# The Examination and Evaluation of Dynamic Ship Quiescence Prediction and Detection Methods for Application in the Ship-Helicopter Dynamic Interface

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# ABSTRACT

Motion sensitive operations at sea are conducted in an unpredictable environment. While occasionally these operations can be planned around suitable weather forecast or delayed until smoother motions are apparent, naval ships conducting flight operations may have little liberty in their mission planning and execution. Tools exist to translate the ocean's harsh conditions into discretely defined low motion operational periods. Particularly of interest, the identification of discrete lull periods or quiescence for shipboard helicopter operations can be better defined using a landing period indicator than with the current method of utilizing static deck angle measurements. While few of these systems exist, assessing their operational benefits is difficult due to a lack of well-defined performance metrics.

This thesis defines and examines the use of two methodical approaches to evaluating Landing Period Indicators (LPIs) and their subject ship-helicopter dynamic interface system. First a methodology utilizing the comparison of a basic transparent algorithm is detailed and a case study employing this methodology is examined. Second, a system dynamics approach is taken to pilot workload analysis, utilizing a dynamic systems model characterizing a subset of the Dynamic Interface. This approach illustrates the realistic gains in understanding and development that can be accomplished by utilizing system dynamics in the analysis of the Dynamic Interface and LPI insertion.

## Dedication

To those who told me I could, when I thought I could not,
Mom, Dad and CDR Steve and Sharley Weiden, thank you for your confidence.

To those who listened when I needed it,
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# Table of Contents

# List of Figures

## List of Tables

# Chapter 1 - Introduction

## Motivation

Ships are meant to be at sea. The sea is universally regarded a harsh, unforgiving and sometimes unpredictable environment. Shipboard operations are consequently subject to a seemingly chaotic environment. Years of naval engineering and much trial and error has helped better define efficient and safe operational procedures.

The motivation of this thesis is to help better define and assess possible tools for improving the prediction and determination of low motion operational periods, specifically here for shipboard helicopter operations. Conclusions can also be applied to other marine applications, such as oil rigs/platforms or other floating structures and other motion sensitive operations carried out in the marine environment.

The prediction of motion events and quiescent periods during ship operations is a valuable objective, enabling enhanced safety and greater operational availability in an otherwise random and uncontrollable environment. In 1985, the loss of operations and effectiveness due to ship motion was estimated to total 10-15 days per frigate at a cost of £100,000/day by the Royal Navy (Brown 1985). Current deck motion evaluation methods for VTOL flight deck operations are based entirely on discrete static pitch and roll observations made by the ship operator and an intuitive assessment of the wave period by the pilots.

**Figure 1- USCG HH-52A lands on board the USCGC WESTWIND, 6 March 1964 (www.uscg.mil)**

## Definitions

- Airwake – the complex and dynamic flow of air/exhaust resulting from the apparent wind (combination of true wind and relative wind) moving past/through a ship's superstructure. Airwake is usually very complex and unsteady and is best visualized using a full-scale experiment, wind/water tunnel test (with smoke, bubble or dye injection), or CFD (computational fluid dynamics) modeling.
- AOG- Active Operator Guidance – a ship operator aid that measures specific ship motions and outputs recommended actions to the ship operator to optimize specific ship dynamics. Generally focused on minimizing motions pertinent to shipboard deck operations and habitability. Depending on configuration, may also be employed to generally minimize ship motions for flight operations by suggesting a best course/speed for the current conditions.
- DI- Dynamic Interface – refers to the ship-air vehicle interface, incorporating ship characteristics (including landing area dimensions, motions, deck illumination schemes and superstructure airwake) as well as the air vehicle characteristics (landing gear geometry, propulsion/lift margins, vehicle geometry, weight) and the factors that influence the dynamics of landing the air vehicle on the ship. The US Navy's DI program began formally in 1971 to determine "the launch/recovery capabilities of a particular model helicopter in the at-sea environment of a particular class ship"(Kolwey and Coumatos 1975).
- DDML-Dynamic Deck Motion Limit – an operational limit based on real-time measurements of motions.
- DDML System – A system that uses DDMLs as a basis for indication of motion characteristics. May be used as an LPI or for other motion sensitive operations like maintenance work.
- LPI- Landing Period Indicator – a device that determines a current/future period of acceptable motions for landing a helicopter or other vehicle and outputs an indication of this period
- LPD – Landing Period Designator- a commercial, proprietary, LPI program currently being tested and implemented on a limited scale.
- LSO/LSE – Landing Safety Officer/Enlisted – person on or near the flight deck, responsible for visually guiding the helicopter's deck landing

- NSWCCD – Naval Sea Warfare Center Carderock Division, formerly the David Taylor Research Center (DTRC), formerly the David Taylor Naval Ship Research and Development Center (DTNSRDC), formerly the Naval Ship Research and Development Center (NSRDC) and formerly the David Taylor Model Basin (DTMB) in Bethesda, MD.
- Quiescence – "The interval of time where all ship motions are within acceptable limits for performing a desired activity," (Colwell 2002).
- Risetime – "The time taken for the accumulated energies in a vessel to produce a ship displacement from quiescence to a high risk condition (outside the normal aircraft operating limits)…" (Ferrier, Bradley et al. 2001).
- SAR – Search and Rescue
- ASUW – Anti-surface warfare
- UAV- Unmanned Aerial Vehicle
- USW – Undersea warfare (also called ASW)
- VLA – Visual Landing Aid
- VSTOL-Vertical/Short Take-off and Launch vehicle

## Motivation for a Landing Period Indicator

Mariners have long roamed the seas and used a variety of non-academic measures to characterize its behavior. Rhymes and songs have been passed down for ages concerning predicting future sea conditions ("Red sky at night, sailor's delight, red sky at morn', sailor take warn"). Historically many things at sea were measured by the seaman's eye, meaning using one's intuition and best approximation. Modern advances in technology have improved our methods of measuring and understanding the sea, but for some operations, seamen's eye is still the tool for measuring and determining correct action.


**Figure 2 – Standard Naval Bubble Inclinometer (Ball) and the HCO's view aft (www.navy.mil)**

The main operation of focus for this thesis, naval shipboard helicopter operations, continues to rely on the seamen's eye of both the ship driver in choosing an optimum course for flight operations, as well as the seamen's eye of the pilot in choosing the appropriate instant in which to land the helicopter on the dynamic ship flight deck. "Recovery procedures and operational envelopes are heavily oriented to wind velocities and orientation while giving only limited attention to the orientation of the ship," (Ferrier and Manning 1998). Typical standard operating procedure for locating an appropriate ship course for flight operations involves quick vector math to determine courses that allow a relative wind speed and direction that are within a pre-defined wind-envelope over the flight deck. Only after this course has been checked for operational wind characteristics, is it checked to ensure operational deck motion limitations aren't exceeded[1]. Regardless of visibility or time of day, there are no standard instruments universally employed by the US naval fleet to indicate to pilot or ship operator, when motions are likely to be safest for helicopter landings or other motion sensitive deck evolutions.

Current U.S. Navy operational limitations related to deck motion are expressed in terms of maximum static pitch and roll angles. Typically, these are measured using a standard naval bubble inclinometer (Figure 2) prior to each landing evolution by the Helicopter Control Officer (HCO). A 1975 U.S Navy report noted, " [i]nclinometers are inaccurate for dynamic measurements of pitch and roll because they are essentially low damped pendulums or air-bubble-level devices which are sensitive to longitudinal and lateral accelerations, respectively. Thus the vertical and longitudinal location of the roll inclinometer within the ship will affect the accuracy of roll readings, and the vertical and lateral placement of the pitch inclinometer will affect pitch reading accuracy," (Baitis 1975). During a ship's life, if an installed inclinometer ever has to be relocated (due to maintenance or refit), there is no standardized procedure to recalibrate them which reduces the integrity of these measurements as a ship gets older (USCG 2004). Additionally, "[t]he timing with which the inclinometers are read is potentially as large a source of error as constituted by their basic inaccuracy as angle sensors," (Baitis 1975). To illustrate the magnitude of inclinometer errors, Figure 3 shows a comparison of inclinometer measurements and electronic measurements of pitch and roll angle. The diagonal line shows where the data would lie if both measurements were equal. The mass of data above the line indicates the inclinometer readings were almost always greater than true values, occasionally in magnitudes greater than the limiting static deck limits (Baitis 1975).

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[1] R.W Prouty provides another good description of the complexity of naval flight operations, Prouty, R. W. (2004). Helicopter-Ship Operations. Helicopter Aerodynamics. A. K. Radecki. Mojave, CA, Helobooks: 225-230.

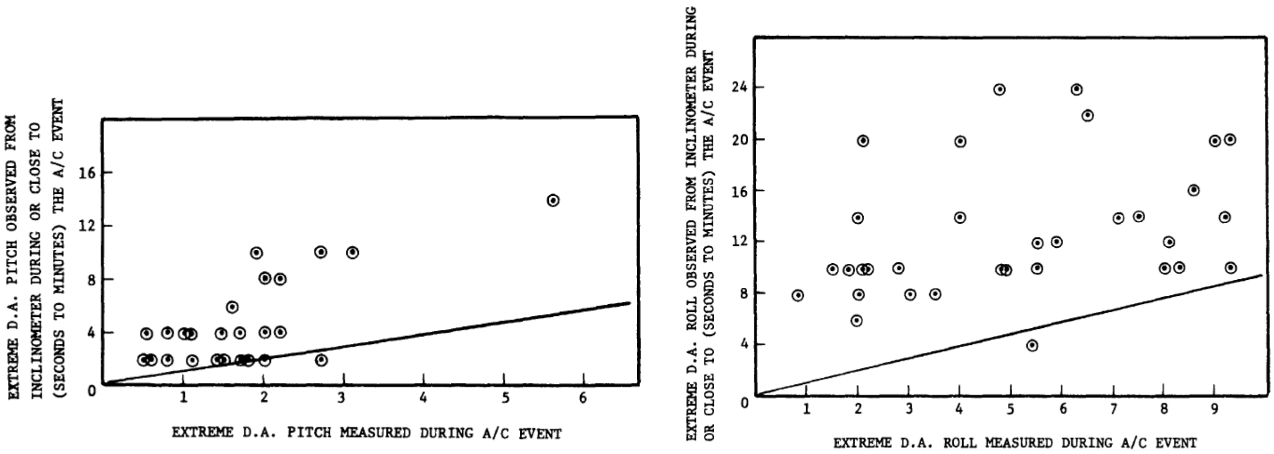



**Figure 3 – Comparison of Inclinometer-Based Readouts and NSRDC Electronic Measurements of Extreme Ship Roll and Pitch during Aircraft Event (Both measurements are given in double amplitudes) (Baitis 1975)**

Most ships have much more accurate sensors as part of their gyro-compass (used for navigation and weapons employment) that measure pitch and roll, however these measurements are not used for any other ship operation. The report specifically recommended improvements that included displays of "RMS or equivalently significant pitch and roll readouts developed from existing ship systems … on the bridge and in the flight control station," (Baitis 1975) that would provide much more accurate information than those of the standard inclinometers, however these recommendations were never implemented.

There are no specific instructions for application of the static deck limits – in particular, no formal guidance with respect to identification of quiescent periods occurring in an otherwise out-of-limits environment. Moreover, simple deck angle limits do not reflect roll rates, heave motion, or frequency of motion, so that the application of the standard limits is somewhat subjective. This responsibility rests entirely on the pilot and LSO/LSE, trusting in their ability to visually ascertain the status and motion characteristics of a moving flight deck on a ship in unpredictable seas (Figure 4).


**Figure 4 – LSE gives landing signals to an SH-60 (www.navy.mil)**

"When attempting to land a helicopter on a ship, the pilot or deck officer, observes the motion of the ship and can with some reasonable accuracy predict the occurrence of a lull in the motion. It would be extremely advantageous to be able to minimize the guesswork and predict the lull more accurately," (Healey 1986). A US Coast Guard Flight Manual for the HH65 Daulphin helicopter illustrates the reliance on the pilot's visual judgment in its extent of instructions to pilots on their landing approach, "Plan the approach to arrive at a point… that will provide sufficient visual cues of flight deck movement, wave period and deck lighting to execute a safe landing," (USCG).

Furthermore, current motion criteria are also flawed as Colwell states,

> Existing ship motion criteria are almost entirely empirical. Limit values are defined by maximum motions encountered during successful operations in flight deck certification trials and are sometimes supplemented, or extended to higher motion limits, by subsequent operational experience. These 'maximum-value' limits are of use for flight planning, providing the applied to the correct motion parameters, but they are of little use for providing guidance in realtime operation. ... Detailed Analysis of instrumented ship and helicopter data clearly shows that the actual motions that can be tolerated while the helicopter is in low hover and attempting to land are very much less than the maximum-value limits.(Colwell 2002)

Colwell also suggests that "traditional, empirical motion indices used to define ship/helicopter operating limits (SHOLs) are no longer relevant" because they are based on older ship designs that typically located the flight deck near the longitudinal center of the ship, whereas modern naval ships have flight decks at the stern (allowing sensitive weapon systems real estate at the low motion longitudinal center of gravity), which increases the magnitude of vertical ship motions beyond the scope of the earlier developed limit systems(Colwell 2002a).

There are a variety of technical improvements that may benefit mariners and the naval aviators with regards to the accurate indication of the real time periods of quiescence, useful for monitoring flight operations or other deck evolutions. Strategic employment for planning future deck evolutions would also greatly benefit the user (i.e. given the current or assumed/forecasted sea state, enabling the operator to plan optimal heading/tracklines for a future time period (Descleves 2007)) as time spent finding an adequate course for winds and motions may be detrimental to other operations (SAR/USW/ASUW). "Even an improvement in capability such that risk to pilot and equipment can be maintained at present levels in seaways of greater severity can be translated directly into improved operational effectiveness," (Dalzell 1965). Long time horizon motion forecasting software tied into weather forecasts would also be helpful for tactical planning in operations and response centers whose asset allocations for various missions are a function of the assumed capability of an asset in an unknown motion environment. Given a tool to better predict the motions in an operational area, decision makers could better allocate appropriate assets to meet the motion requirements, reducing response times and improving efficiency and safety.

Although an improved operational envelope is substantial advantage derived from a functional Landing Period Indicator, worthy gains are also likely in various safety improvements. Studies surveying U.S. Navy helicopter shipboard mishaps from 1980 to March 2005 concluded "[a]n initial survey of the complete collection identified a total of 46 mishaps that potentially involved deck motion, representing 7.5% of all the mishaps…A total of 14 mishaps from 1980-2004 are considered to have been potentially DDML-preventable, including two Class A mishaps, 2 Class B mishaps and ten Class C mishaps.." which incurred $12M in damages total. "The costs for a notional DDML system, had it been available over the time period covered by the reports" is $23M, however over half of the costs for improved operational capability would have been recovered by avoiding $12M in accidents. Additionally, "these accidents always involve the potential for serious injury or loss of life – this changes the outlook entirely," (Milgram 2006-2007).

In January, 2001, the US Coast Guard had a Class A flight mishap onboard USCGC CAMPBELL (WMEC 909) where during the twilight hours, a HH65A entered a dynamic rollover after landing before tiedowns could be installed. After the helicopter's main rotor blades contacted the deck, the helicopter rolled completely onto its right side and then spun 130º counterclockwise until it faced the stern of the ship. Although only minor injuries resulted, three members of the flight deck crew jumped overboard to avoid the rolling and spinning helicopter. Additionally, total damages between the cutter and helicopter totaled almost $2 Million. The investigation of the incident stated "it was unlikely CAMPBELL rolled to … an exceptional degree, but rolled at a rate which created enough momentum to allow (the helicopter) to continue its roll… (leading) to the dynamic rollover of (the helicopter) and was the primary cause of this mishap." The investigation report continued suggesting adding a reminder to the pertinent procedures manual, for the HCO to recalculate the ship's motion (pitch and roll angular displacement) and weather data and update the helicopter as "significant changes occur." In its conclusion, the report suggested "expedite(d) evaluation of LPD technology for implementation on current and future… cutters.(USCG 2004b)"


**Figure 5 - Coast Guard HH65A 6571 Post-Rollover Orientation (USCG 2004)**

Preferably, discrete real-time prediction of near future periods of quiescence would give the pilots and ship operators a tool to confirm their seaman's eye approximations or with increasing accuracy, may be the pushbutton solution for landing period indication. Furthermore, Landing Period Indicators are becoming more important due to the deployment of high value, non-expendable UAVs lacking visual judgment of deck motion. Without the ability to perceive deck motions as a human pilot would, unmanned sea and air vehicles could use the predictive information as an impetus to land or approach a docking cradle.

Wider application of this technology can also be employed for a variety of safety intensive naval deck evolutions including underway/connected replenishment and launching small boats or amphibious craft. Both naval combatants and commercial masters could use LPI technology for improving the embarkation of personnel (by pilot ladder or Jacobs ladder or fast roping (Figure 6)) or topside movement of personnel in heavy seas, a man-overboard shipboard recovery, delicate machinery or cargo movements at sea, efficient track management, minimizing cargo damage during heavy weather, stabilization systems and MEDEVAC planning.

**Figure 6 –Naval Personnel Fast Roping to the Flight Deck of a DDG (www.navy.mil)**

In addition to decrypting a highly random environment, clear solutions to this technological gap face many operational and technical challenges. A ship's motion at sea is defined by six degrees of freedom and displaying extremely complex motion calculations rapidly and in a way that could be easily understood by someone uneducated in ship dynamics is required. Regardless, before being implemented, these solutions must be tested to determine their accuracy and determine their correct operational implementation. Many approaches to this type of system have been studied and developed with varying success.

## Literature Review

In reviewing pertinent literature, it was immediately clear that the concept of a LPI was not new. J. Dalzell wrote a note on carrier deck motion prediction in 1965 (Dalzell 1965). In 1969, P. Kaplan investigated the effects of possible filtering methods to improve linear prediction errors (Kaplan 1969). Subsequently studies in Dynamic Interface (DI) began in the early 1970s, and as early as 1973, U.S. Navy reports recommended establishment of a research program to develop a motion prediction landing aid for improving flight operations (Baitis 1975; Baitis and Woolaver 1975). "To improve future naval VSTOL operations we must develop a lull predictor that gives us at least 8-10 second forecast into the future for pitch and pitch related responses and 20 second forecast in the future for roll," (Baitis 1977). Despite this early work, operational implementation of DDML technology has been limited and to date, no methodical examination of these systems and their effectiveness has been accomplished.

Ship motion cannot be captured simply by observing its roll or pitch motion. Early flight standards for "non-aviation ships", as destroyers and frigates were designated, recognized the need to establish both wind envelopes and static motion limits for flight operations. The U.S. Navy began to improve established standardized wind envelopes in 1974 (Beck 1976) and in the following year, a U.S. Navy report documented the influence of ship motions on flight operations (Baitis 1975). The first attempts at predicting small ship motions (aircraft carrier predictions began in 1965 (Dalzell 1965)) started in the late 1970's and early 1980's with varying methods including a variety of filter based models, Autoregressive Moving Average Models (ARMA), and energy based approaches.

The original efforts to predict motion were made with a Wiener filter linear prediction technique (Dalzell 1965) however it required complete information about the power spectrum of the motion to be predicted and although it was successful in 6 second predictions of carrier pitch motions, implementation of this method was too complex (Kaplan 1969). Kaplan proposed alternatively using a Kalman filter. A variety of approaches were taken creating and using a Kalman filter for ship motion purposes (Weiss and DeVries 1977; Triantafyllou, Bodson et al. 1983). Triantafyllou and Bodson's approach resulted in 5 second predictions (20-25% RMS error) for all ship motions, with a 10 second prediction for roll (Triantafyllou and Bodson 1982) while Sidar and Doolin found good pitch and heave predictions up to 15 seconds with nearly perfect phase prediction of up to 60 seconds using modeled carrier motions (Sidar and Doolin 1983). Bodson and Athans also studied a controller for VTOL aircraft to automatically "chase-the-deck" allowing the pilot to solely focus on a vertical decent to the flight deck (Bodson and Athans 1985). In 1992, Lainiotis, Charalampous et al. improved on the Kalman filter approach applying the Adaptive Lainiotis Filter (ALF) which includes a bank of multiple Kalman filters, allowing for a more robust approach that enabled parallel processing and improved performance for non-Gaussian initial conditions (Lainiotis, Charalampous et al. 1992). A similar approach was also applied using a neural network to estimate ship position (Lainiotis, Plataniotis et al. 1993).

The first published Autoregressive Moving Average Models (ARMA) used real ship motions to predict 2 to 4 seconds of heave response with phase predictions up to 10 seconds in 8 second waves with 24.5% RMS error (Yumori 1981). This approach was later expanded to predict heave, pitch and roll for up to 10 seconds with a 30% LPI error rate (Broome and Hall 1998).

Indexes began as a way to inform the pilot and LSO/LSE of quiescence by combining a specific set of motions into a scalar quantity that could efficiently indicate the ship's current motion characteristics. Paulk, using only vertical position and velocity measurements, produced a binary index that indicated "lulls and swells" in a ship's motion (Paulk and Phatak 1984). His indicator was very accurate in indicating lull periods, but because its indication was slow to differentiate between the motions, it was only timely enough to confirm a pilot's intuition of a current lull. With increased confidence in the ship's quiescence, however, "the lull/swell guidance resulted in significantly shorter landing times (by 30-50 sec) than occurred without its use," (Paulk and Phatak 1984).

Although he had started his work on the Landing Period Designator (LPD) in the late 1970's, O'Reilly's first published work on the Energy Index (EI) didn't appear until 1987. "The original premise was that if you continuously calculate a number – the energy index – by a formula containing deck displacement and velocity terms and if you look at this number as a ship proceeds underway, the number will give an indication of the roughness of motion," (O'Reilly 1987). O'Reilly defined his original Energy Index as follows:

$$EI = \sqrt{(x)^2 + (\dot{x})^2 + (y)^2 + (\dot{y})^2 + (z)^2 + (\dot{z})^2} \qquad \textbf{(1)}$$

where x, y, and z are the three translational displacements at the landing deck. B. Ferrier has kept O'Reilly's LPD moniker but his efforts have diverged from O'Reilly's (Ferrier and Manning 1998). Ferrier has also continued to work on commercially producing the LPD.

LPD EI (Landing Period Designator Energy Index, B. Ferrier) is a heavily published DDML system. As all systems currently fielded (experimentally or commercially), LPD is reflective of current and previous motions and not predictive in nature. Integration of LPD has been suggested with AOG (Active Operators Guidance) as well as many UAV programs. Likewise, implementation of LPD EI has promising uses from autonomous landing of UAVs to docking submarines or routine welldeck operations. Difficulties arise, however, with understanding how LPD EI is formulated and how much safety margin is actually built into the system (seeing that it is not predictive the program depends on an average risetime or the nominal time it takes for the ship motions to go from acceptable to out of limits.)

