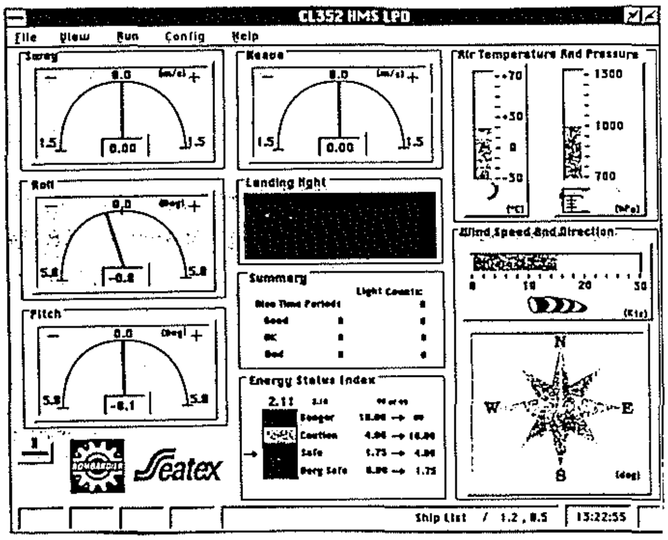


Figure 15- CL353 LPD Internal Screen

At-Sea Testing

At-sea testing of the LPD was conducted by the Naval Air Warfare Center Aircraft Division at Patuxent River under a NAVAIR sponsored program, the Naval Surface Warfare Center Carderock Division under a NAVSEA sponsored program, and on German, Canadian and British warships. The most recent testing and evaluation programs are briefly discussed below.

Early analysis indicated possible operational advantages when LPD was available. Opportunities to recover helicopter safely may increase by using the LPD to identify, earlier than would be possible by the pilot's visual examination alone, the onset of a quiescent period of ship motion. Initial at-sea, pilot-in-the-loop, tests were conducted on-board the RFA Fort Victoria (AOR) which took place between the 7 - 15 May in the North Sea and the North Atlantic Ocean.

Five general activities were devised to achieve project goals. The participating pilots and engineers were asked to evaluate LPD performance during helicopter daily evolutions. The test activities included a pilot general course and brief, operational pilot evaluation, pilot/engineer event marker, data recovery and evaluation, and miscellaneous activities.

Operational Pilot Evaluation

Pilots launch and recover normally. The LPD is placed fully visible to both landing spots on the flight deck. The pilot refers to the LPD on launch, along side hover, transition to deck hover and final recovery. The evaluation form also has reference to a scenario condition (raised seas and severe conditions on-board the Type 23). Pilots are interviewed using the evaluation form during the debrief phase of the mission.

FLYCO Event Marker

From the FLYCO position over the flight deck, the User records the onset and duration of each phase of the recovery. Recovery phases recorded are along side hover, transition to deck hover, and hover to recovery. The Event marker is recorded using a switch box pulse to a VAX computer.

Data Recovery and Analysis

The LPD and ship motion data are recorded on both the HMS computer and DRA PC using compass heading and date/time to identify equivalent recordings. Both data-banks will be analyzed at a later time by the DRA to judge LPD performance.

Pilot Evaluations[16]:

a. Task Cues (how is the LPD as a cue for the pilot to complete recovery) 1 excellent, 2 good, 3 fair, 4 poor, 5 inadequate: 2= 75%, 2.5= 25%

b. Aggression (chance that the LPD could cause aggressive pilot behaviour) 1 minimal 2 low 3 moderate 4 high 5 maximum: 2= 25%, 3= 75%

c. Workload (how does the LPD affect pilot workload) 1 minimal/reduces workload 2 moderate/reduces workload 3 considerable/no change 4 extensive/increases workload 5 intolerable/greatly increases workload; 2= 100% (at night comments indicated 1=100%)

d. Scenario T23 x EH101 or Lynx; sea state 4/5, HQR (with and without the LPD): without LPD HQR=5, with LPD: HQR 2= 25%, HQR 4= 75%

The light indicator was like-wise evaluated (initially the scale was flashing green; green; amber and red). Early in the analysis, the number of colour states was reduced from 4 to 3. It was thought that 4 states were too many and possibly distracting. However on evaluation of 3 states it was found that 3 states did not communicate tendency or trends of the energy in the deck. The final signal consisted of 4 colour states with green; green-amber; amber and red as the energy markers.

HMS Marlborough (Type23 Frigate)

The purpose of this phase of the LPD project during Trial AVALON (on-board the HMS MARLBOROUGH Type 23 frigate) was to demonstrate continued LPD applicability as manifested by pilot performance and evaluation [17]. In this test, the LPD evaluations were to be accomplished during standard pilot launch and recovery evolutions. Test squadron leader would perform envelope expansion manoeuvers for the Wessex (taken as a Seaking by the LPD) and the Lynx helicopters. Each evolution would contain four touch and go events. The LPD would be made available on 2 of the four.

Secondary concerns to be addressed, included light specification, testing of certain experimental improvements such as the ship list compensation program and the best course to steer pilot program. These activities would be analyzed passively during the course of the mission.