Also, because the EI is a scalar index, there is no way quickly see which direction the motions are headed (towards a safe deck or away) or how long the system will indicate any deck condition. Further discussion of LPD will be presented in Chapter 2.

In examining the DI problem at the grassroots level, J.L. Colwell identified the "primary factors limiting helicopter/ship operations are: pilot workload, aircraft limits (power, control, etc), wind over deck/turbulence, and ship motions," (Colwell 2002). He also motivates the use of a system that allows ship operators to chose from a selection of parametrically determined flight operation course/speed alternatives (instead of the current single relative wind vector method.) With regard to better understanding the dynamic deck problem, Colwell includes a critical observation regarding the scalar index approach to pilot cueing. "…the critical challenge for providing improved pilot cueing from measured ship motions, is to gain a clear understanding of which ship motions are limiting which aspects of the helicopter/ship operation. This understanding tends to be obscured by considering only a scalar representation of the motion environment," (Colwell 2002).

Colwell states that pilots have sufficient visual clues for judging lateral ship motions but not for vertical motions and vertical accelerations (Colwell 2002), which concurs with a much earlier U.S. Navy report which noted that "pilots inadvertently used the worst possible motions four out of five times for pitch and two out of five times for pitch-associated vertical acceleration" (verses two of five for roll, and once of five for lateral acceleration) (Baitis 1977). Colwell's studies (Colwell 2002; Colwell 2002a; Colwell 2004) determined that Flight Deck Vertical Acceleration (FDVA) was a critical parameters for flight deck operations and suggested defining a real time limit value for it. Because a measured quiescent period can be of any length, Colwell also redefined quiescence such that all critical parameters have to be within their limits and any motion that had exceeded its limits must "experience a subsequent motion peak below its limit" before a quiescent period can be designated (where the second peak limit is 80% of the original limit) (Colwell 2002a).

Colwell's motion system (Flight Deck Motion System-FDMS) although not predictive, allowed the relaxation of the maximum pitch angle limit for the Canadian Patrol Frigate, which corresponded to a "15% increase in percent time operable for winter in the northern North Atlantic" (Colwell 2004). FDMS includes a tactical planning display and also functions as a flight deck data recorder allowing for future motion studies. Motion recording devices are not generally installed onboard U.S. naval combatants, but their implementation was recommended because they are "invaluable in reconstructing critical events that lead to a mishap," (USCG 2004b). Additional benefits of FDMS include the ability to use multiple criteria sets (for other motions sensitive operations), incorporate helicopter performance data via data link (for more accurate wind envelope development) and implement asymmetric criteria to account for the helicopter's non-zero static roll due to tail rotor torque effects, asymmetrically sloped flight decks and wind-induced ship heel angle (Colwell 2004) (the latter two of which were considered a contributing factor in the earlier referenced Coast Guard mishap (USCG 2004b)).

There are also other approaches to the LPI solution that are still in the various stages of development. One approach, early in its research stages, linked Finite-Time Lyapunov Exponents (FTLE) to possible quiescent prediction (McCue and Bassler 2005). Another was issued a U.S. Patent in 2000 for a LPI that uses multiple rapid measurements from a forward looking range-measuring sensor to predict future motions which are then compared to a set of static motion limits to determine periods of quiescence (Fleischmann 2000). The future quiescent period is then indicated to the ship operator and aircraft in terms of its duration and its time till occurrence. Although a similar system called Quiescent Period Predictor (QPP) is still in the early research stages (Lumsden, Padfield et al. 1999), no further implementation of a "forward looking" LPI has been found.

Some approaches may be easily confused for LPI solutions (post-landing programs and ship operator guidance programs). A combination of GPS and INS (inertial navigational system) has been proposed as a solution to automate the task of precisely following a dynamically moving ship (Ford, Hardesty et al. 2005), however the method does not really approach the LPI problem as there is no particular connection to a limiting system or a method of verifying when to land. Similarly, many programs have approached the "post-landing" problem which is more concerned with ensuring the helicopter will not skid, slide, or dynamically tip over after successfully landing (Gallagher and Scaperda 2001; Gray 2002). These programs, as similar as they seem, do not approach the more complex LPI issue of "when" to land and are more applicable to commercial application where helicopters remain on deck for long periods (>5mins) without being restrained. Dynaface® is a program that simulates the effects of ship motion on embarked aircraft to clarify the need for various restraint types (Figure 7) (Langlois, LaRosa et al. 2003), however, again does not provide landing guidance.

**Figure 7 –Deck restraint systems –Traditional chock and chains and RAST (seen beneath helicopter) (www.navy.mil)**

Likewise, ship operator guidance programs have been developed to assist ship operators in locating a course with minimal motions (Ferrier, Baitis et al. 2000; Hardy 2006). These programs goal will also serve to improve the efficiency of conducting flight operations and their use alone may increase the safety of flight operations, however, they are do not specifically address or indicate landing periods, and therefore are not considered an LPI.

## Terminology Clarification

While many other authors writing on LPI and DDML systems have attempted to identify the pertinent motions when examining a dynamic deck's limitations, there is no obvious consensus among any of them. Generally, throughout all of the studies, including those previously mentioned, no standard nomenclature or methodology exists, making comparison of results or operational capabilities very difficult as each author and system approaches DDMLs with an original premise and concludes with similarly varied outputs that are difficult to compare. In addition, some systems (like Ferrier's LPD), although well documented and developed, are proprietary in detail.

The variety of terminology employed in ship motion documentation and complex essence of ship motion studies has rendered defining programs and approaches confusing and occasionally misleading. For instance, the use of the term prediction in reference to "Ship Motion Prediction (SMP)" software is confusing as used currently. Compared to weather predictions and forecasting, ship motion predictions are for a discrete or finite time horizon… in this case SMP programs are really ship motion modeling programs. Much like a weather model is used for understanding possible historical/future weather trends in the week, month or year timeframe, real-time data and RMS weather data are used for hourly and daily weather predictions. The difference lies in the need to separate what is actually predictive (i.e. taking past finite time motion history to forecast or predict the future finite time motion) and what is motion modeling (i.e. taking generalized ship characteristics, wave spectrums, and producing a collection of academically modeled motions for the purposes of future study, refinement or control.)

Although this line is not easily drawn, following these definitions, land based academic computer programs would likely be motion modeling programs unless they were used to predict (and thus be compared to) actual motion of a model traversing a tow tank or the like. Modeling programs are useful for design purposes, understanding various engineering change or damaged/dynamic stability impacts on a current design. Modeling software may be run by technicians and scientists with complex and variable interfaces and may be non-real time in processing nature using real data collected previously or generated synthetically. Modeling programs are not truly predictive in nature, although they may model the motions of a future design.

Predictive programs must have much finer fidelity for real-time risk adverse mission application and their purpose will lend to a much more discrete future time period, with little operator focus on data history. The predictive programs, conversely, must be very simple to run and maintain with comparatively few operational variables and by definition must process data in real-time with available installed sensor packages.

To ensure further clarity, the following distinctions, concepts and definitions should be used:

- Modeling Program- a program that bases its output on data collected at a previous time or synthesized data which is used for research and development purposes
- Reflective program – a program that bases its output on recent, but not real-time, measurements and produces an indicator reflective of slightly time late information. This type of program might improve or assist in clarifying a pilot's mental picture of the ship's motions, but may not tell him anything about future motions.
- Predictive program – a program that bases its output on recent and real-time measurements and produces an indicator that predicts future information. This type of program should improve the pilot's accuracy when locating landing periods but would not reflect current motions.
- Academic or development use – employment in concept, design, or research development to aid future development outcomes. The accuracy of programs for academic use could range from a few significant figures to exact measurements.
- Strategic/Tactical use- employment in operational planning periods to aid near future operations. The accuracy of programs used tactically will be limited by the type and

accuracy of data they incorporate, their inherent predictive capabilities and the desired prediction time frame.

- Operational use – employment in real-time to aid current operations. The accuracy of programs used operationally should be as high level as possible, without degrading the purpose of the program (i.e. rapid, but accurate fluctuations may not be helpful.)

## Timeline, Approach Map, and DI System Diagram

Research for this thesis has been organized in two tables. First, a timeline of Naval Helicopter Operations and DI related advancements has been included to better illustrate the slow but continual advancement of LPI concepts (Table 1). Second, the approaches and improvements towards LPI systems have been grouped to better understand the plethora of research that has impacted current practice and theory (Table 2). The Dynamic Interface issue has also been mapped to a diagram to illustrate the various system relations and interdependence (Figure 8).

**Table 1- Timeline of Naval Helicopter Operations and DI Advancements**

| Year | Author | Effort |
|---|---|---|
| 1903 | Wright Brothers | First powered aircraft flight |
| 1911 | Eugene Ely (Carico 2004) | First fixed wing shipboard landing |
| 1930s | US Navy (Carico 2004) | Autogyro experiments on ships |
| 1943 | US Army (Carico 2004) | First Helicopter Shipboard Landing |
| 1949 | US Navy (Carico 2004) | Rotary Wing Branch established at Naval Air Test Center (NATC) |

| Year | Author | Effort |
|---|---|---|
| 1960 | | |
| 62 | US Navy (Kolwey and Coumatos 1975) | Initial effort to define marking/lighting for night ops |
| 65 | (Dalzell 1965) | Suggests possible predictions for carriers |
| 65 | (Durand and Wasicko 1965) | Analysis of Carrier Landing |
| 69 | US Navy (Kolwey and Coumatos 1975) | Visual Landing Aids bulletin established first standard lighting and aviation facility standards for non-aviation ships |
| 69 | (Kaplan 1969) | Wiener prediction for aircraft carrier (pitch) |

| Year | Author | Effort |
|---|---|---|
| 1970 | | |
| 70 | US Navy (Kolwey and Coumatos 1975) | Light Airborne Multi-Purpose System (LAMPS) Program elevated to High Priority |
| 71 | US Navy (Beck 1976) | Dynamic Interface test program launched |
| 71-73 | US Navy (Kolwey and Coumatos 1975) | Glideslope, line up lights, floodlights and deck markings evaluated |
| 71-73 | US Navy (Baitis and Woolaver 1975) | First Comprehensive shipboard VSTOL Aircraft testing includes recommendation for motion prediction program |
| 73 | US Navy (Kolwey and Coumatos 1975) | Defined certification process for shipboard decks |
| 74 | (Gold 1974) | Visual Perception of Pilots in Carrier Landings |
| 75 | (Tuttle 1975) | Report on improvements to H-2 Helicopter for small ship operations |
| 75 | (Kolwey and Coumatos 1975) | Report from 1974 USS Bowen/SH-2F testing |
| 75 | US Navy (Baitis 1975) | Study of the influence of ship motions on flight operations (SH-2 and DE-1052 Destroyer) |
| 76 | (Beck 1976) | Motivates flight testing for safe operating envelopes |
| 77 | (Olson 1977) | Suggests Seakeeping analysis WRT VSTOL as a design consideration for ships |
| 77 | (Garnett and Davis 1977) | Reports on the use of a Wind tunnel and smoke flow testing to examine DI |
| 77 | (Weiss and DeVries 1977) | Design of a ship motion measurement filter (Kalman Filter) |

| Year | Author | Effort |
|---|---|---|
| 1980 | | |
| 81 | (Yumori 1981) | Develops an ARMA/Kalman filter prediction package for Amplitude and Phase |
| 82 | (Comstock, Bales et al. 1982) | Examine ship flight deck performance for various aircraft |
| 82 | (Triantafyllou and Bodson 1982) | Prediction of ship's motion (w/in 25%) for 5s and up to 10s for roll using Kalman Filter approach |
| 83 | (Triantafyllou, Bodson et al. 1983) | Modeling Motions |
| 83 | (Sidar and Doolin 1983) | Carrier/aircraft longitudinal landing predictions (Kalman filtering) |

| | | |
|---|---|---|
| 84 | (Paulk and Phatak 1984) | Lull/Swell binary index, good for confirming pilot's intuitions |
| 85 | (Brown 1985) | Quantifies cost of lost operations due to ship motions |
| 85 | (McCreight and Stahl 1985) | Predicts ship percent time of operation (PTO) and Limiting Significant Wave Height (LSWH) |
| 85 | (Bodson and Athans 1985) | Developed control to chase deck motions, pilot controls vertical descent (Kalman Filtering) |
| 86 | (Healey 1986) | Suggests simulation of DI for inexpensive results |
| 87 | (O'Reilly 1987) | The first motion index, EI indicates energy levels of the flight deck |

| Year | Author | Effort |
|---|---|---|
| 1990 | | |
| 91 | (Negrin, Grunwald et al. 1991) | Studies the benefit of inertial stable visual cues on pilot hover ability |
| 91 | (Berbaum, Kennedy et al. 1991) | Study of helicopter shipboard landing tasking levels in approach phases |
| 92 | (Lainiotis, Charalampous et al. 1992). | Presented improved ALF filter employing multiple Kalman Filters |
| 93 | (Lainiotis, Plataniotis et al. 1993) | Used ALF filtering for neural network approach to prediction |
| 98 | (Burton, deKat et al. 1998) | FREDYN introduced for motion analysis and simulation |
| 98 | (Broome and Hall 1998) | Introduces another ARMA Model for roll motions |
| 98 | (Ferrier and Manning 1998) | Simulation and Testing of the LPD Helicopter Recovery Aid |
| 98 | (Ferrier 1998). | LPD in High Sea States |
| 98 | (Ferrier, Langlois et al. 1998) | Design and Test of Automated UAV/VTOL Shipboard Recovery System |
| 99 | (Lumsden, Padfield et al. 1999) | Human Factors Challenges at the Helicopter Ship Dynamic Interface |

| Year | Author | Effort |
|---|---|---|
| 2000 | | |
| 00 | (Fleischmann 2000) | US Patent for a LPI using a mast mounted range-measuring sensor |
| 00 | (Ferrier, Baitis et al. 2000) | Evolution of the LPD for Shipboard Air Operations |
| 00 | (Ferrier, Applebee et al. 2000) | LPD Visual Helicopter Recovery Aide; Theory and Real Time Application |
| 01 | (Gallagher and Scaperda 2001) | MSI, tipping/sliding index for commercial use |
| 01 | (Ferrier, Bradley et al. 2001) | LPD/EI Development for Australian LPA |
| 01 | (Advani and Wilkinson 2001) | DI modeling and simulation comprehensive study, including pilot workload |
| 02 | (Colwell 2002a) | Ship/Helicopter Operating Limits (SHOLs) |
| 02 | (Gray 2002) | Safety Index based on helicopter type and MIIs |
| 02 | (Colwell 2002) | Ship Motion Criteria - Operating Challenges |
| 03 | (Lynch and Baker 2003) | Joint Venture DI (for high speed catamarans) |
| 03 | (Langlois, LaRosa et al. 2003) | Dynaface, securing system simulation program |
| 04 | (Ferrier, Baker et al. 2004)l | LPD Autoland Operations for UAV |
| 04 | (Lee and Horn 2004) | Analysis of Pilot Workload with Airwake Study |
| 04 | (Carico 2004) | Reemphasizes necessary future paths for DI |
| 04 | (Colwell 2004) | FDMS Operating Concepts and System Description |
| 04 | (USCG 2004) | MISHAP analysis firmly recommends LPI approaches for mitigation |
| 05 | (Ferrier, Duncan et al. 2005). | Manned Flight Simulation of LPD (Type 45/Merlin Helicopter) |
| 05 | (Lee, Sezer-Uzol et al. 2005) | Continuation of Pilot Workload analysis with Airwake modeling |

| | | |
|---|---|---|
| 05 | (Ford, Hardesty et al. 2005) | GPS/INS ship approach |
| 05 | (Rowe, Howson et al. 2005) | Additional commercial application of MSI |
| 05 | (Ferrier, Chang et al. 2005) | LPD application to LPD 9 Class Amphib and Firescout UAV |
| 05 | IDEA | Airwake CFD work |
| 06 | (Carico and Ferrier 2006) | Simulator evaluation of LPD as a VLA on Naval combatants |
| 07 | (Descleves 2007) | Tactical use of weather combined with ship motion predictions |

**Table 2 –Contributing Research Grouped by Type of Research or Advancement**

| **Indexes** | | | |
|---|---|---|---|
| **Name** | **Author** | **Year** | **Type** |
| LULLSIM | (Paulk and Phatak 1984) | 1984 | Early binary system looked at just vertical position and velocity of helicopter-pad |
| EI | (O'Reilly 1987) | 1986 | Energy Index |
| LPD | Ferrier (various) | Present | Energy Index |
| MSI | (Gallagher and Scaperda 2001) | 2001 | Motion Severity Index (MSI) Focused on post-landing issues for Offshore industry |
| SI | (Gray 2002) | 2002 | Safety Index (SI) focused on post-landing nondimensional parameters |
| | | | |
| **ARMA** | | | |
| | **Author** | **Year** | **Prediction Specifics** |
| | (Yumori 1981) | 1981 | 4s prediction of Heave using real data (25% error rate) |
| | (Broome and Hall 1998) | 1998 | 10s prediction of Heave and Pitch (30% error rate in LPI) |

| **Wiener/Kalman/Lainiotis Filtering** | | | |
|---|---|---|---|
| | **Author** | **Year** | **Prediction Specifics** |
| | (Dalzell 1965) | 1965 | N/A |
| | (Kaplan 1969) | 1969 | Wiener found not useful, suggested Kalman Filter approach |
| | (Weiss and DeVries 1977) | 1977 | Creation of Kalman filter for ship motions |
| | (Triantafyllou and Bodson 1982) | 1982 | 5s prediction of all motions (10s for roll) using modeling input |
| | (Sidar and Doolin 1983) | 1983 | 10-12s prediction of Carrier Pitch/Heave |
| | (Triantafyllou, Bodson et al. 1983) | 1983 | Systematic application of Kalman Filter to DD-963 destroyer motions |
| | (Lainiotis, Charalampous et al. 1992) | 1992 | Introduction of Lainiotis filtering for ship motion prediction |
| | (Lainiotis, Plataniotis et al. 1993) | 1993 | Incorporation of Neural Network to Lainiotis filtering approach |

| **General Advancements in Dynamics** | | | |
|---|---|---|---|
| | **Author** | **Year** | **Type** |
| | (Comstock, Bales et al. 1982) | 1982 | Flight Ops performance comparison |
| | (McCreight and Stahl | 1985 | Percent Time of Operation (PTO) method defined |

| | | | |
|---|---|---|---|
| | 1985) | | |
| | (Burton, deKat et al. 1998) | 1998 | FREDYN introduction |

| **Advancements in DI** | | | |
|---|---|---|---|
| | **Author** | **Year** | **Type** |
| | (Baitis and Woolaver 1975). | 1975 | Report on VSTOL DI Testing, includes recommendation for motion prediction program |
| | (Beck 1976) | 1976 | Composed testing requirements |
| | (Olson 1977) | 1977 | DI as Design Consideration |
| | (Bodson and Athans 1985) | 1985 | Developed Kalman Filter Controls Approach to "Chase the Deck" allowing pilot to focus on vertical decent |
| | (Healey 1986) | 1986 | Simulation of DI |
| | (Lumsden, Padfield et al. 1999). | 1999 | System approach to human factors challenges involved in DI |
| | (Fleischmann 2000) | 2000 | US Patent for a LPI using a Mast Mounted Range Measuring Sensor |
| | (Advani and Wilkinson 2001) | 2001 | Comprehensive Study of Modeling and Simulation of DI |
| | (Colwell 2002; Colwell 2002a)l | 2002 | DDML, SHOLs, new quiescent definition |
| | (Lynch and Baker 2003) | 2003 | Established First DI and WOD Envelopes for High Speed Catamarans |
| | (Colwell 2004) | 2004 | Introduces FDMS, Operating concepts and System Description |
| | (Carico 2004) | 2004 | Emphasis of continuation of DI, suggested system of systems approach to testing |
| | (Lee and Horn 2004; Lee, Sezer-Uzol et al. 2005) | 2004 /2005 | Studied airwake models and influence on pilot workload |
| | (Carico and Ferrier 2006) | 2006 | Evaluation of LPD as a VLA in Simulator |

| **ETC** | | | |
|---|---|---|---|
| | **Author** | **Year** | **Type** |
| | (Brown 1985). | 1985 | Quantitative Measure of the Cost of Lost Operational Ability due to Ship Motion |
| | (Negrin, Grunwald et al. 1991) | 1990 | Inertial Stable Cube assisted hover, reduced pilot workload |
| | (Berbaum, Kennedy et al. 1991) | 1991 | Studied Specific Visual Tasks in Helicopter/Shipboard Landings |
| | (Langlois, LaRosa et al. 2003) | 2003 | Dynaface deck securing simulation |
| | (USCG 2004) | 2004 | Mishap final action message suggests investigation of future employment of LPI System |
| | (Ford, Hardesty et al. 2005) | 2005 | Suggested highly accurate GPS/INS based tracking system |
| | (Rowe, Howson et al. 2005) | 2005 | Improving Offshore Helicopter Safety using MSI |
| | (Descleves 2007) | 2007 | Tactical use of Ship Motion Prediction |

As defined previously, Dynamic Interface is a broad encompassing term that is subject to many variables which could be grouped by influence type (operations, policy and design). Figure 8 is a depiction ship-helicopter DI and the variables that have important influence. The diagram was made to show the dynamic system variable relationships in each area of influence and variable alternatives that will define the DI of a particular combination of ship and helicopter. Although only parts of this system diagram are reviewed and investigated here, it is important to remember their dynamic impact on the makeup of a ship-helicopter DI. Seen as a whole system, the contributions of each influence area are better understood.

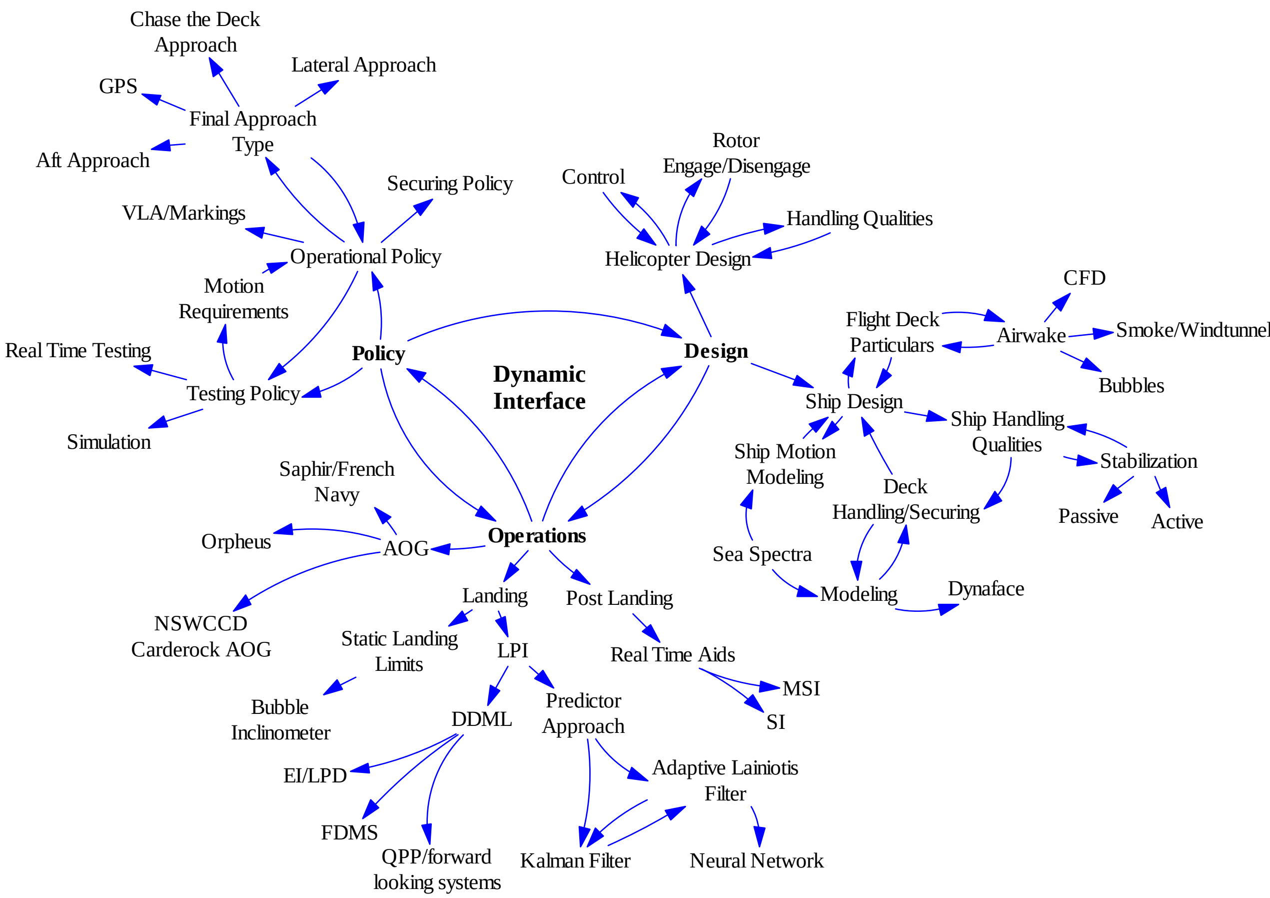



**Figure 8 – Dynamic Interface (DI)**

For example, policy influences occur both in testing policy and in operational policy. Operational policy variables include deck securing policy, VLA/Markings required, and the prescribed final approach (aft/GPS/Lateral/"Chase the deck"). Testing policy may specify real-time testing or simulation or a combination thereof. These policy choices will feedback to design and operational variables.

DI is also dependent on design variables - specifically those of helicopter design and of ship design. Although the focus here is on ship variables, some basic helicopter variables are included as an example. In ship design, many variables influence the resulting dynamic interface. DI, in terms of ship design, is defined by flight deck particulars and airwake optimization which can be approached using CFD, windtunnel experiments, or simple bubble tests to verify. Ship motion modeling programs and final handling qualities will determine the need for and type of stabilization and may result in required deck handling or securing equipment to conduct helicopter operations. The need for deck handling and securing devices may be modeled and the decisions of whether or not to implement these devices will feedback to the overall ship design. Choices affecting these variables will affect the conduct and difficulty of standard operations.

At the point policy has already been determined and the ship and helicopter are well past the design stage and begin operating together, there are few manners of improvement to DI that may be affected. Operators guidance programs (AOG/Orpheus/Saphir) can be employed to assist efficient and accurate determination of low motion courses suitable for helicopter operations. Landing limit systems (reliant on static, dynamic or predicted motions) may be employed to define specific operational envelopes and identify optimal landing periods, and implementation of a post-landing system can help reduce the likelihood of a skid, slide or dynamic rollover. Operational lessons learned are generally applied to future design and policy considerations, resulting in further improvements in the ship-helicopter DI.

## Thesis Objective

The prediction of motion events and quiescent periods during ship operations is a valuable objective, enabling enhanced safety and greater operational availability in an otherwise random and uncontrollable environment. As mentioned, current deck motion evaluation methods for flight deck operations are based entirely on discrete static pitch and roll observations made by the ship operator and an intuitive assessment of the wave period by the pilots. Operational implementation of DDML/LPI technology has been limited and to date, and no systematic comparison of various systems and their effectiveness has been accomplished. While a few DDML systems exist, assessing their operational benefits is difficult due to a lack of well-defined performance metrics. This thesis examines and evaluates quiescent period detection and prediction methods to quantify their accuracy and application in the shipboard environment and proposes two methodologies for better understanding and consistent comparison of candidate systems.

# Chapter 2[2] - Defining a Metric for DDMLs

## The Data and LPI Methods

In March, 2006, the Navy conducted at-sea testing of Ferrier's LPD onboard USS Preble (DDG-88), a Flight IIA Arleigh Burke Class Destroyer. During the entire underway period, each hour's motions were recorded at approximately 60 samples per minute and stored as an individual file which included heading, displacements in roll and pitch, velocities in six degrees of freedom (surge, sway, heave, roll, pitch, yaw), and accelerations in the planar (x, y and z) directions.

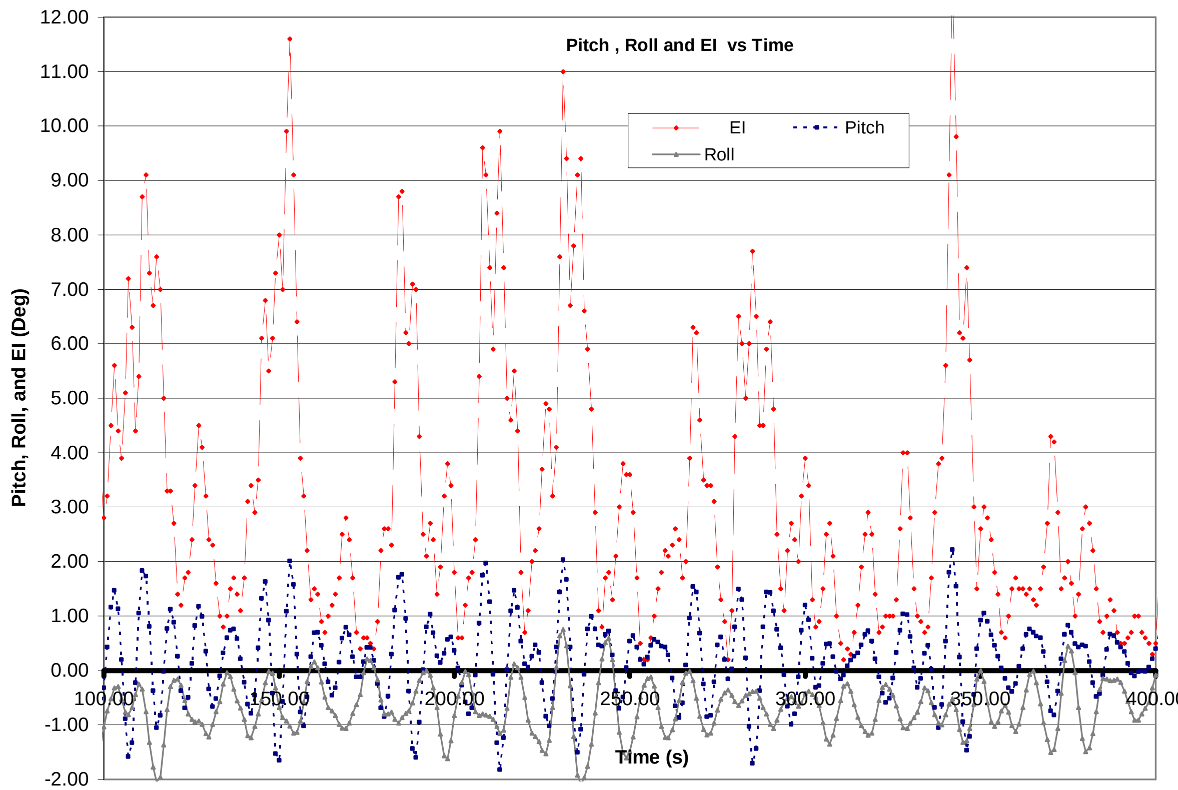



**Figure 9– Sample Plots of EI Output and Pitch and Roll Displacement Time History (Run # 6031521,Table 4)**

Each sample also included the scalar output of LPD. To quickly visualize the effect of motions on EI during the sampling period, plots were made of EI output, roll and pitch displacements and surge, sway and heave velocities over time.

Additionally, a second index, the Benchmark Safety Index (BSI), was formulated by the author using just pitch and roll displacements to attempt to bridge the gap between static deck angle limits and

[2] Large portions of this chapter were submitted to the 10th International Symposium on Practical Design of Ships and Other Floating Structures, Houston, TX, 2007 with co-authors Dr. Leigh McCue, Dr. Naipei P. Bi, and Dr. Judah Milgram.

an EI system, and to illustrate a transparent algorithm not formally proposed as a solution, but as a simple benchmark for comparison and evaluation of DDML systems (Eq.2).

$$BSI = 2*|Roll| + 2*|Pitch| \qquad (2)$$

with the Roll and Pitch angles in degrees.

## Motion Limits and Their Measurement

The LPD algorithm is proprietary but was originally developed using the Ship Motion Simulation (SMS) and the Ship Motion Program (SMP) (Ferrier, Baitis et al. 2000). LPD is not predictive and "makes no attempt to extrapolate ship motion based on historical values. … It capitalizes on the rate at which a vessel can displace because of the natural hydrodynamic forces against the structural and dynamic characteristics of the matching air vehicle," (Ferrier and Manning 1998).

More specifically, EI measures displacement, velocity and acceleration in four degrees of freedom (yaw and surge are monitored but not implemented in the algorithm), assigning weighted dynamic coefficients to each of eight ship/aircraft interface motion terms. It then calculates relative coefficients for each degree of freedom and its derivative. Finally, it considers the aircraft limits before finalizing the weighting of each degree of freedom. Using the element product of an 8x3 matrix of these terms, the EI coefficients are produced, EI is calculated, compared to a deck availability scale and finally graphically displayed to the user (Ferrier and Manning 1998). Generally, the visual cueing scale is defined like a stoplight, where a green indication depicts a very safe landing period, red indicates an unsafe landing period, and green/amber and amber indicate the stepwise transition between the green and red deck conditions. Specifically, the scale is defined as (0-1.74 ) green, (1.74-4) green/amber, (4-10 ) amber, and (>10) red (Ferrier, Bradley et al. 2001). In the data presented here, the Energy Index coefficients were defined to be consistent with deck motion limits of 2 degrees in pitch, 6 degrees in roll (8 degrees, at night), 8 ft/s heave rate, and 3 ft/s sway rate. These nominal limits were established for evaluation purposes by the LPD developer in coordination with the cognizant engineers overseeing the tests onboard Preble. The EI thresholds, and the single-parameter deck pitch angle limit are superimposed on the data from Table 4 below in Figure 10.

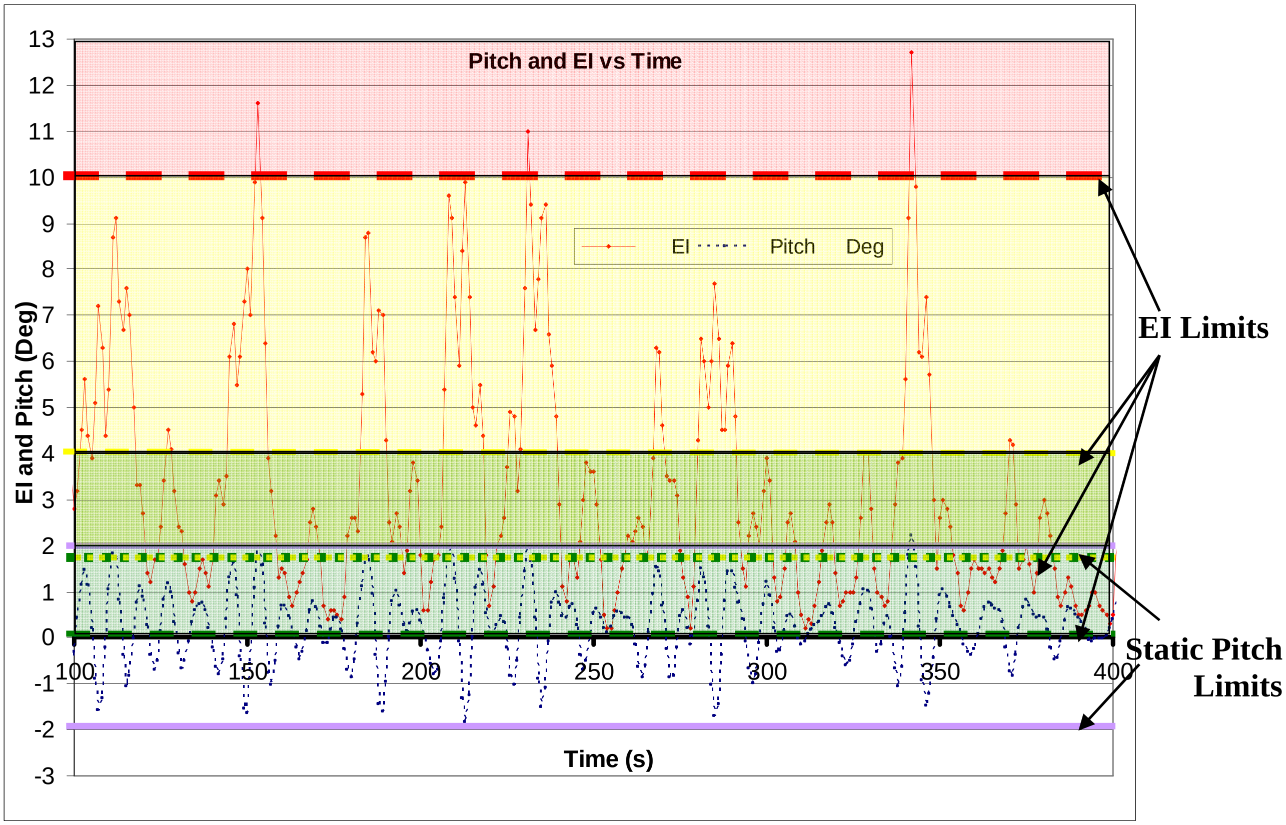



**Figure 10 - Sample Plot of EI Output and Pitch Displacement with Static and EI Limits Superimposed (Run # 6031521,Table 4)**

## The Challenge of Comparison

Although simple deck pitch and roll limits are the current standard for U.S. naval shipboard helicopter operation envelopes, a DDML system or other LPI may allow the definition of new operational limits based on real-time dynamic measurements. The goal of LPI systems is not to provide a more accurate way to ensure compliance with the limits as currently, but to define the dynamic operational envelope of the ship-helicopter interface with a more complete picture than that provided by such static limits. Thus, the purpose of comparing simple deck angle limits with any DDML system is not to validate the DDML system against established limits, but to illustrate the differences in operational envelopes defined by these limit systems, and to highlight possible areas of increased operational capability. The goal of this chapter is to present a transparent benchmark algorithm and suggested comparison methodology as an example for future DDML system evaluation methods.

Difficulties arise when understanding how DDML systems are formulated and how much safety margin is actually built into the system. To date, no DDML system claims to be predictive in nature. As such, a scalar based system can only process and reflect current or slightly time-delayed deck motions or energy levels. When doing so, the basic question is, what is, or should be, the specific meaning of a landing period indication (green light)? Can an algorithm based on real-time measurements produce a useful indicator for future time periods? If so, what specifically is useful about it and how long is the relevant period of quiescence (defined risetime)? In essence, does a green light mean "land now" or "you could have landed now"? If the former, how much time does a pilot or UAV have to complete a landing before that advice is no longer valid? Is the measured rise time repeatable and consistent or probabilistic in nature? Because of the operational, economical, and safety implications of these questions, they must be addressed completely before any LPI or DDML system can be certified and deployed.

### Comparison Against Simple Benchmarks

The questions in the previous section define the basis for a systematic evaluation of DDML systems. In order to examine a DDML System more completely, it is necessary to define a simple process for systematic comparison of approaches. The following steps are suggested as a way to develop a metric for any DDML system comparison and validation process:

1. **Develop a realistic and transparent benchmark algorithm for basic comparison employing similar physics to both original and proposed systems.**
2. **Examine the DDML System for duration of landing opportunities (using synthesized data or real ship's data if available.)**
3. **Compare results (here risetime) against DDML System creator's stated results to check for consistency and percentage error.**
4. **Compare DDML System results to benchmark results and currently employed limit system to determine and quantify possible areas of gained improvement.**

   **Accuracy may be measured in a variety of ways, and could be considered an evaluation of expanded operational capabilities, or a measure of the indicator's failure to warn the operator of certain conditions. Clarity of exactly what is being measured (each sample's indication or the entire period of a particular indication) is important. Here, indications are defined on a sample level, not a period level,**

**however the following comparisons could also be conducted at the period level and would find different results:**

- **Compare the number of indication/period conflicts with the current limit system over the number of total current limit system excursions**
- **Compare the number of conflicted indications/periods of the indicator to the total number of indications/periods of that type - of the indicator**

5. **Create a database from results in step 3 and 4 for comparison against future DDML systems.**

As a case study, an examination of Ferrier's LPD has been used as an example of the above methodology. Following this approach, the BSI is defined. The formulation is chosen to be representative of traditional static limits and similar in concept to the energy based approaches (O'Reilly 1987). The second objective is to examine the duration of the LPD displayed landing opportunities. Next, each landing period indicated by LPD (green light) is examined to see if any of the static deck limit exceedances occurred during the indicated landing period and a closer examination of the assumed LPD rise-time for a destroyer was conducted to validate the program's consistency. Finally, a comparison of the number and duration of landing periods indicated by LPD, BSI and the static deck limits are presented for comparison (Table 4).

When examining static deck limit exceedances occurring during LPD green light indications, the dynamic nature of the indication was expected to cause a number of exceedances by its definition. Part of the motivation of pursuing DDML systems is to widen the operational envelope and find landing periods outside of those suggested by the more confining static limits. Furthermore, the generally excellent safety record of naval aviation suggests that these relatively simple static limits are sufficiently conservative to ensure routine safe flight operations despite the difficulty and level of accuracy of monitoring these static limits. Therefore, it may be expected that a more sophisticated dynamic motion limit system would identify additional landing opportunities outside of these more conservative limits allowing the definition of significantly expanded dynamic deck motion envelopes with similar safety margins.

Out of 41 hours of data (for motion characteristics see Table 3), most of which included ten or more static limit exceedances during each hour, the stated static limits conflicted with LPD green light indications in only three of the hours of data[3]. During three of the hours with the highest roll displacements and sway velocities (Table 3, files 06032209, 06032213 and 06032216), 0.53-0.91% of the static limit exceedances were associated with green light indications from the LPD (i.e. LPD green light conflicts/total static limit exceedances), which accounts for 0.5-1.2% of LPD total green light indications (i.e. LPD green light conflicts/total LPD samples that indicated green, not total green light periods - which are an accumulation of all local green indications) during the hours (compared to 1.05-6.85% and 0.7-4.7% for BSI). When the sway velocity constraint was removed, this disagreement was completely eliminated for both indicators. Conversely, during these same hours, LPD indicated red only 0.03% of the total indications where the static limits were within parameters (i.e. LPD red light conflicts/total indications within static parameters), which accounts for 1-1.7% of all LPD indications (i.e. LPD red light conflicts/total LPD red lights indicated) (14.4-17.8% and 88.7-91.5% for BSI).

The error percentages here for BSI are much higher because of the roll amplitudes experienced during these particular sample periods (i.e. With regular rolls of >5°, using the EI/LPD scale, BSI is regularly indicating a red condition while the ship is still within static limits.) This further emphasizes the need to better address scaling between the benchmark index and the LPI to be compared. Here, one solution would be to scale BSI's coefficients to indicate a red period upon threshold of one of the standard static limits (i.e. coefficient=[10/(roll/pitch static limit)]). While this results in better agreement with the established static limit system (although more conservative when motions are combined), this modification only serves to duplicate the results of the static limit system, and doesn't improve the illustration of differences between indicators.