The CL352-LPD was mounted over the center of the hangar door on the starboard center side of the SHARK display. The Ship list compensation program was active early in the testing program and in very light sea state conditions (the most applicable state). The Ship List program operated to specifications but was discontinued as the sea rose.

Pilots executed recoveries with the LPD as a visible cue. Sea States 4 - 6 were desired, however, owing to unusual weather, Sea State 8 was attained (see figure 16). LPD functioned, with minor fluctuations in extreme conditions, according to specification. The LPD was evaluated through very high sea states. Confidence was gained early by the flight crews tasked to use the device.

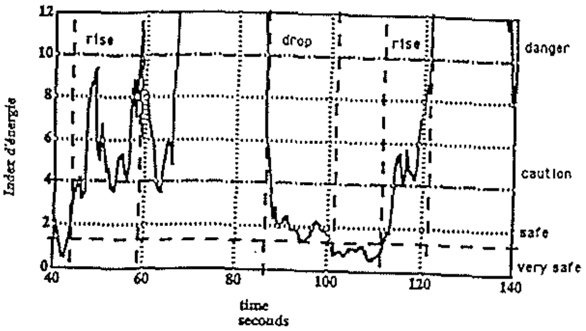


figure 16- Lynx x T23 Sample Hurricane Data (5 meters)

When recovery was accomplished during a green light, touch down was invariably smooth and confortable with the deck consistently level. When using the LPD, the pilot would wait for an amber/green-green light before moving across the deck. Once over the deck, the aircraft would be retrimed as the pilot waited for the green indicator. On the green indication, the pilot would land vertically in a very controlled, but with out delay, manner. According to the flight crews, this procedure consistently allowed for a gentle controlled recovery. Pilot confidence was such that flight crews required the use of the LPD for all non test point landings including refuel, passenger transfer, and so forth. By night, the LPD was of great assistance in confirming the suitability of the deck for landings.

According to pilot evaluations, LPD promoted pilot confidence by consistently and correctly interpreting ship motion as a function of aircraft limits. LPD contribution to flight safety, according to pilot evaluations included, reduction of pilot workload, confirmation of the suitability of day and night landing, and very useful for non-test point landings (refuel), passenger transfer, etc. Finally, the assessment of the LPD in terms of the UK pilot rating scale (difficulty with HQR 5 being very high and HQR 1 being very easy) was conducted. From an HQR =5, the use of the LPD reduced the scale to HQR =3. Throughout Hurricane Lill, the LPD performed its service even when flying stations were discontinued.

HMCS Halifax (City Class Frigate)

A demonstration program was conducted on-board the Canadian Frigate HMCS HALIFAX during its four month deployment in the North and South Atlantic. The primary objective was technical and the devices activities on-board were entirely passive. More than 2400 hours of shipmotion and energy index information were recorded covering climatic zones from the Antarctic to the Georgian Banks. The recordings were manually stopped during port visits (Cape Town, Ushuaia, etc) . Recordings could be interrupted by hangar power outages. To encourage wide observation and comment, the LPD was placed in a high visibility area of the hangar. The demonstration was characterized as satisfactory. At the time of this report with 90 hours representing 2 randam hourly samples per day, the ship/helo risetime analysis was calculated at better than 98% correct (see figure 17). Much of the same comments and conditions found during the HMS Marlborough evaluation were confirmed during the HMCS Halifax demonstration.

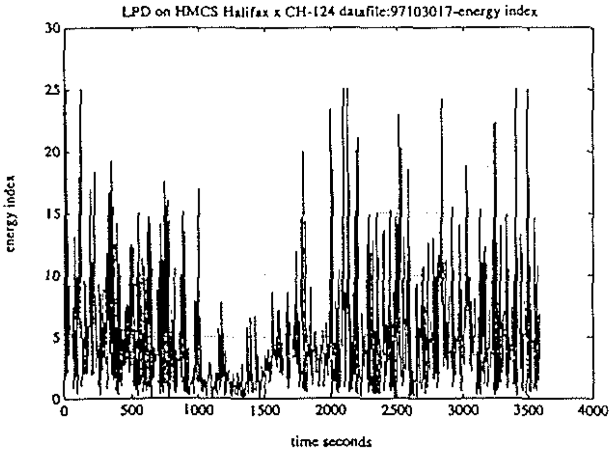


figure 17- sample HMCS Halifax x CH124, EI

Concluding Remarks

The LPD, an empirical formulation, relates real-time ship motion to safe times for aircraft recovery of a given aircraft-ship combination. The User may apply this information to perform launch and recovery operations or other motion sensitive tasks. Many motion sensitive activities and aircraft/ship combinations can be programmed for various on-board locations.

The LPD Phase 1 analysis program has provided significant data from which to build scientific confidence in the energy index approach. The LPD has been found to be sensitive to changes in aircraft , ship and climatic parameters. For the size of a FFG-7 class frigate, the LPD has been shown to respect a 5 second rise-time (which is directly dependent on the aircraft and ship combination). Under normal conditions, an unacceptable rise-time was never detected.