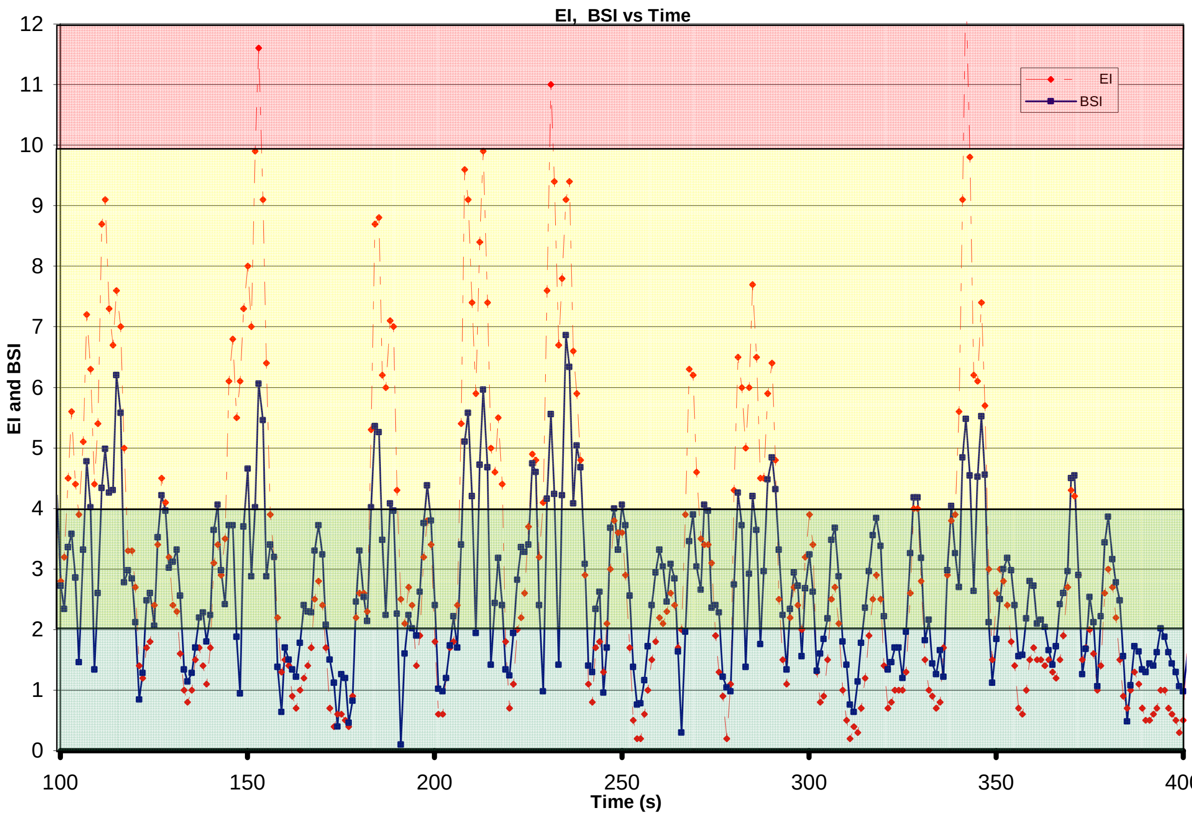
[3] Data analysis was completed with extensive collaboration assistance from Dr. Naipei Peter Bi, NSWCCD

**Table 3 –Summary of Maximum Motions during Trial Period (listed by file number)**

| 0603… | Max Pitch | (deg) | Max Roll | (deg) | Max Heave Rate (ft/s) | | Max Sway Rate (ft/s) | |
|---|---|---|---|---|---|---|---|---|
| **1519** | -1.910 | 2.410 | -2.470 | 1.590 | -3.543 | 3.707 | -0.787 | 0.755 |
| **1520** | -0.220 | 1.290 | -3.270 | 4.450 | -1.575 | 1.772 | -1.378 | 1.411 |
| **1521** | -2.650 | 0.750 | -2.590 | 1.400 | -1.400 | 1.400 | -0.310 | 0.330 |
| **1522** | -2.580 | 3.000 | -3.230 | 1.680 | -5.085 | 4.823 | -1.312 | 1.050 |
| **1523** | -3.620 | 3.960 | -4.820 | 5.500 | -7.316 | 7.316 | -3.412 | 3.215 |
| **1601** | -3.670 | 3.760 | -4.470 | 5.170 | -6.758 | 6.299 | -2.657 | 2.920 |
| **1604** | -4.050 | 4.400 | -3.780 | 1.400 | -6.955 | 7.283 | -1.542 | 1.640 |
| **1609** | -2.790 | 2.930 | -3.540 | 1.810 | -5.643 | 5.052 | -1.739 | 1.804 |
| **1614** | -3.740 | 3.690 | -4.670 | 1.370 | -6.234 | 6.660 | -2.264 | 1.968 |
| **1619** | -2.280 | 2.490 | -6.300 | 7.220 | -4.134 | 4.724 | -3.150 | 2.953 |
| **1701** | -4.830 | 5.270 | -5.050 | 3.250 | -9.777 | 9.908 | -3.379 | 3.215 |
| **1705** | -4.150 | 4.520 | -5.310 | 3.930 | -8.038 | 8.661 | -3.248 | 4.068 |
| **1712** | -2.960 | 3.030 | -9.620 | 8.570 | -7.283 | 6.890 | -4.101 | 4.528 |
| **1718** | -2.960 | 3.950 | -6.640 | 6.980 | -7.218 | 7.775 | -4.068 | 4.724 |
| **1723** | -2.960 | 3.720 | -4.760 | 3.650 | -6.726 | 8.005 | -3.707 | 3.445 |
| **1802** | -3.700 | 4.500 | -4.090 | 4.360 | -7.119 | 7.447 | -2.953 | 2.887 |
| **1806** | -2.380 | 3.090 | -3.490 | 3.190 | -4.856 | 4.692 | -2.493 | 2.133 |
| **1811** | -1.490 | 1.870 | -1.660 | 5.390 | -3.117 | 2.887 | -2.001 | 1.804 |
| **1815** | -1.310 | 1.380 | -2.830 | 5.000 | -2.920 | 3.215 | -2.133 | 2.165 |
| **1819** | -1.790 | 2.230 | -2.310 | 3.070 | -3.937 | 4.199 | -2.165 | 2.034 |
| **1901** | -1.440 | 1.900 | -2.080 | 2.610 | -3.707 | 4.003 | -2.297 | 2.329 |
| **1905** | -1.240 | 1.690 | -2.910 | 2.970 | -3.051 | 3.609 | -2.165 | 2.329 |
| **1912** | -1.010 | 1.360 | -1.930 | 3.420 | -2.625 | 3.051 | -1.608 | 1.673 |
| **1917** | -0.810 | 1.040 | -1.990 | 4.110 | -1.936 | 1.936 | -1.575 | 1.378 |
| **1921** | -0.900 | 1.050 | -3.240 | 5.100 | -2.034 | 2.100 | -1.968 | 1.936 |
| **2003** | -0.400 | 0.770 | -7.290 | 9.230 | -3.314 | 3.117 | -2.329 | 2.231 |
| **2006** | -1.190 | 1.410 | -6.370 | 7.980 | -2.526 | 2.428 | -2.264 | 2.133 |
| **2010** | -2.320 | 2.260 | -5.220 | 7.140 | -3.806 | 3.543 | -1.017 | 1.181 |
| **2014** | -2.460 | 2.260 | -6.570 | 8.750 | -4.363 | 3.871 | -2.690 | 2.756 |
| **2020** | -3.410 | 4.330 | -4.550 | 6.660 | -5.610 | 6.890 | -2.198 | 2.559 |
| **2100** | -3.040 | 3.570 | -9.270 | 12.190 | -4.462 | 5.085 | -3.642 | 4.068 |
| **2102** | -2.770 | 2.710 | -7.630 | 9.850 | -4.035 | 4.429 | -2.723 | 2.887 |
| **2106** | -3.240 | 3.760 | -3.920 | 3.640 | -5.315 | 5.971 | -1.903 | 2.198 |
| **2111** | -2.290 | 2.460 | -7.850 | 10.670 | -3.839 | 4.396 | -4.462 | 3.084 |
| **2117** | -2.490 | 3.040 | -6.710 | 6.540 | -5.381 | 5.381 | -3.478 | 3.281 |
| **2122** | -3.190 | 2.920 | -6.830 | 10.180 | -5.512 | 6.004 | -4.035 | 4.003 |
| **2200** | -2.580 | 2.990 | -4.710 | 3.880 | -6.365 | 5.545 | -3.970 | 4.134 |
| **2204** | -2.370 | 3.140 | -4.670 | 7.470 | -5.020 | 5.184 | -3.182 | 3.248 |
| **2209** | -2.970 | 3.520 | -6.010 | 10.900 | -5.545 | 5.840 | -4.888 | 4.363 |
| **2213** | -2.460 | 2.820 | -9.600 | 12.340 | -5.577 | 6.693 | -4.396 | 4.790 |
| **2216** | -2.330 | 2.860 | -8.940 | 9.450 | -5.676 | 6.004 | -4.396 | 4.626 |

To validate LPD's risetime hypothesis, risetimes were derived from the DDG data files and the minimum values were examined. Minimum risetimes are different for each ship/helicopter combination. A Type 22 Class Frigate has a minimum rise time of 4.9s with a Lynx Helicopter, while a Type 23 Class/Lynx has a minimum rise time of 4.8s (Ferrier, Applebee et al. 2000), a FFG-7/Sea King combination has a minimum risetime of around 5s (Ferrier, Bradley et al. 2001), a LPD-4 Class/Sea King combination has a minimum risetime of approximately 8s (Ferrier, Baker et al. 2004) and the new Type 45 Class Destroyer has a estimated minimum risetime greater than 6s combined with a Merlin helicopter (Ferrier, Duncan et al. 2005). Considering the different ship classes and airframes reported and the data examined, it is assumed that the minimum risetime for a DDG Flight IIA is 5.5s.

For DDG-88, of 922 risetimes measured over 40 hours of data, 5% of the risetimes were shorter than 5.5 seconds. The statistical mode of risetimes less than 5.5s was 5 seconds in duration, however there were many values lower than 5 seconds, with a minimum value of risetime of 1.92 seconds. The question is whether this 5% rate is acceptable to the user. If so, then LPD with a 5.5 second minimum deck energy risetime offers a significant improvement over the minimum risetimes of BSI and the static deck angle limits, 0.93s and 0.88s respectively. Using static limits allowed more than 5.5s of risetime during 51% of their exceedances (1034 of 2025 risetimes.) Although the BSI benchmark is based on similar fundamental principles, it outperformed the static deck angle limits, allowing more than 5.5s of risetime during 73% of the quiescent periods identified (846 of 1159 risetimes.) Here, risetime for the static limits was defined by the entire time the motions were within the previously stated limits (effectively green to red) while BSI was evaluated against the EI scale.



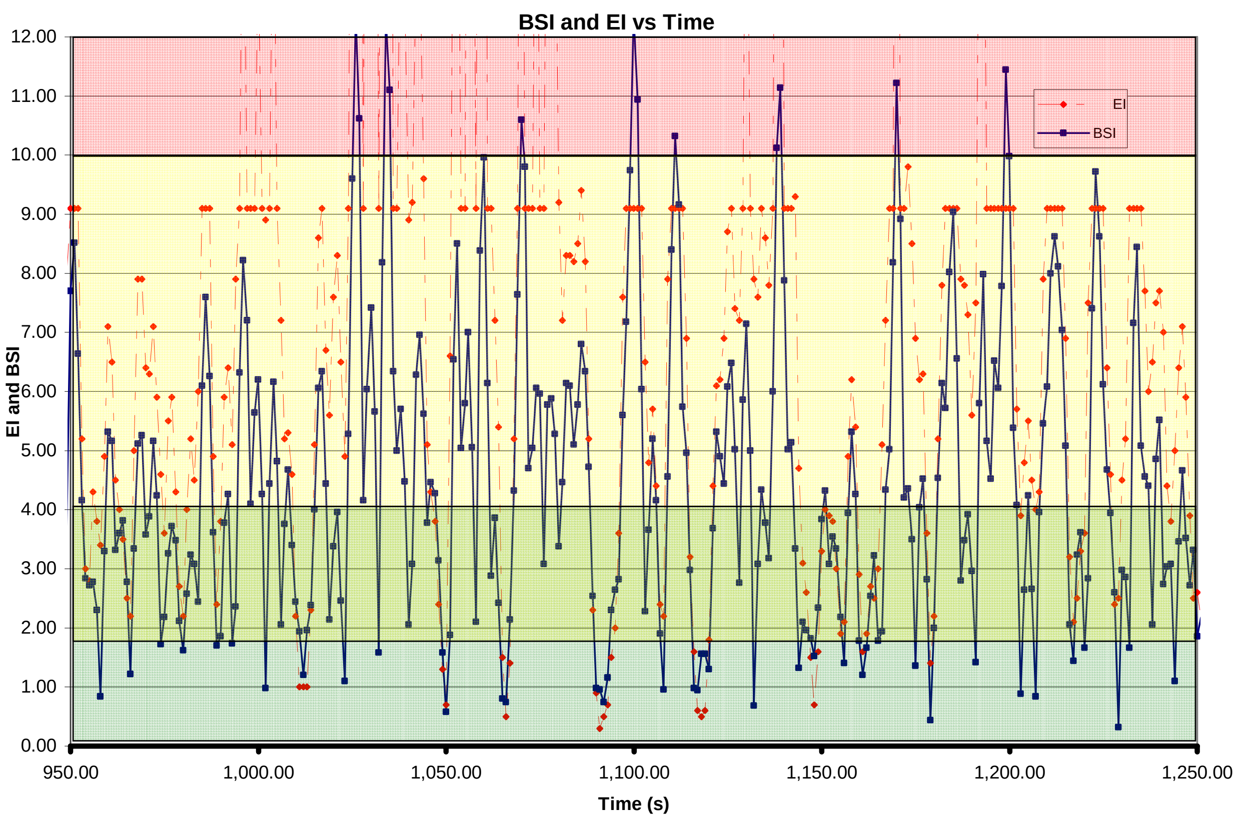




**Figure 11- EI and BSI Sample Time History (Runs 6031521 and 6031701, Table 4)**

If scaled static deck angle, BSI yellow and red limits were created and used for evaluation, benchmarking comparisons would be improved due to the lack of similarly defined risetimes and the significant difference in amplitudes of the EI and BSI (Figure 11.)

Other than scaling differences, EI also occasionally behaves unpredictably during highly dynamic periods compared to BSI. During some high motion periods, while BSI responds to a high pitch or roll displacement, the EI measurement appears artificially clipped and registers a value of 9.1, just short of entering the red zone. While this occurs regularly in Figure 11, it is most apparent in run 631701 at 1,100s where BSI peaks at 12, while EI's value is exactly 9.1 for a little over two seconds.

Run 6031521 (Table 4) shows the impact of the scaling differences between the EI and BSI amplitudes on number of indications for the two indicators.

**Table 4-Landing Period Indications by Indicator**

*(yellow periods are defined here as both green/amber and amber periods combined or from departure of a green period to arrival at red period)*
*count= number of yellow periods, t_total=total yellow time/hr, t_avg=average yellow time (risetime)*

| Run | EI_count | EI_t_total | EI_t_avg | BSI_count | BSI_t_total | BSI_t_avg | static_count | static_t_total | static_t_avg |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| 6031519 | 4 | 3580.89 | 895.22 | 1 | 3597.9 | 3597.9 | 4 | 3593.01 | 898.25 |
| 6031521 | 29 | 3348.7 | 115.47 | 1 | 3597.85 | 3597.85 | 41 | 3543.62 | 86.43 |
| 6031523 | 36 | 3058.06 | 84.95 | 30 | 3509.22 | 116.97 | 65 | 3494.85 | 53.77 |
| 6031601 | 67 | 2561.47 | 38.23 | 49 | 3426.95 | 69.94 | 162 | 3323.65 | 20.52 |
| 6031604 | 80 | 2755.23 | 34.44 | 14 | 3549.01 | 253.5 | 140 | 3372.13 | 24.09 |
| 6031609 | 19 | 3451.9 | 181.68 | 5 | 3585.87 | 717.17 | 27 | 3562.72 | 131.95 |
| 6031614 | 49 | 2839.73 | 57.95 | 29 | 3450.93 | 119 | 96 | 3445.5 | 35.89 |
| 6031619 | 12 | 3483.12 | 290.26 | 73 | 3339.03 | 45.74 | 7 | 3590.94 | 512.99 |
| 6031701 | 88 | 1919.25 | 21.81 | 82 | 3277.84 | 39.97 | 277 | 3095.9 | 11.18 |
| 6031705 | 101 | 2018.49 | 19.99 | 86 | 3288.78 | 38.24 | 266 | 3096.73 | 11.64 |
| 6031712 | 28 | 2699.62 | 96.41 | 141 | 2997.28 | 21.26 | 112 | 3349.64 | 29.91 |
| 6031718 | 55 | 2554.32 | 46.44 | 93 | 3153.57 | 33.91 | 150 | 3343.43 | 22.29 |
| 6031723 | 68 | 2730.61 | 40.16 | 40 | 3465.12 | 86.63 | 142 | 3384.29 | 23.83 |
| 6031802 | 82 | 2112.69 | 25.76 | 30 | 3507.82 | 116.93 | 293 | 3138.84 | 10.71 |
| 6031806 | 29 | 3275.03 | 112.93 | 1 | 3597.85 | 3597.85 | 43 | 3548.09 | 82.51 |
| 6031811 | 6 | 3551.81 | 591.97 | 7 | 3479.98 | 497.14 | 1 | 3597.9 | 3597.9 |
| 6031815 | 2 | 3591.8 | 1795.9 | 3 | 3588.79 | 1196.26 | 1 | 3597.91 | 3597.91 |
| 6031819 | 4 | 3562.81 | 890.7 | 1 | 3597.85 | 3597.85 | 4 | 3594.87 | 898.72 |
| 6031901 | 1 | 3597.93 | 3597.93 | 1 | 3597.93 | 3597.93 | 1 | 3597.93 | 3597.93 |
| 6031905 | 1 | 3597.83 | 3597.83 | 1 | 3597.83 | 3597.83 | 1 | 3597.83 | 3597.83 |
| 6031912 | 1 | 3597.91 | 3597.91 | 1 | 3597.91 | 3597.91 | 1 | 3597.91 | 3597.91 |
| 6031917 | 4 | 3586.84 | 896.71 | 1 | 3597.89 | 3597.89 | 1 | 3597.89 | 3597.89 |
| 6031921 | 1 | 3597.96 | 3597.96 | 2 | 3593.9 | 1796.95 | 1 | 3597.96 | 3597.96 |
| 6032003 | 5 | 3467.93 | 693.59 | 114 | 3113.6 | 27.31 | 4 | 3592.89 | 898.22 |
| 6032006 | 10 | 3480.14 | 348.01 | 63 | 3346.24 | 53.11 | 1 | 3597.91 | 3597.91 |
| 6032010 | 15 | 3480.12 | 232.01 | 50 | 3375.21 | 67.5 | 10 | 3581.1 | 358.11 |
| 6032014 | 11 | 3471.71 | 315.61 | 72 | 3289.77 | 45.69 | 22 | 3552.18 | 161.46 |
| 6032020 | 51 | 2496.68 | 48.95 | 102 | 3105.06 | 30.44 | 108 | 3394.34 | 31.43 |
| 6032100 | 40 | 2800.75 | 70.02 | 71 | 3211.78 | 45.24 | 89 | 3433.11 | 38.57 |
| 6032102 | 21 | 2808.85 | 133.75 | 208 | 2479.38 | 11.92 | 47 | 3501.77 | 74.51 |
| 6032106 | 57 | 2799.02 | 49.11 | 5 | 3587.11 | 717.42 | 121 | 3401.74 | 28.11 |
| 6032111 | 18 | 2904.11 | 161.34 | 170 | 2675.21 | 15.74 | 98 | 3345.04 | 34.13 |
| 6032117 | 26 | 3345.57 | 128.68 | 16 | 3522.86 | 220.18 | 43 | 3537.28 | 82.26 |
| 6032122 | 22 | 3302.32 | 150.11 | 119 | 3033.53 | 25.49 | 44 | 3531.44 | 80.26 |
| 6032200 | 39 | 3183.35 | 81.62 | 5 | 3577.19 | 715.44 | 64 | 3508.98 | 54.83 |
| 6032204 | 42 | 3094.85 | 73.69 | 58 | 3326.26 | 57.35 | 58 | 3515.13 | 60.61 |
| 6032209 | 37 | 2711.76 | 73.29 | 170 | 2581.19 | 15.18 | 141 | 3261.75 | 23.13 |
| 6032213 | 20 | 2667 | 133.35 | 209 | 2539.81 | 12.15 | 176 | 3187.15 | 18.11 |
| 6032216 | 24 | 2642.33 | 110.1 | 190 | 2694.94 | 14.18 | 136 | 3325.99 | 24.46 |

Run 6032003 illustrates the drastic difference in indications apparently due to the impact of the artificial damping built in to EI  Overall, BSI indicates more total yellow time (amplitude fails to reach the red limit) because of the scaling difference between BSI and the EI scale it was evaluated against.

## Insights from the Proposed Methodology Approach

From the methodical comparison presented, Ferrier's LPD might be considered for naval flight operation guidance due to its improvement over static deck angle standards.  It is slightly concerning, however, that LPD does not statistically show operational envelope expansion over that of static deck angle limited flight operations.  LPD, as configured for this research, actually presents a more stringent envelope if used as a bound for flight operations.  Additionally, the comparison to BSI shows that a simple untuned indicator performs comparably well in most conditions.

Within 5% error, LPD's superior minimum risetime translates to increased safety for helicopter/ship interfaces that allow for a successful wave off within 5.5s of being secured on deck.  Although this may not translate to a great number of reduced landing casualties, the slightly advanced indication of impending energy may help the pilot better gauge approaches and deck operations.  Further examination of the clipping of EI at a value of 9.1 and the possible decrement of the flight operation motion envelope whilst abiding solely by LPD may also be useful.

The methodical approach presented is necessary to better understand and define the correct operational implementation of LPI systems. Results from a simple benchmark index, similar in nature to BSI, can assist in illustrating key advantages or disadvantages of more complex LPIs.  Stepwise examination and comparison will help to thoroughly distinguish needed recommendations and system conclusions.  Suggestions for future work include creating specific logical limits for BSI to allow for better comparison to future LPI and DDML systems (O'Reilly's EI, Colwell's FDMS).  Examination of post-landing systems such as Gallagher's MSI (Gallagher and Scaperda 2001) or Gray's SI (Gray 2002)) is suggested to determine the extent and implications of incongruence or possible overlap between LPI and post-landing system recommendations.

# Chapter 3

*"System dynamics is a powerful method to gain useful insight into situations of dynamic complexity and policy resistance (Sterman 2000)."*

The dynamics of complex systems are usually difficult to understand as a whole. Dynamic interaction between various components creates a variety of sub-system dynamics that are not inherent to what can be observed at a top-level perspective and may include delays in information or material that play a significant role in a system's dynamics. In order to fully understand the dynamics of a complex system, it is important to identify all the variables that are relevant to the problem of interest and determine their relationship to each other. Furthermore, pioneers in the study of aircraft handling qualities[4] noted "the source of a fundamental problem in the study of handling qualities [is] the complete dynamic system is seen only by the pilot," (Cooper and Harper 1986). This problem is also apparent in shipboard-helicopter DI and thus a system approach is vital to better understanding various dynamic interface solutions and how these solutions interact with all facets of the complex DI problem. This chapter employs a system dynamics approach to pilot workload as an example of a method to clarify and explore the complexities of the ship-helicopter dynamic interface.

Increased understanding of the human factor involved in DI is important to better address future system improvements. In a study of 12 different complex military systems, Hutchins states "The need to place greater emphasis on the role of human factors in the design of complex systems can not be overemphasized. … Systems that have not been designed with user-centered emphasis (1) are much more difficult to operate than they ought to be, (2) produce high levels of frustration and workload, and (3) are extremely difficult for people to become trained on," (Hutchins 2000). In a similar analysis, the U.S. Army pre-

[4] The focus of this chapter, pilot workload in the shipboard-helicopter DI, may also be considered an output of a broader research area called handling qualities. "Handling Qualities is defined as those qualities with which a pilot is able to perform the tasks required in support of an aircraft role," Cooper, G. E. and R. P. Harper (1969). The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA. "Handling quality is characteristic of the combined performance of the pilot and vehicle acting together as a system in support of an aircraft role", Cooper, G. E. and R. P. Harper (1986). "Handling Qualities and Pilot Evaluation." Journal of Guidance, Control and Dynamics **9**(5): 515-529. While the essence of handling qualities focuses on pilot workload as a factor of aircraft design and control specifics, here the focus is on pilot workload as a factor of the entire shipboard-helicopter Dynamic Interface.

design human performance testing of the Comanche Helicopter resulted significant redesigns, accommodating two pilots instead of only one to reduce mental workload and increase overall task performance (Allender 2000).

Various academic fields have contributed to better understanding ship-helicopter dynamic interface, however one of the most difficult and important metrics for any proposed improvement is the affect on the human pilot and their workload. Quantifying this is difficult, however. "The major difficulty with [handling qualities] analysis has been the analytical representation of the adaptive human pilot. The other elements of the system can be accurately represented; the pilot and his actions are only partially understood," (Cooper and Harper 1986).

From a human factors perspective, previous work has investigated visual perception/tasking in both carrier (Gold 1974) and small ship landings (Berbaum, Kennedy et al. 1991; Negrin, Grunwald et al. 1991). A measurement scale for fixed-wing aircraft pilot workloads and aircraft handling qualities was defined in the late 1960's by NASA (Cooper and Harper 1969; Cooper and Harper 1986) (Figure 12). A similar scale called Deck Interface Pilot Effort Scale (DIPES) is used to define safe ship-helicopter operational envelopes. It systematically measures pilot effort levels during DI flight testing (Lynch and Baker 2003) (Figure 13).

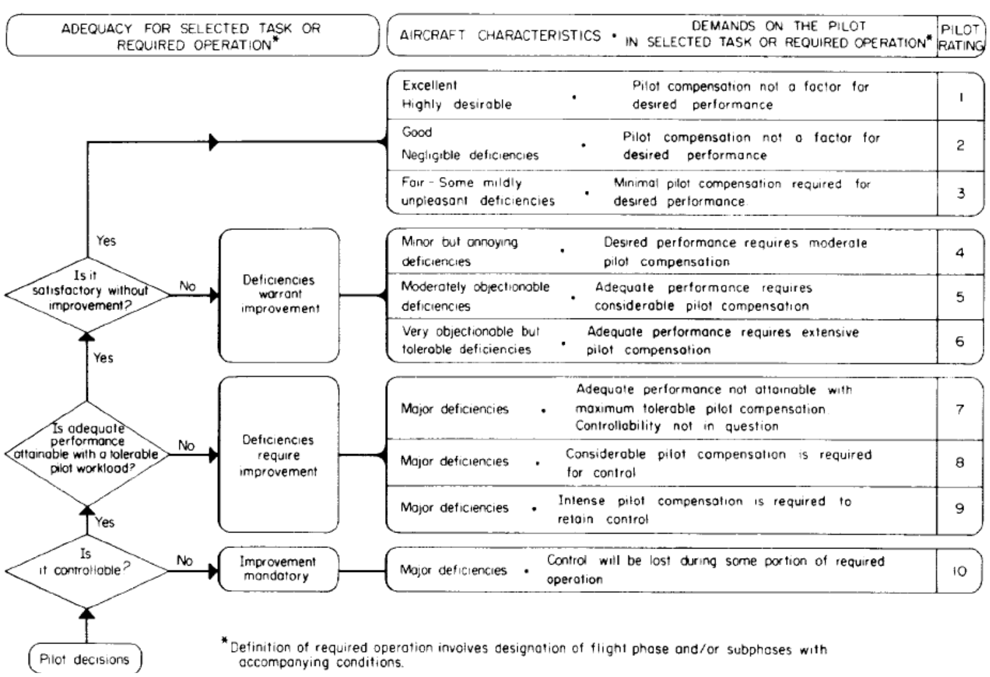



**Figure 12 – Handling Qualities Rating Scale ("Cooper-Harper Scale") (Cooper and Harper 1969)**

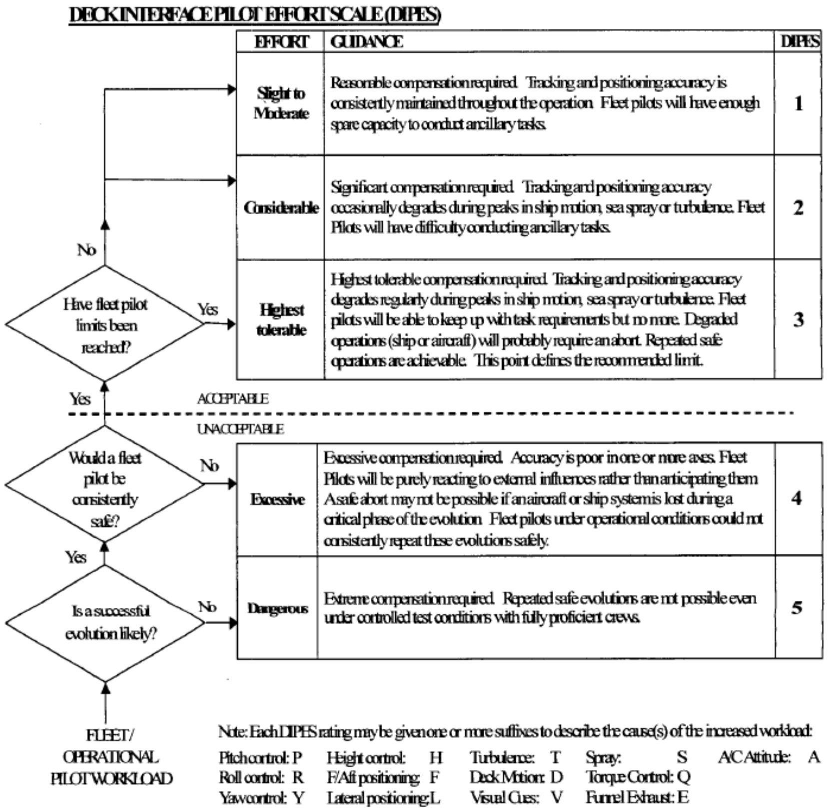



**Figure 13 – Deck Interface Pilot Effort Scale (DIPES) (Lynch and Baker 2003)**

Pilot workloads have been simulated and compared using airwake models to analyze different approaches in various wind conditions (Lee and Horn 2004; Lee, Sezer-Uzol et al. 2005). "A total system approach to the human factors challenges at the helicopter-ship dynamic interface" including an overview of general operational/technical problems, navigation/recovery guidance, data-link integrated return to ship technologies, airwake implications, augmentation controls/displays for shipboard recovery, deck operations, and a virtual dynamic interface has also been conducted to continue to examine the very complex man-machine system performance interactions (Lumsden, Padfield et al. 1999).

Carico suggested a system-of-systems DI Virtual Systems Approach to incorporate all of the various subsystem knowledge and testing databases into one integrated interface, allowing full system sensitivity analysis to parameter changes including virtual flight test feedback (Figure 14) (Carico 2004).

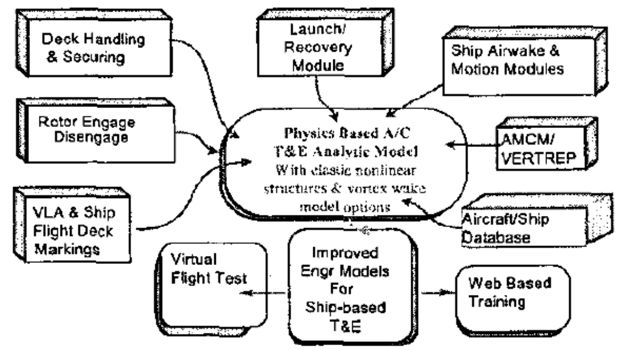



**Figure 14 – DI Virtual Systems Approach (Carico 2004)**

Jay W. Forrester describes the system dynamics approach to design as follows:

- *Identify a problem*
- *Isolate the factors that appear to interact to create the observed symptoms*
- *Trace the cause-and-effect information-feedback loops that link decisions to action to resulting information changes and to new decisions.*
- *Formulate acceptable formal decision policies that describe how decisions result from the available information streams.*
- *Construct a mathematical model of the decision policies, information sources, and interactions of the system components*
- *Generate the behavior thorough time of the system as described by the model*
- *Compare results against all pertinent available knowledge about the actual system.*
- *Revise the model until it is acceptable as a representation of the actual system.*
- *Redesign, within the model, the organizational relationships and policies which can be altered in the actual system to find the changes which improve system behavior.*
- *Alter the real system in the directions that model experimentation has shown will lead to improved performance*

*(Forrester 1999))*

## Introduction to System Dynamics Modeling[5]

In system dynamics the first conceptual model is generally called a causal loop diagram (CLD). In a CLD, variables are related by a manner of arrows that indicate the affect of one variable on another.

For example, in Figure 15a below, if Variable 1 increases, Variable 2 increases above what it would otherwise have been (a positive link) and likewise, if Variable 1 decreases, Variable 2 decreases below what it would otherwise have been. In a loop where all the causal links are positive, or the number of negative links is even, the loop is identified as a positive or reinforcing loop (indicated here with an R). In Figure 15b, if Variable increases, then Error decreases below what it would have been, whereas if Variable decreases, then Error increases above what it would have been otherwise (a negative link). A loop where the number of negative links is odd is called a negative or balancing loop (indicated here with a B). Figure 15c shows how delays in information or materials may be indicated in a CLD.

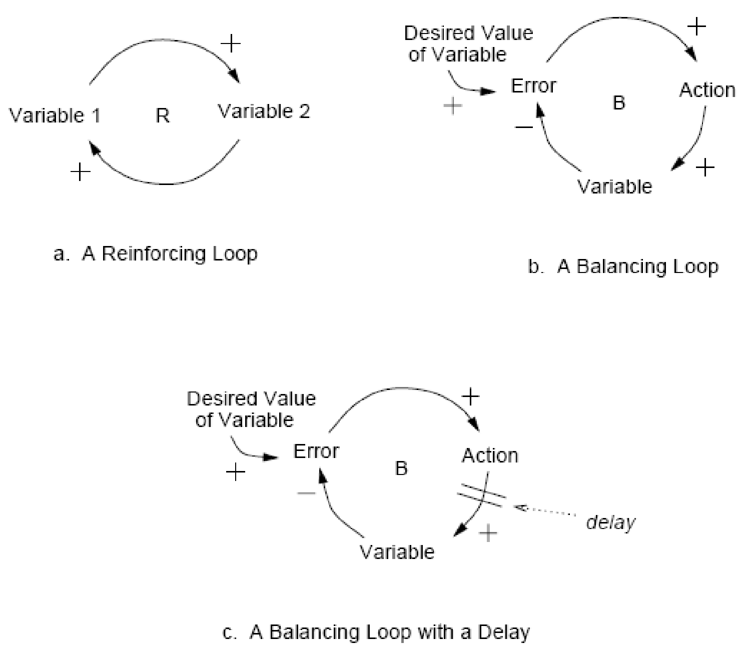



**Figure 15 – The Three Basic Components of System Dynamics Models (Leveson 2002)**

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[5] Definitions and method taken from Sterman, J. D. (2000). Business Dynamics - Systems Thinking and Modeling for a Complex World, Jeffrey J. Shelstad. CLDs, dynamics models, resulting graphs, trees and model documentation were made using Vensim© PLE for Windows Version 5.5d, Ventana Systems Inc., available at http://www.vensim.com/

## Formation of a Model

Following Forrester's previously listed steps, a list of important variables influencing helicopter landing execution was created (Table 5). Some of these variables were then used in a CLD showing the causal loops affecting the execution time of a shipboard landing (Figure 16). Exogenous variables in the CLDs are indicated in green font and negative links are indicated in red. A model depicting the same process, but employing a LPI to assist the pilot is illustrated in Figure 17. Structure differences between the two models include the addition of Landing Period Indicator Effectiveness/Accuracy (highlighted) and new causal links (in bold). The model specifics are discussed in depth more following their presentation.

**Table 5 – Table of System Variables**[*]

| **Stocks** | **Units** |
|---|---|
| Time Required for Landing | seconds |
| Ground Affect Force | ft-lbs |
| Airwake* | non-dimensional |
| Visibility | feet |
| Hover time | seconds |
| Pilot Workload/Stress | non-dimensional (DIPES) |
| Pilot Experience | flight hours or Training Evolutions |
| Approach Distance | feet |
| Sea State | SS1-SS7 |
| Wind | kts |
| Wave Amplitude | feet |
| Confidence Level* | non-dimensional |
| Risetime (of an indicator) | seconds |
| Landing Period Indicated | seconds |
| Accuracy of Perceived Motion | % |
| Deck Stability | Energy or other LPI Measure |
| Wave Period | seconds |
| Perceived Risk* | non-dimensional |
| Altitude | feet |
| Deck Motion Displacements | feet |
| Landings | non-dimensional |
| Wave Train Complexity* | non-dimensional |
| Risk Mitigation Level* | non-dimensional |
| **Flows** | **Units** |
| Experience Rate | experience/landing |
| Deck Motion Velocities | feet/s |
| Deck Motion Accelerations | feet/s^2 |
| Successful Landing Rate | successful landings/green light indicated |
| Landing Period Indicator Accuracy | % |
| Approach Velocity | ft/s |
| Approach Acceleration | feet/s^2 |
| Change in Deck Stability | energy Change/s (or other metric) |
| Decent Rate | feet/s |
| Mitigation Adjustment Rate | /s |
| Perceived Risk Adjustment Rate | /s |
| Hover time Accumulation Rate | s/s |

[*] indicates a normalized variable using average or assumed average value

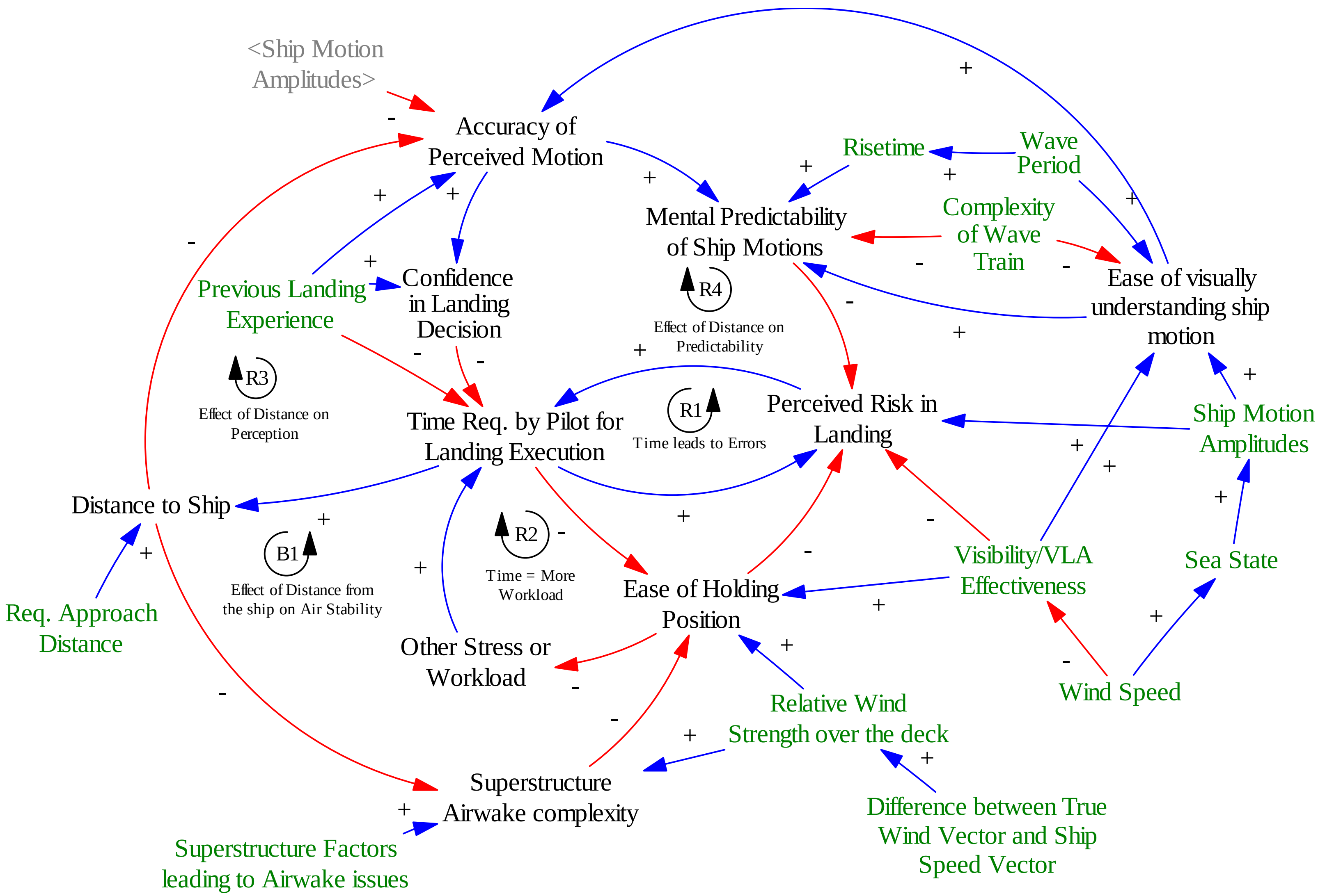


**Figure 16 – Causal Loop Diagram of Variables Affecting Landing Execution Time (Using Mental Prediction)**

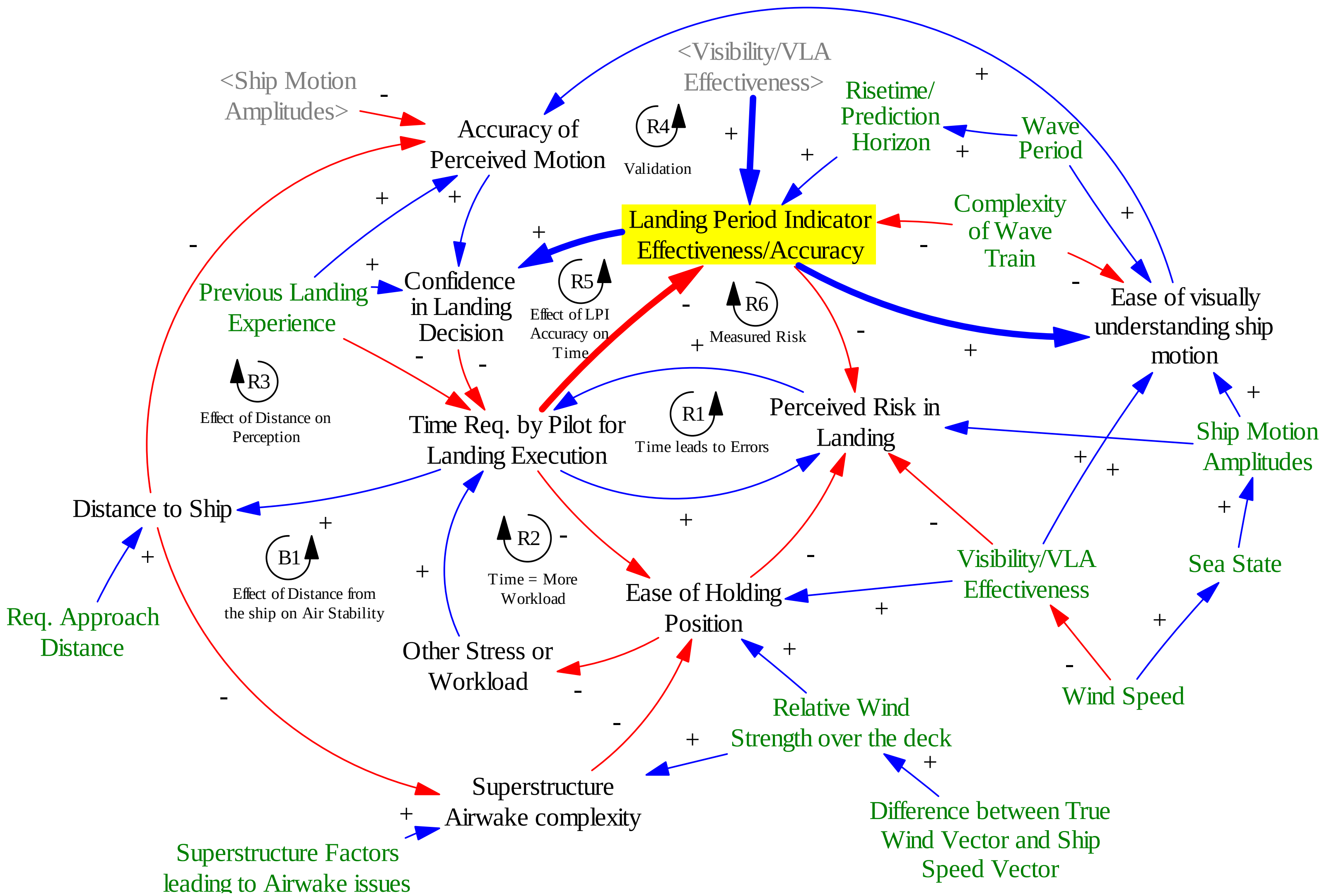


**Figure 17 - Causal Loop Diagram of Variables Affecting Landing Execution Time (Using a LPI)**

**Figure 18 – An H-60 Lands at Night (www.navy.mil)**

Executing a shipboard landing is not a simple problem, nor are the casual loop diagrams above, complete. The pilot is attuned to many environmental factors when making a landing, although their importance and impact vary with each landing (Figure 18).

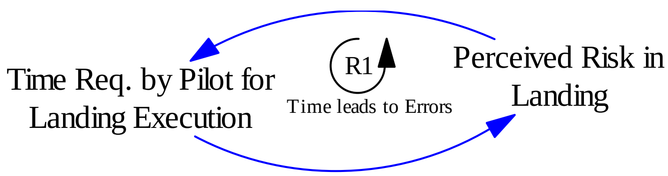


**Figure 19 – R1 Loop**

The R1 loop (Figure 19) in both of the CLDs illustrates that as an increase in risk is perceived, more time is needed by the pilot to adjust to or mitigate the risk perceived. In turn, as the total time required for landing increases, the helicopter and pilot are subject to increased motion events as well as, environmental, mechanical and other unknown risks which when perceived, cause further delay in landing.

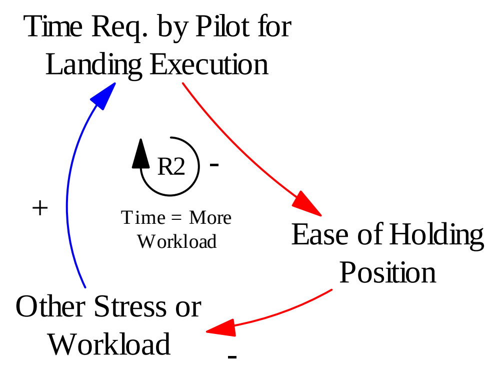


**Figure 20 – R2 Loop**

The R2 loop (Figure 20) illustrates that as the length of time required to land increases, holding position becomes more difficult (even with an automated hover capability, ship movements may require regular adjustments.) As holding position or hovering becomes increasingly difficult, the pilot's stress and workload increases which increases the time required by the pilot to execute a landing. Similarly, (Figure 21) the closer a helicopter gets to the ship, the apparent airwake off the ship's superstructure becomes more complex, decreasing the ease of holding position, increasing pilot stress or workload, increasing the time required by the pilot to execute a landing, which may result in the pilot creating more separation between the ship and helicopter in order to reduce the affect of the airwake.