The LPD performed equally well when programmed with real ship motion data. The LPD performed sufficiently well during rate-table testing of the entire pre-prototype assemble to prompt USN support for immediate at-sea testing.

The LPD, however, is not in its optimal condition, for either software or hardware. Further research, leading to program improvements, is needed to ensure maximum reliability. At sea testing, while limited in actual scientific value, is invaluable in building confidence within the User community. For this reason, the Dynamic Interface Community strongly supports early at-sea testing of the pre-prototype LPD Assembly.

Acknowledgement

The Authors wish to dedicate this article to the venerable Peter J. F. O'Reilly, a founding father of the dynamic interface discipline, mentor and counselor. The Authors wish to thank L Cdr. Chris Taylor, RN for his assistance and collaboration. Also the Authors wish to thank for their assistance: Terrence R. Applebee (Carderock), Cdr. Langlois, CN, Olivier Le Bihan, DCN, Ole Budde, Seatex, Thomas Tubbesing, ETW, Cdr. G. Bell, RAN and Bernard Langlois, Bombardier (Mirabel).

REFERENCES

[1] Healey, J. Val (1986). Simulating the Helicopter-Ship Interface As An Alternative to Current Methods. NPS 67-86-003 (U). Naval Postgraduate School. Monterey.

[2] Carico, D (1988). Introduction to the Proceedings of the First Dynamic Interface Working Group Meeting. Dynamic Interface Department. Rotary Wing Directorate. NAWC. Patuxent River.

[3] Ferrier, B., Polvi, Lt.(N) H., Thibodeau, F (1991). Helicopter/Ship Analytic Dynamic Interface. *(U). Proceedings AGARD (NATO) Meeting on Helicopter-Ship Interface.* AGARD-CP-509.Seville.

[4] O'Reilly, P.J.F (1978). Ship Motion Analysis. Bell Helicopter Textron. BHTI 699-099-087. Fort Worth.

[5] Meyers, W.G., Applebee, T.R., Baitis, A.E (1981). User's Manual For the Standard Ship Motion Program, SMP.(U) DTNSRDC/SPD-0936-01. Bethesda.

[6] Love, J., Upton, J., O'Reilly, J.F.P (1976). Evaluation of an Helicopter Landing Period Designator abord the USS Koelsh. Vol. 1. BHTI 699-099-014. Ft. Worth.

[7] O'Reilly, J.F.P (1983). Landing Period Designator Mk II. BHTI 699-099-118. Ft. Worth.

[8] Love, J., Upton, J., O'Reilly, J.F.P (1976). Evaluation of an Helicopter Landing Period Designator abord the USS Koelsh. Vol. 1. BHTI 699-099-014. Ft. Worth.

[9] Hutchins, Dale (1987). Technology Transfer Document.(U) TTCP-HTP-6. NAVAIR-932J. Washington.

[10] Thibodeau, F.A., Bakus, N (1990). Landing Period Designator, Mk III Research and Development Program.Canadair SRD-000-90/20. Montréal.

[11] Ferrier, B., Semenza, J (1990). NATC Manned Flight Simulator VTOL Ship Motion Simulation and Application. Proceedings of the AHS. Washington.

[12] Muntigl, J (1992). Calibration of Landing Period Designator Algorithm. Canadair IRAD Project. LPD060592.JM. Montréal.

[13] Ferrier, B., Semenza, J (1993). LPD - Ship Motion Package Rate Table Test Results. Canadair IRAD LPD160793.MEM. Montréal.

[14] Padfield, G. D., Charlton, M. T., Kimberley, A. M. (1992). Helicopter flying qualities in critical mission task elements. Initial experience with the DRA Bedford Large Motion Simulator. 18th European Rotorcraft Forum, Avignon, France, September, 1992.

[15] Tate, Lt (RN) S. (1995). (U) "Report on AFS Trial TRISTRAM; Further evaluations of supplementary pilot visual aids for the operation of helicopters from small ships". DRA/AS/MSD/CR95154/1.Farnborough (UK).

[16] Ferrier, Dr. B [1995]. (U) "Test Log Book Report; Trial FORTRESS on-board RFA Fort Victoria". Bombardier Inc, Division Systèmes de défense (Mirabel, Canada); ASF/2894-DRA Bedford. Farnborough (UK).

[17] Ferrier, Dr. B. [1997]. (U) "Test Log Book Report; Trial AVALON on-board HMS Marlborough". Bombardier Services Corp (Arlington, USA); ASF/3124-DRA Bedford. Farnborough (UK).

Bibliography

Bonnefille, R (1976). Cours d'Hydraulique Maritime. École Nationale Supérieure de Techniques Avancées. Paris.

Ferrier, B (1992). Étude Analytique D'Interface dynamique aéronef-navire. Dept. de Génie civil. École Polytechnique de Montréal. Montréal.

Neumann, Gerhard (1952). Über die komplexe Natur des Seeganges- Tweiten Teil- Das Anwaschsen der Wellen unter dem Einfluss das Wind. *Deutsch Hydr. Zeit.* Band 5, Bonn.

Ouellet, Y (1973). Analyse spectrale de la houle. GCI-60-333.Presse de l'Université Laval. Québec.