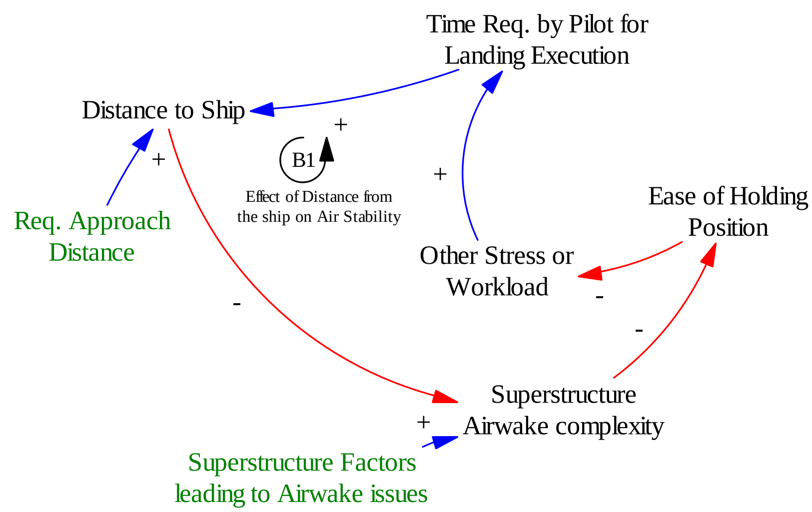


**Figure 21 – B1 Loop**

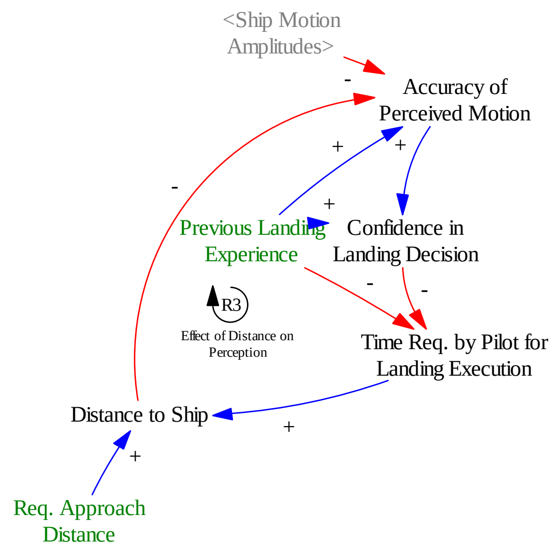


**Figure 22 - R3 Loop**

The R3 loop illustrates that as the pilot closes the distance to the ship, the accuracy of their perception of the ship's motion increases, leading to better confidence in making a landing and reducing the time necessary to execute a landing, and in essence causing the pilot to further close the distance to the flight deck in order to land.

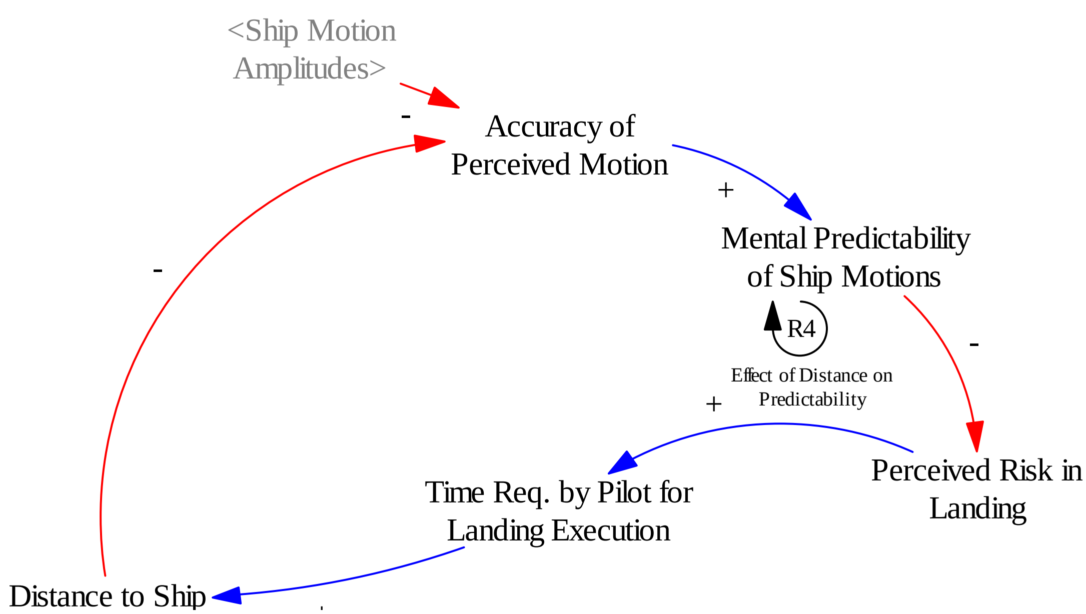


**Figure 23 - R4 Loop of Mental Prediction Model (Figure 16)**

Figure 23 displays the R4 loop of the model using mental predictions (Figure 16). As distance to the ship closes, accuracy of perceived motions improve, which improves the ability to mentally predict future ship motions, decreasing the perceived risks of an unpredictable deck motion, reducing the time required to land, and thus causing the pilot to approach the ship to execute the landing.

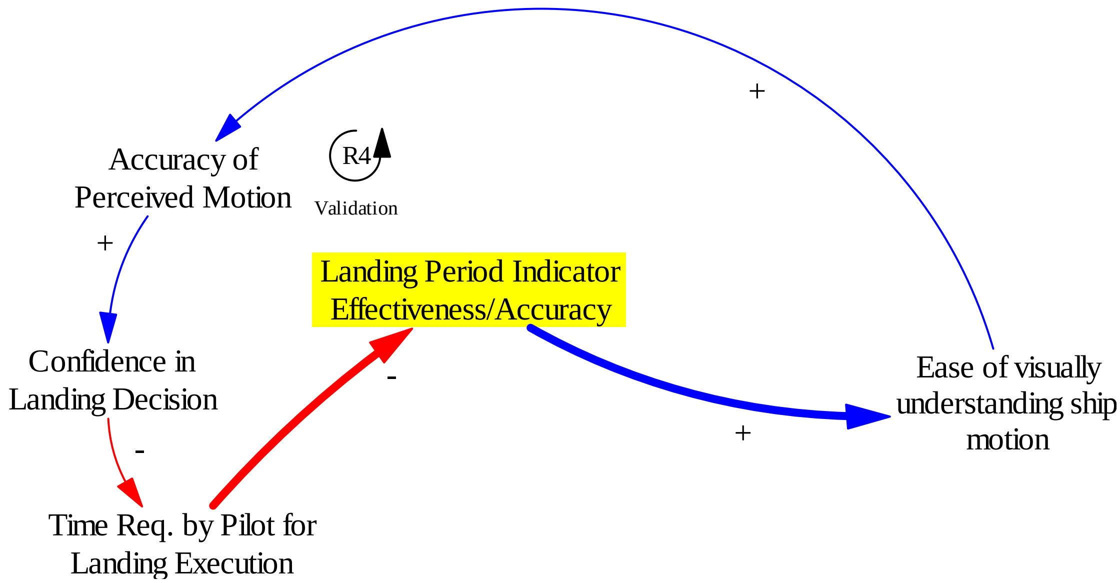


**Figure 24 –R4 Loop of the Model using an LPI (Figure 17)**

Figure 24 shows the R4 loop of the CLD for LPI implementation (Figure 17). Here, as the time required for landing reduces, the accuracy and effectiveness of the LPI increases (as predictors and energy methods are more accurate over shorter timeframes and quiescent periods of shorter duration are more probable.) The more accurate indication of a landing period helps tune the pilot's mental model of the ship's motion, making visually understanding the ship motion easier, and increasing the accuracy of the perceived motions. Confidence in landing is increased and the time required by the pilot to execute a landing is decreased.

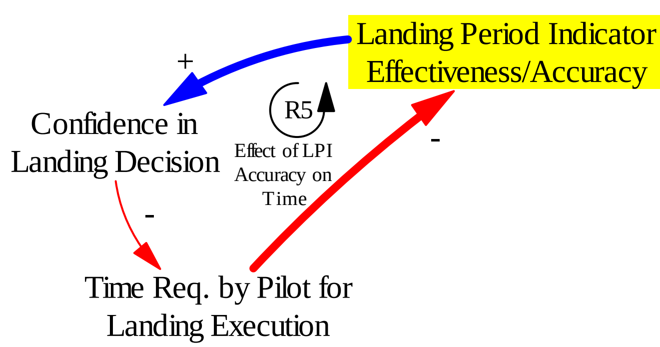


**Figure 25 – R5 Loop**

In the R5 loop, a highly accurate LPI, increases confidence in landing decisions, which reduce the time required by the pilot to land, further increasing the LPI accuracy (due to the shorter duration of necessary prediction.)

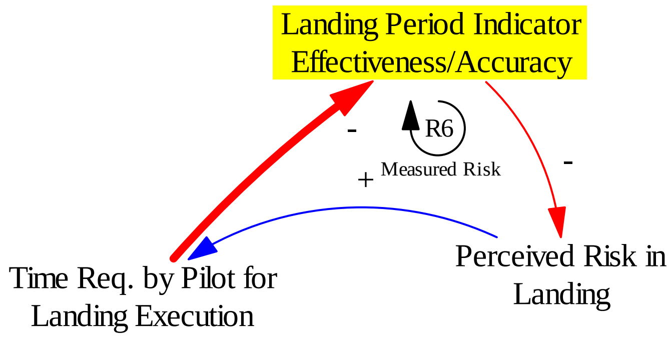


**Figure 26 –R6 Loop**

In the R6 loop, high accuracy landing period indications lead the pilot to perceive less risk in executing the landing, reducing the time required to land.

## Dynamic Model Variable Representation

The variables listed in Table 5 were further organized by the designation stock or flow. The concept of a stock in system dynamics is something that accumulates a cumulative flow of some sort over time (mathematically, a stock integrates a rate). They create delays and decouple inflow and outflow rates, giving system inertia and memory of previous dynamics.

$$\text{Stock} := \left( \int_{t_o}^{t_f} \text{Flow}\, dt \right) + C$$

(where C is the initial condition of the stock)

**Figure 27 – Mathematical Definition of Stock-Flow Relationship**

A simple example of a stock in terms of motion would be displacement where the flow would be velocity (Figure 28). Displacement is measured in feet or meters while the flow adjusts the total displacement over time and is measured in ft/s or m/s. Therefore, as the time step increases by one, a positive velocity of 3ft/s would increase displacement by 3 feet and likewise, a negative velocity would decrease the total displacement. The cloud on the left end is called a source or sink and has infinite capacity, allowing the velocity to be unconstrained.

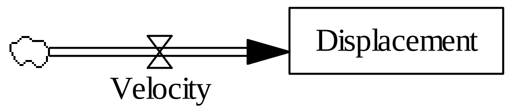


**Figure 28 – Example of Stock and Flow Notation**

The structure of an information delay depends on the basic modeling above. An information delay models the way someone's perception of something changes when compared to a real value. A simple information delay "and one of the most widely used models of belief adjustment and forecasting is called exponential smoothing or adaptive expectations. Adaptive expectations mean the belief gradually adjusts to the actual value of the variable. If your belief is persistently wrong, you are likely to revise it until the error is eliminated," (Sterman 2000).

Figure 29 shows an example of an information delay. As a pilot compares their perception of risk to that of the actual risk involved in a landing, an adjustment is made to their perception so that it more closely meets the actual risk of a situation. This change occurs over the time period required to adjust their perception.

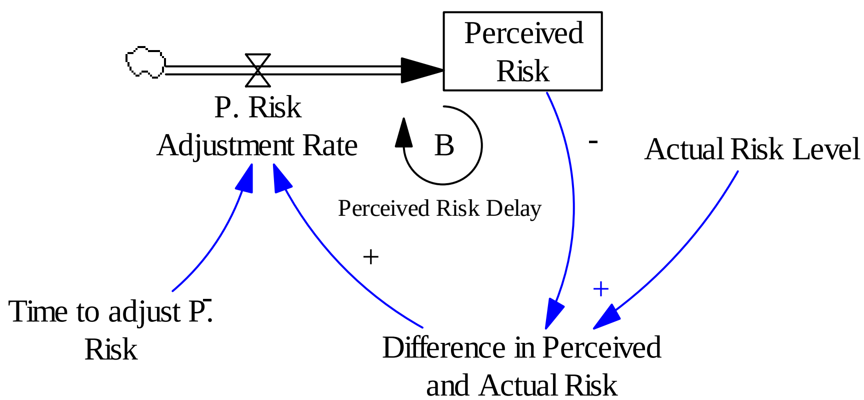


**Figure 29 – Illustration of Information Delay**

Similar to the information delay in Figure 29, a production delay or adjustment to a goal is modeled in Figure 30. Here, current risk mitigation levels are compared to perceived risk levels, with the difference creating an adjustment to current risk mitigation levels over a time period required to actually adjust risk mitigation. Examples of temporary risk mitigation techniques employed by the pilot might include increasing altitude, increasing vertical or horizontal separation distance to the ship (to decrease airwake or allow for more maneuverability).

Occasionally semi-permanent risk mitigation techniques may also be employed like dumping fuel or other weight (for a fuel/gear heavy helicopter, it is sometimes necessary to either dump fuel, take another pass to expend fuel, or in emergency situations, dump nonessential heavy equipment to allow larger power margins during landings), or even breaking away for another approach. Semi-permanent risks are not included in the model. Both the information and production delay illustrated are included in the full dynamic model (Figure 31) of a pilot's stress level during a shipboard landing execution.

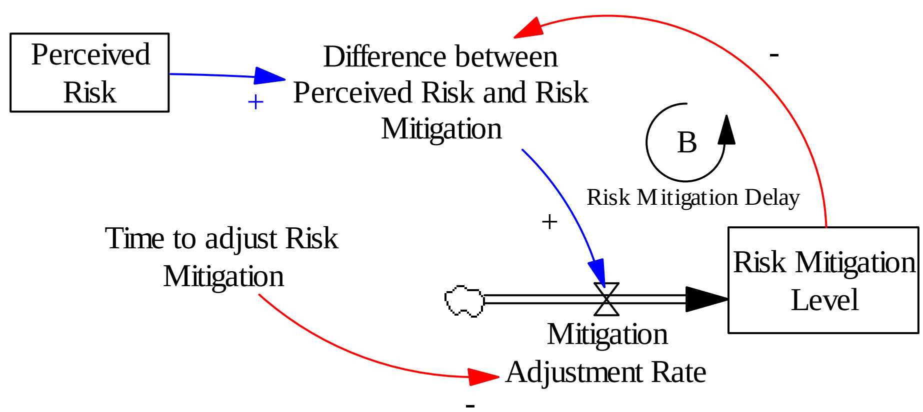


**Figure 30 – Illustration of Adjustment to Goal**

## Dynamic Modeling

Cooper and Harper present a functional diagram of an pilot-aircraft system from the controls perspective where "the pilot's role is delineated as the decisionmaker [sic] of what is to be done, the comparator of what's happening vs. what he wants to happen and the supplier of corrective inputs to the aircraft controls to achieve what he desires," (Cooper and Harper 1986). Although this dynamic system description is not the same type of dynamic system model discussed in this chapter and was not defined to consider shipboard landing operations or DI, it is included here because of the similarities, particularly to the variables considered in the dynamic system model presented in Figure 31.

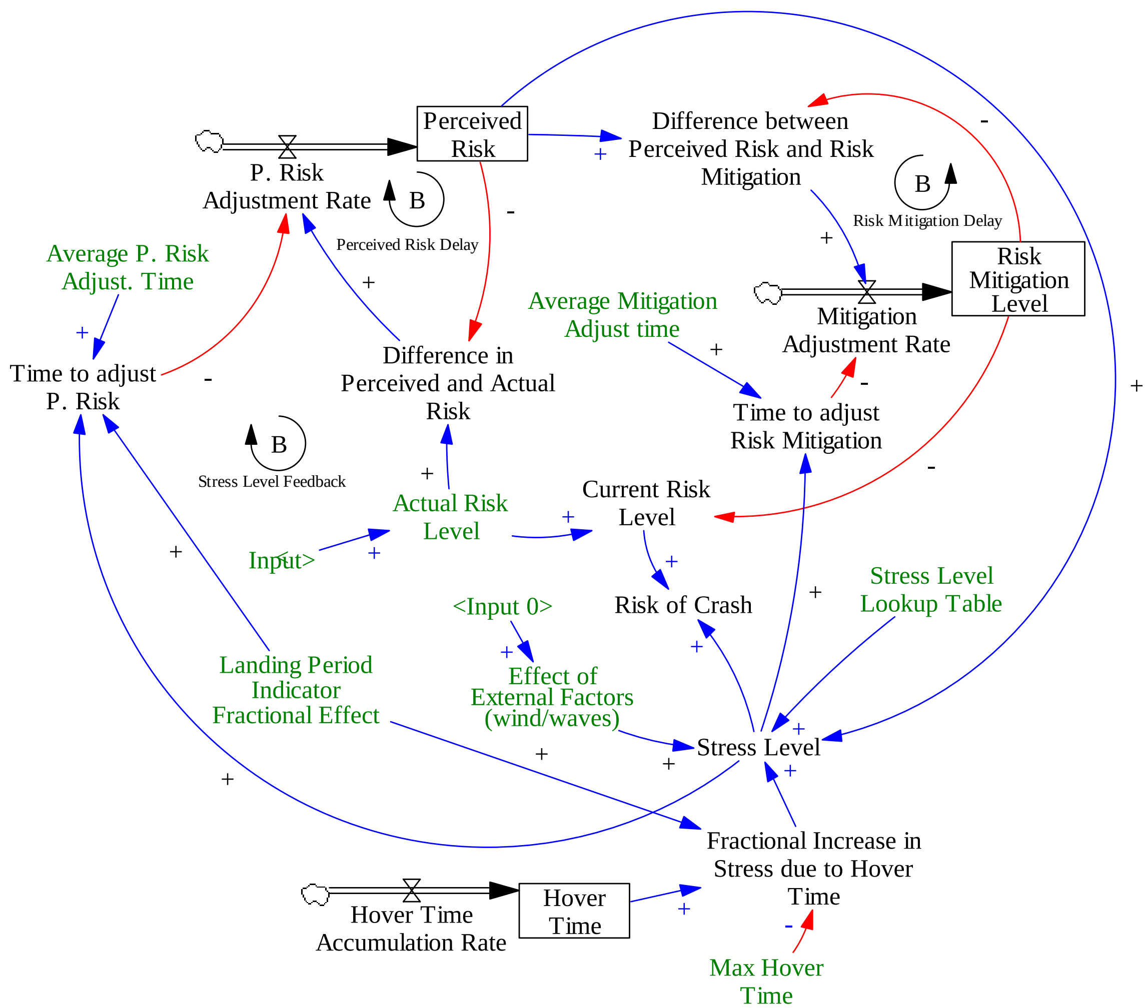


**Figure 31 –Stock and Flow Diagram of Pilot Stress Level during Landing Execution**

The dynamic system model (Figure 31) reflects the modeling translation of the Perceived Risk in Landing, Time Req. by Pilot for Landing Execution (here called Hover time), and Landing Period Effectiveness/Accuracy (here called Landing Period Indicator Fractional Effect) loops from Figure 17. First, there is the information delay in the pilot's ability to adjust their perceived risk to that of the actual risk involved in landing. The perceived risk then triggers some amount of risk mitigation on the pilot's part, but again, taking risk mitigation actions takes time and is delayed as the pilot measures the amount of risk mitigation necessary to offset the perceived risk. The actual risk is compared to the risk mitigated and this current level of risk is then multiplied by the pilot's stress level to determine the risk of mishap or crash. The pilot's stress level is a function of increasing hover time (which increases with model run time), the risk perceived in the evolution, and external factors like waves and wind which complicate the process. The stress of the pilot also impacts the time it takes for them to adjust their perception of risk as well as the time it takes for them to take mitigating actions. The model illustrated in Figure 31 is fully documented in the Appendix (Documentation for Vensim Dynamic Model).

To simplify these relations, a "uses tree" (how a variable is used or what it affects) is presented for Perceived Risk (Figure 32) and "causes trees" (what affects a variable) are presented for Stress Level (Figure 33) and Risk of Crash (Figure 34). In all figures, the direction of causality is from left to right.

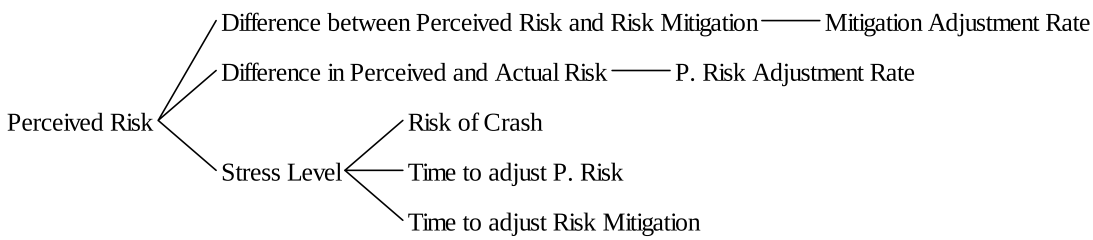


**Figure 32 – Uses Tree for Perceived Risk**

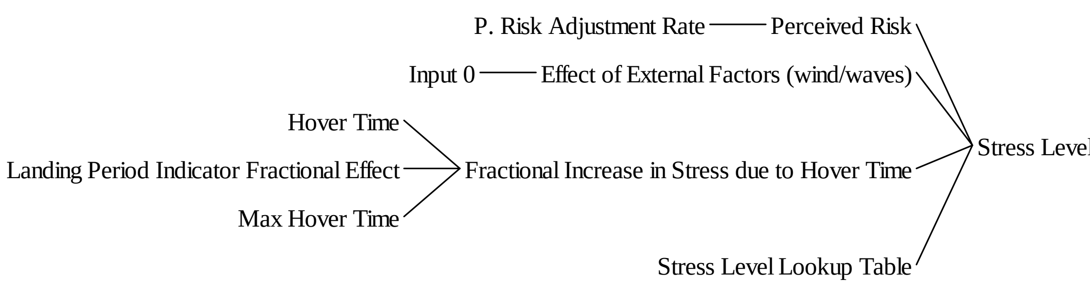


**Figure 33 – Causes Tree for Stress Level**

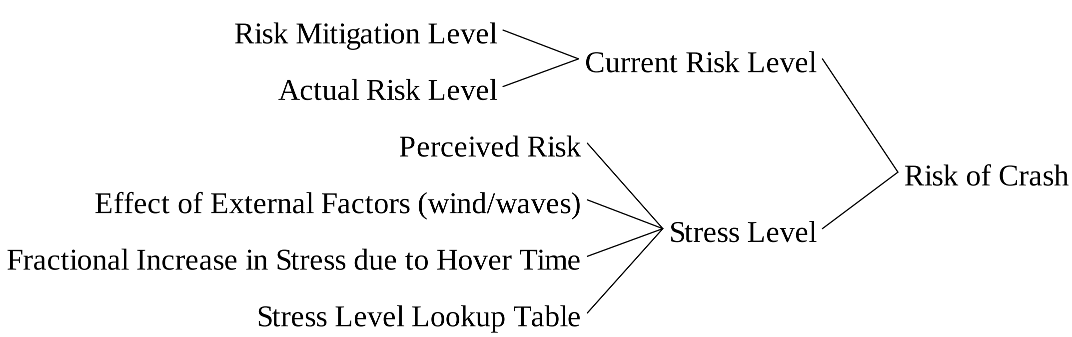


**Figure 34 – Causes Tree for Risk of Crash**

### Model Notes

To clarify, the risk variables are measured by dimensionless probabilities (of an unsafe landing.) Given landing helicopters on ships w/o incident is a regular practice, a realistic average value of actual risk is assumed between 2-8%, meaning a 92-98% success rate for shipboard landing is appropriate. Actual risk, however, will change dynamically with every wave crest and real time changes in wind speed. This is modeled with a Sine input of some amplitude.

Stress level is defined such that 1 is an average stress level, 2 is a max stress level (at this point, the pilot aborts and decides to land somewhere else or makes another approach), and 0.24 is the minimum stress level possible while piloting a helicopter (0 represents no stress condition.)

External factors represent weather conditions and sea state that generally don't change instantly (i.e. sustained conditions, not instantaneous wave height and wind speed.) Here it is simplified to a normalized sea state. That is, the average sea state for flight operations is sea state 2 (with stormier or higher wind conditions resulting in higher sea-states and more difficult operations). A value less than 1 represents a sea state less than the average. A value greater than one represents a sea state greater than the average. This input might change during the simulation to indicate a change in weather conditions (ramp input) or sudden storm (step increase.) The maximum sea state is 10, so normalized values range between 1 and 5.

Finally, the landing period indicator fractional effect indicates the actual impact of the indicator on the operations. The effect of the landing period indicator is such that it decreases total hover time (by more accurately and efficiently indicating landing periods) as well as decreasing the pilot's stress (as a landing period indicator helps to validate the pilot's mental model of the ship's motion and if accurate, relieves a portion of the pilot's stress of locating or predicting landing periods – as an example, it is stressful to attempt to cross a busy road by watching the traffic flow, however a crossing light reduces the stress, allowing the walker to depend on a walk signal and modify its suggestions with their visual judgments of current traffic flow.) A good fractional effect would be 0.5 (halves necessary hover time and adjustment time) while a poor effect (1.5) would illustrate an inaccurate indicator that may distract the pilot and indicate unsafe landing periods during calm periods, extending the total hover time. A value of 1 means the indicator has no effect on the hover time (and thus no effect on the stress level or time to adjust perceived risk.) The limit of the fractional effect of the device is assumed to be from 0.24-1.5. Information delays and correction delays are based on perceived risk, not actual risk.

The Stress Level Lookup table was created with best estimates and judgments of intermediate values and is presented as an example (Figure 35). Specifically, the inputs "Effect of External Factors", "Perceived Risk", and "Fractional Increase in Stress due to Hover Time" are multiplied by each other and this value is then entered into the Stress Level Lookup Table (in Figure 35 as an x value) which returns the corresponding y value as the "Stress Level".

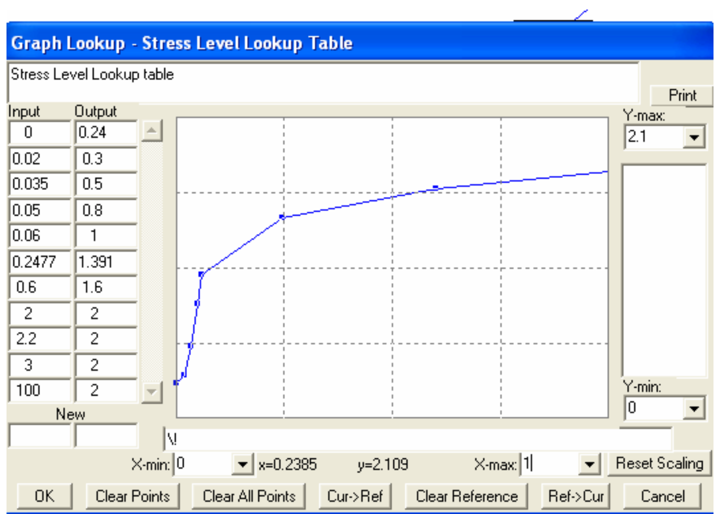


**Figure 35 – Graph of Stress Level Lookup Table Values (from input=0-1)**

It follows an "S" curve such that stress increases rapidly and then begins to taper off to a max level of 2. The final point is set such that the table function values will not be exceeded unless the simulation is run for a time period greater than an hour (average max hover time is only 5 minutes.) Analysis (below) has proved that it is a good rough estimate.

The model is originally set in equilibrium, with the exception of factors that are a function of time (hover time, stress level, time to adjust perception and time to adjust mitigation.) If Hover Time is set equal to 0, it shows the model in something that looks like equilibrium, however it is meaningless because it means the helicopter doesn't actually hover while it's waiting to land.

Given large amplitude inputs to either External Factors or Actual Risk, Stress will increase to a point where it becomes 2 (max) statically. This means (at a stress level of 2) our pilot decides to cancel their landing approach and either try another approach or find another landing location (which makes sense for large amplitudes in waves/winds or weather in general.) Time does become clipped when Stress Level is at 2, but any data past this point is useless because of the assumption that at a Stress Level of 2, the pilot is done with the current approach.

Actual Risk Levels, (here defined as instantaneous risk due to real-time affects like wave crests and wind gusts or other quickly varying risk factors), and Effect of External Factors (here, longer building changes in wind/waves or visibility) are driven by two controllable inputs that allow ramp, step, sinusoidal and pulse type input (Figure 36). It is also possible to include white or pink noise, however this was not included in this model. The two factors here are uncorrelated and are modeled totally independent of each other, but with similar periodicity. In the real world, Actual Risk Levels would see increasing variability of larger amplitude as the Effect of External Factors increased. The number and magnitude of instantaneous risks would increase with an increase in external factors like an approaching frontal passage or slowly dropping visibility due to fog or darkness.

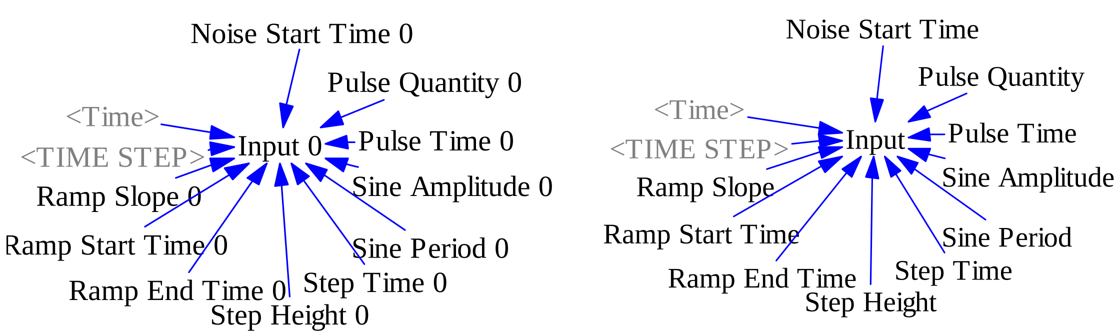


**Figure 36 – Input Functions for Actual Risk Level and Effect of External Factors (wind/waves)**

## Hypothesis building and analysis

At each step during the following analysis, a non-cumulative change to the model is specified, followed by an explanation of the resulting observations. The purpose is to provide an example for future system dynamic modeling for expanding understanding of the dynamics of the Ship-Helicopter Dynamic Interface.

*Input to Actual Risk (Sin amplitude, 0.2)*

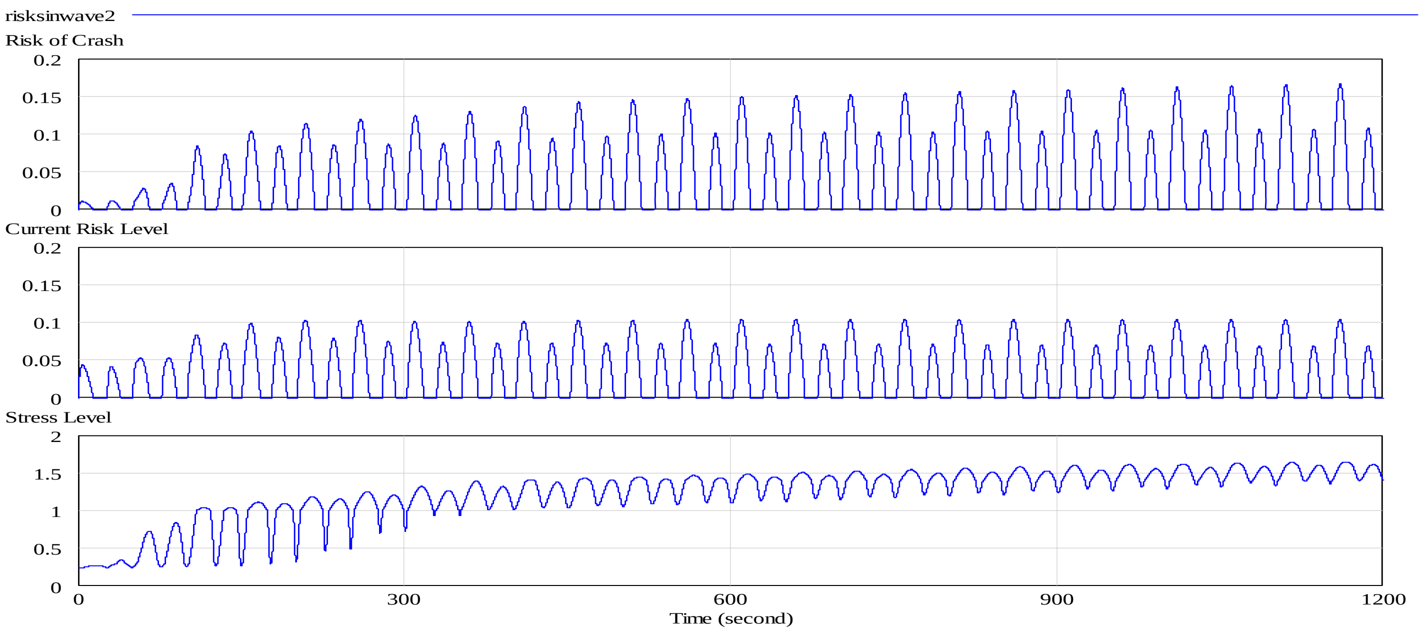


**Figure 37 – Stress Response to Variable Risk Level and Hover Time**

In Figure 37, stress level slowly increase over time (due to hover time) and as stress level increases, so does current risk level and risk of crash. Also, this graph shows periods where risk level is minimal which would constitute good landing periods. The strange amplitude irregularities in the stress level graph are due to the lookup function singularities, but the climbing trend of the stress level is correct. Model time was increased to over 300s to capture what seemed like a constant (steady state) stress level and risk level (although both still increase due to hover time.) With a varying input of about 21% actual risk, the model shows about 10% of actual risk remains unmitigated and when combined with a steadily rising stress level, risk of crash is about 15% over the 20 minutes at this risk level. It is interesting to note that at this risk level, stress level surpasses the average stress level within 100s.

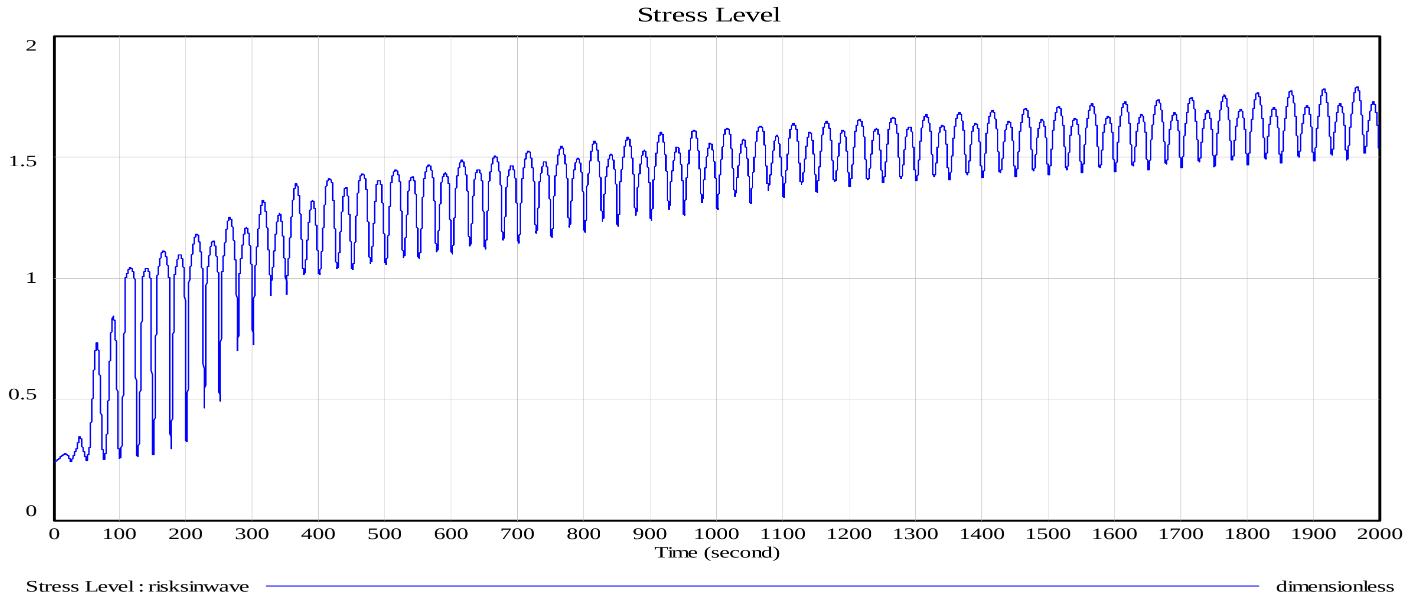


**Figure 38 – Stress Level over a long duration**

Figure 38 reflects the stress effects of hovering for a long period of time. A Coast Guard pilot indicated that most pilots need a break after 30 minutes of unaided hovering (Walker 2006). 2000s is little over 33 minutes, and you can see that stress level at this time approaches an uncomfortable (but not maximum) level.

*Adjust input to both Actual Risk and Effects of External Factors (Sin amplitude, 0.1)*

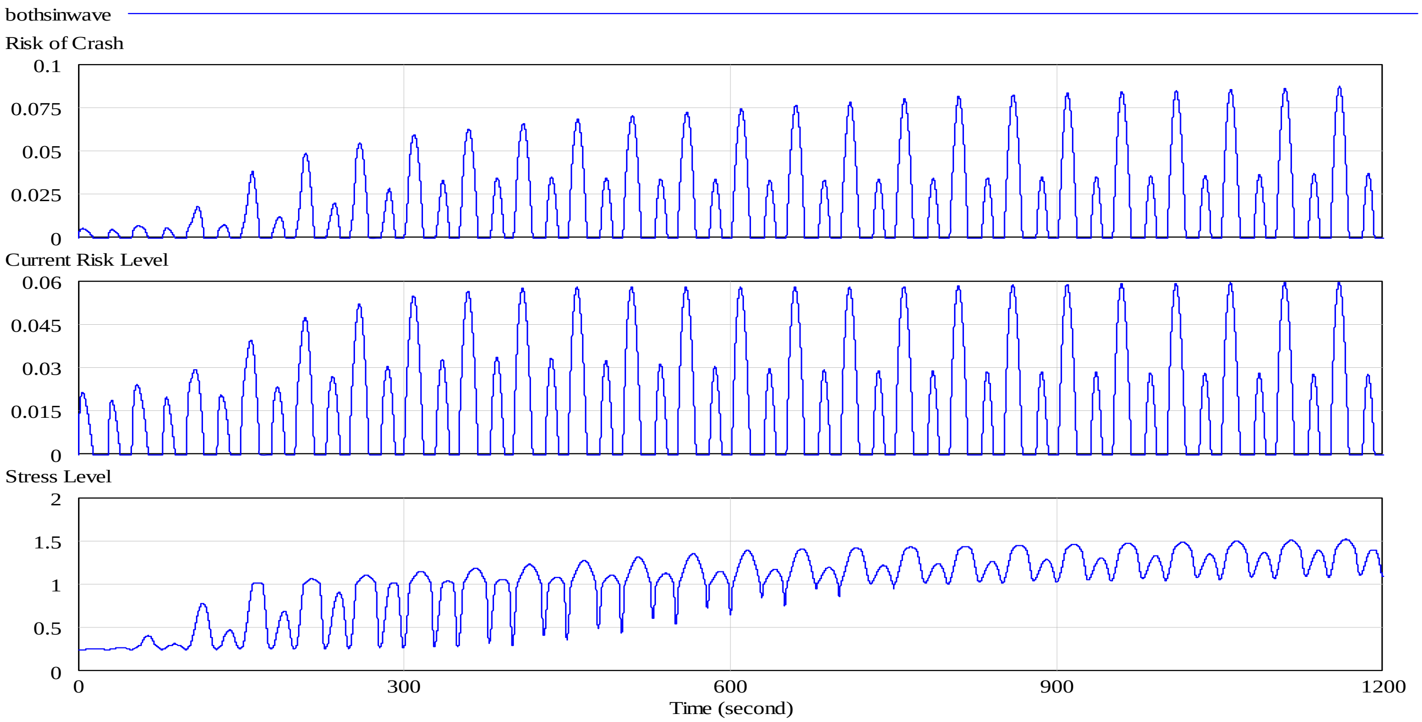


**Figure 39 – Varying Risk and External Factors**

The effects of both Actual Risk variations and variations in the Effects of External factors can be seen in Figure 39. Again the gradual increase in risk levels due to increasing stress can be seen over time. Variation in the period of the sine wave was conducted to get the different distinct affects of the two inputs, however the period of the actual risk input always dominated. This is because the Effects of External Factors is smoothed by both time to adjust perceived risk and time to adjust mitigation level and makes less difference to the Risk of Crash and Current Risk Level. Although modeled here as a more complex changing variable, in the real world, the effect of slowly changing conditions may be mitigated over time by the pilot with either a gradual adjustment, or some discrete adjustment after a threshold is exceeded. Figure 40 shows that increasing the Effect of External Factors compared to only increasing the Actual Risk from equilibrium state results in a longer feedback delay to stress.

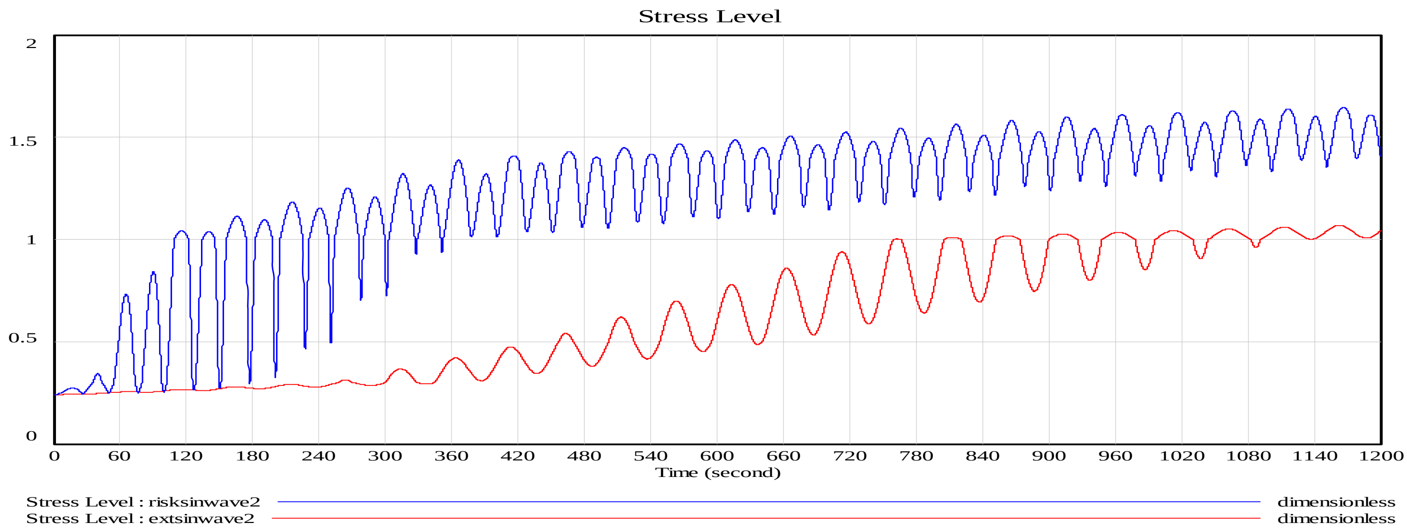


**Figure 40 – Feedback Delays from inputs to resulting Stress Levels**

*Increase Ave. Perceived Risk Adjust Time ((20s), Both input functions = Sin amplitude, 0.1)*

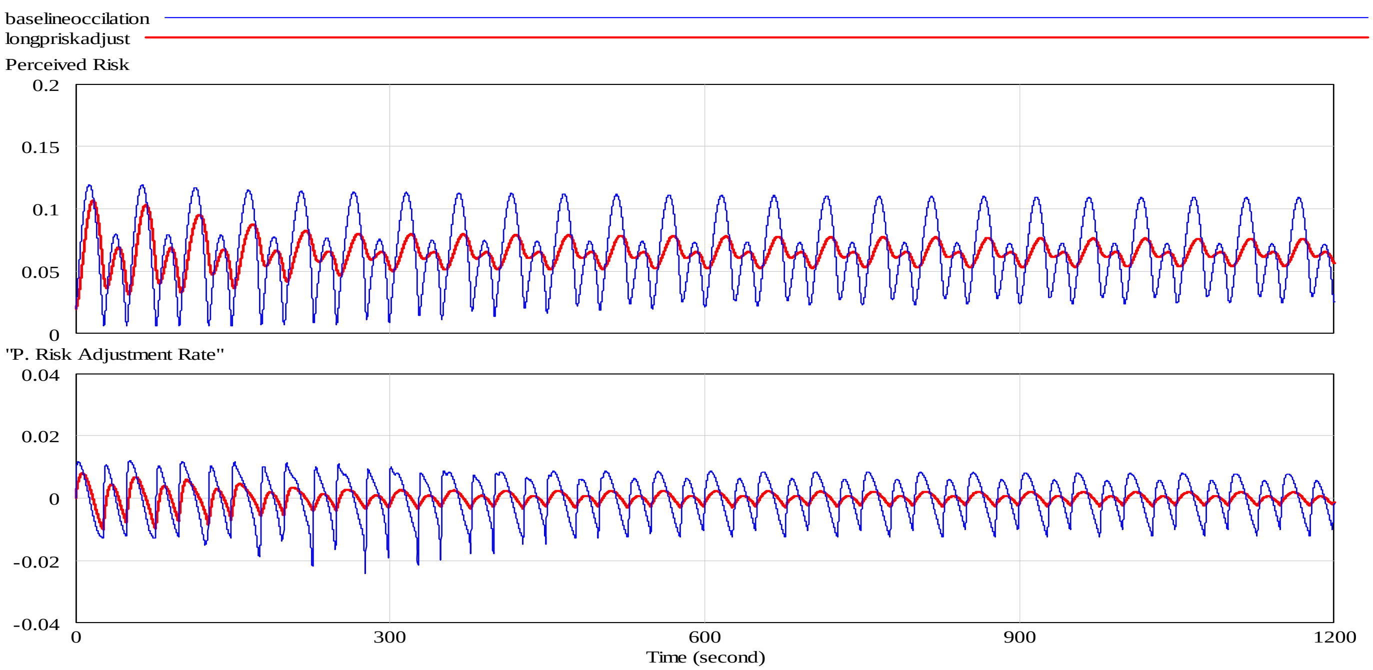


**Figure 41 – Implementation of a longer adjustment time**

By increasing the adjustment time, neither Perceived Risk nor P. Risk Adjustment Rate reach their full amplitude before they begin heading the opposite direction. It was expected that this would be reflected by lower mitigation levels and result in higher crash rates, however this was not the case. As seen in Figure 42, steady state Current Risk levels are very similar. Similar changes occur when increasing Average Mitigation Adjustment Time to 30 or 40s. If both Average Adjustment Times are increased at the same time, mitigation levels become almost completely level over time.

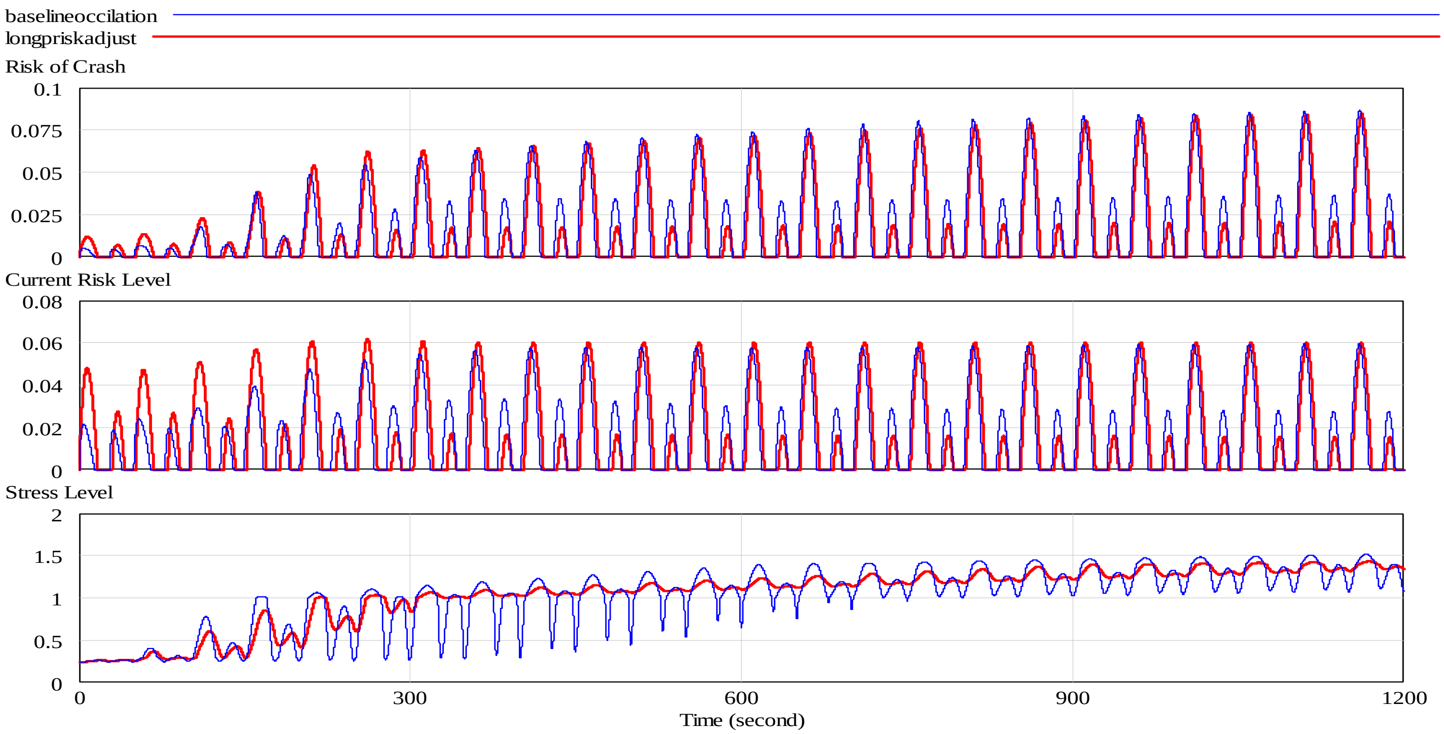


**Figure 42 – Longer Perceived Risk Adjustment Time**

For higher amplitudes, Current Risk and Risk of Crash levels are 1 or 2% less because the mitigation levels don't recover as quickly and thus oscillate less (mitigation is still high when the risk level returns.) This may be a better simulation of reality for cases where it takes the pilot a longer time to either adjust to the risk (here external factors like visibility may have an affect) or take necessary mitigation steps (slowly changing separation distance or altitude). When pilots take these types of mitigation actions to reduce hard to perceive risk, it is unlikely that they undo them when the oscillatory risk only momentarily decreases. More likely, once the pilot has made these types of changes, adjustments decreasing mitigation levels may not be made unless the mitigation actions taken impede the future landing operations of the helicopter (pilot may choose to land from a high hover instead of a low hover due to a difficult to understand motion oscillation). In this case, it may also take a longer period of quiescent time for the pilot to execute a landing (to build confidence in the situation or to conduct a landing from a further approach distance.) Note stress levels are also more constant for this case (Figure 42.)

Another interesting result from increasing the adjustment time, the feedback loop affect from higher stress levels continues to increase adjustment times (Figure 43).

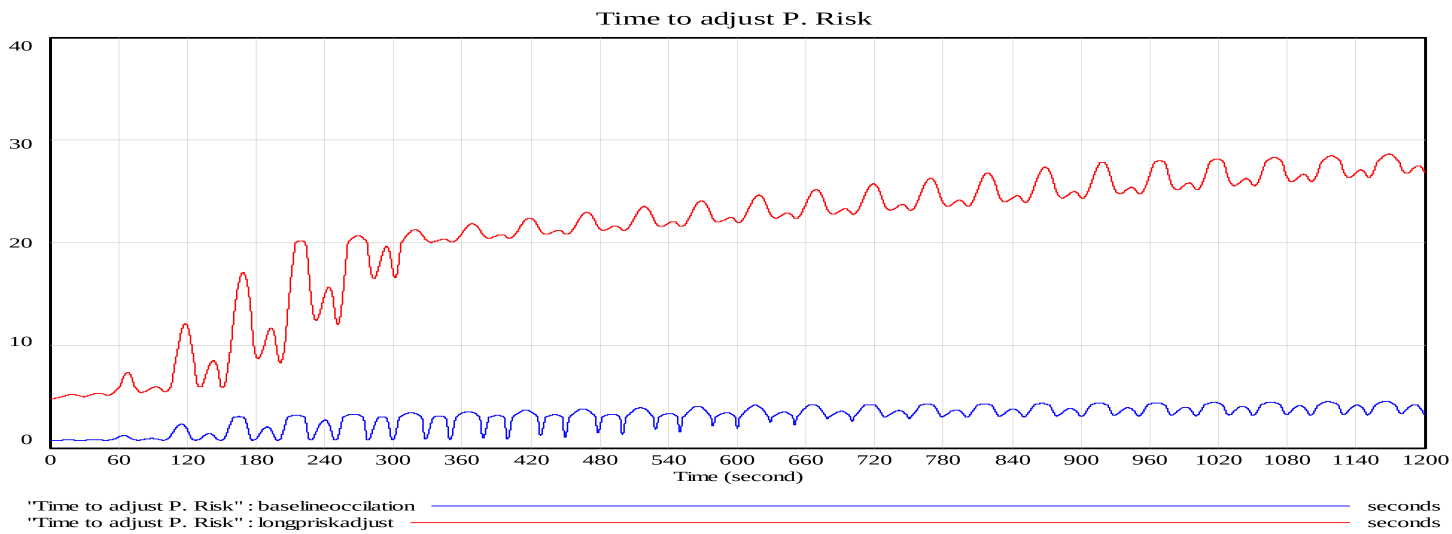


**Figure 43- Stress Feedback implications on adjustment times**

## The Introduction of the Landing Period Indicator

So far all the analysis has only focused on the basic model, with the Landing Period Indicator (LPI) at 1 (i.e. not a factor.) However the real effects of the LPI can be seen in Figure 44 and Figure 45.

*Adjust LPI to 0.24, Both input functions = Sin amplitude, 0.1)*

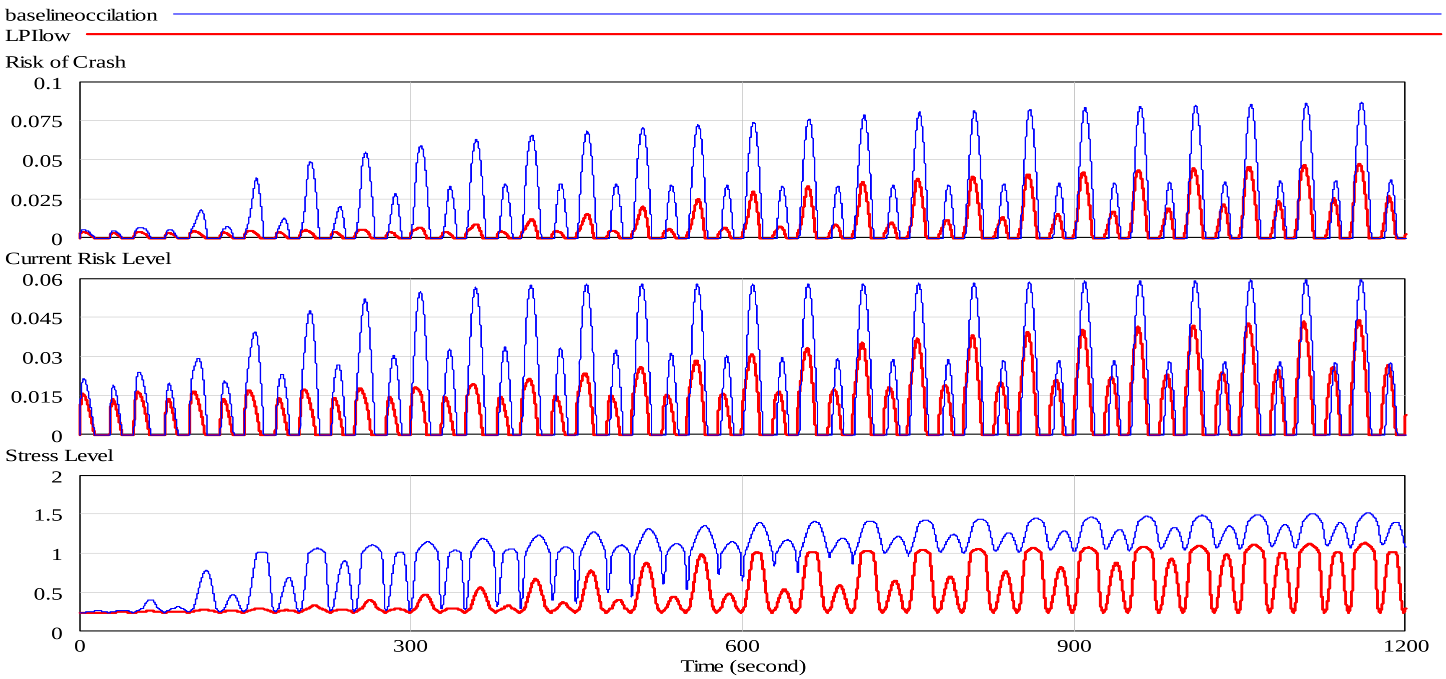


**Figure 44 – LPI Highly Effective**

The model bounds illustrate a plausible range of effects of an LPI. As represented, its maximum effectiveness values can effectively quarter (LPI=0.24) or greatly lengthen (LPI=1.5) both stress level during landing, and the pilot's mental adjustment time to perceive risks. With LPI set to equal 0.24, the reduction in Risk of Crash, Current Level of Risk and Stress Levels is significant. A maximum effective LPI (LPI=0.24) reduces Risk of Crash by 50%. At the worst (LPI=1.5, in other words, degrading the pilot's perception of safe landing periods and increasing stress levels), a LPI dampens stress levels and only marginally increases the Risk of Crash from the baseline oscillations (Figure 45.) From this observation, the use of a LPI would only increase the efficiency and safety of flight operations.

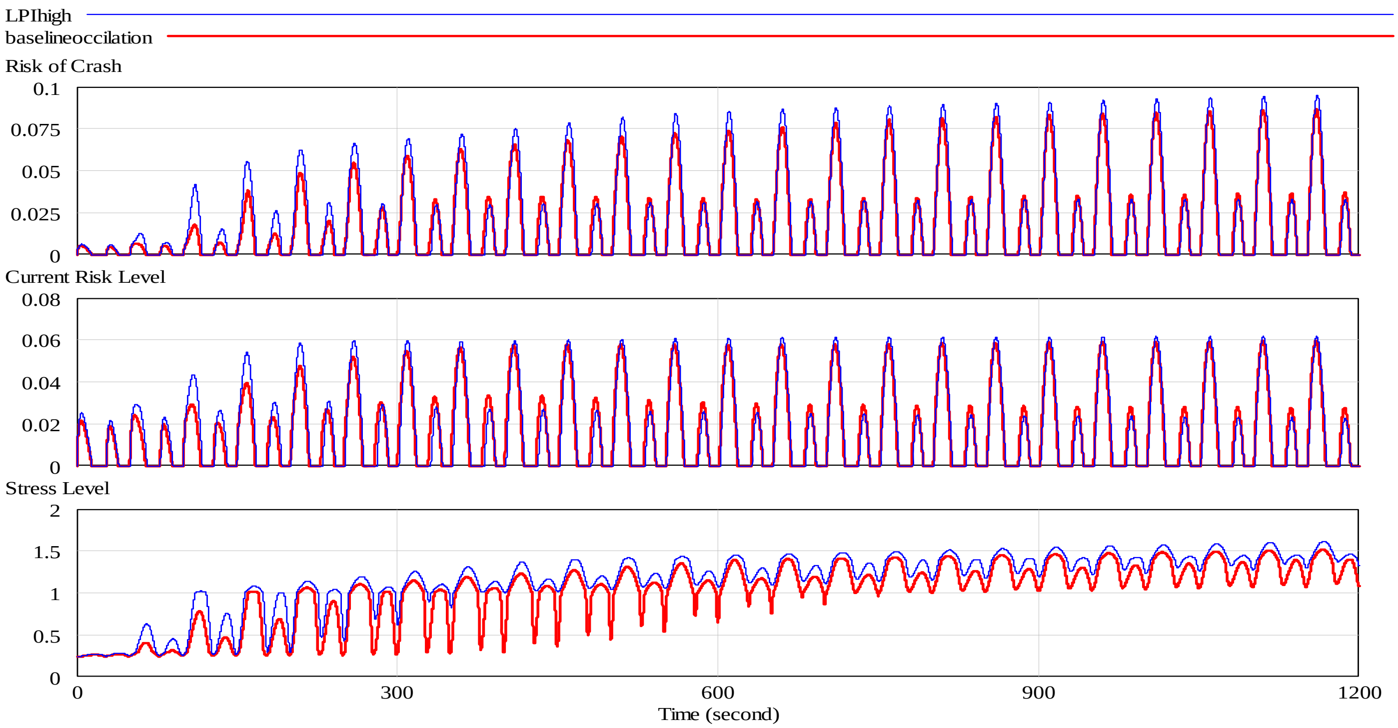


**Figure 45- LPI Low Effectiveness**

The affect of a LPI is even more apparent in large amplitude risk variations (Figure 46). LPI keeps stress levels within bounds (less than 1.7, so the pilot doesn't have to wave off for another approach.) The pilot is also much more aware of the risks (Perceived Risk better matches Actual Risk.) In all, Risk of Crash decreases by almost 20% due to lower stress levels.

*(LPI=0.24 and set Actual Risk input Sin amplitudes to 1)*

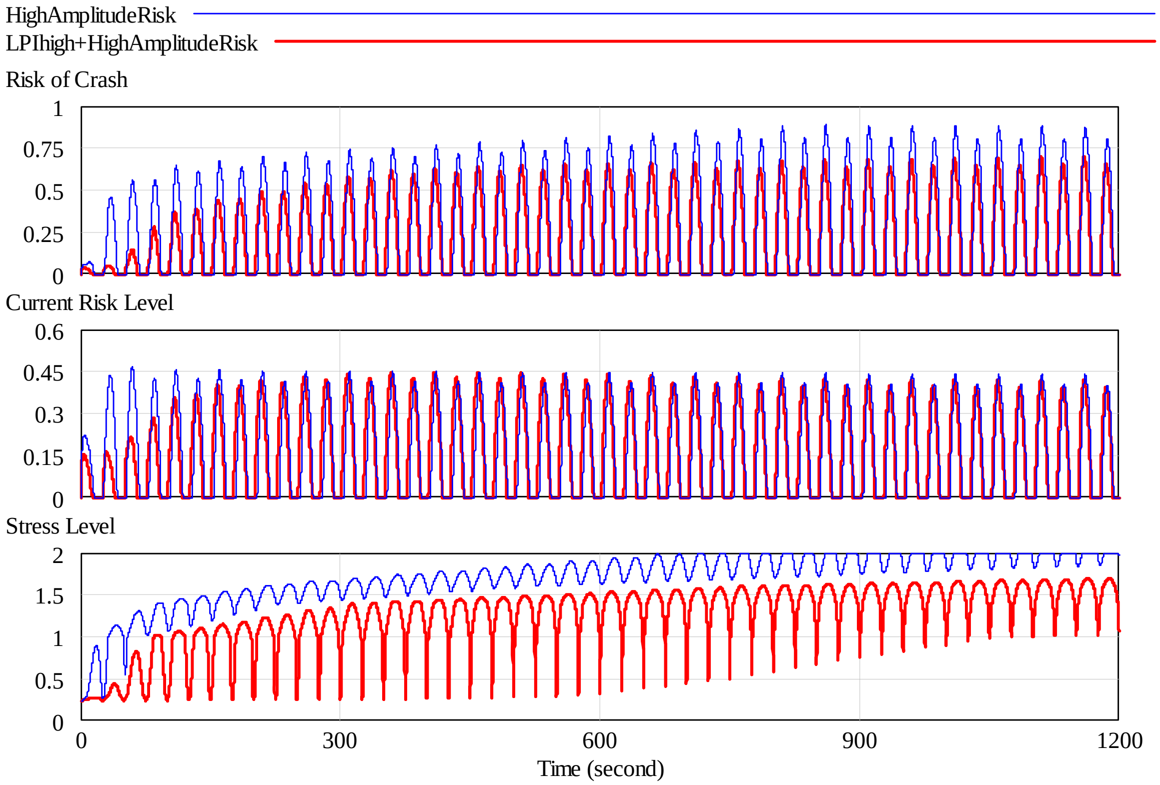


**Figure 46 –Highly effective LPI and high amplitude risk variations**

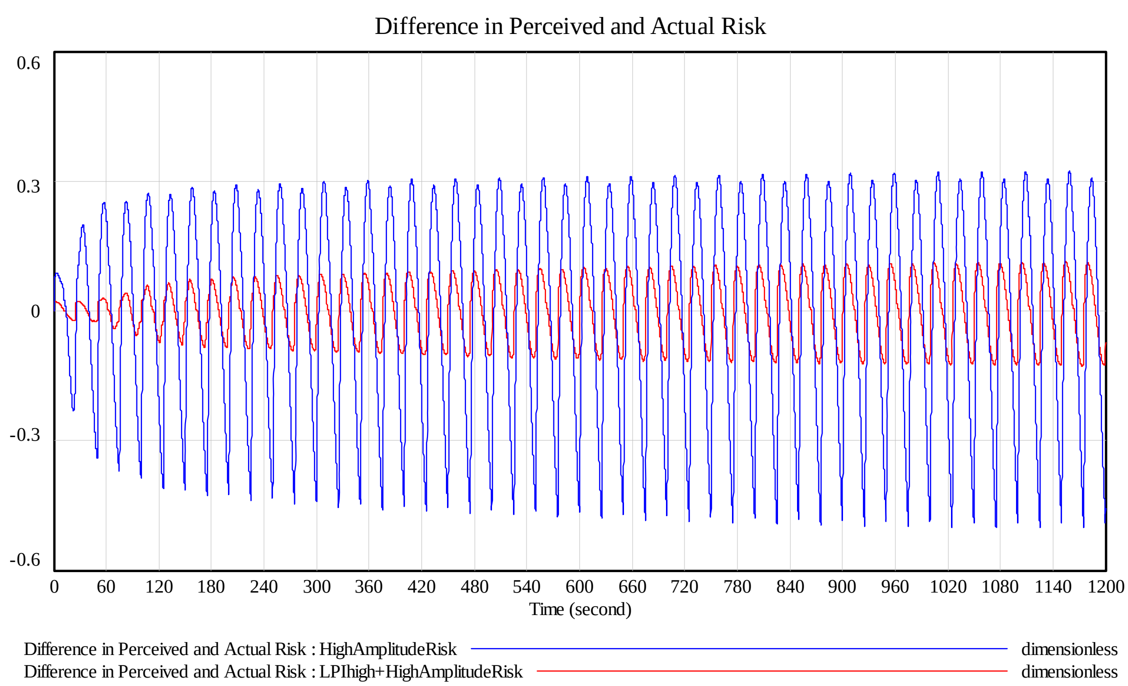


**Figure 47 – High LPI effectiveness impacts perceived risk accuracy**

## Generation of insights

In essence, given a variety of sea conditions, a Landing Period Indicator that was accurate and dependable could reduce the risk of a helicopter crash at sea by up to 20%.

Insights on model specifics:

- Slower reaction to actual risk will cause a slight reduction in current risk because mitigation measures will still be in effect when the actual risk increases again.
- It is possible to somewhat accurately model stress build up for a pilot conducting a static unassisted hover (compared to values from an interview.) Along the same lines, it is possible to model how quickly a pilot's stress may limit landing operations.
- Real time risk variations (waves, wind, etc) drive the problem more than slow emerging external factors like fronts and squalls. Also, stress oscillations were seen throughout the model, and although they may not have been realistic to the amplitudes shown, stress is dynamic, and more responsive to immediate issues like wave heights and wind gusts, than to slowly emerging factors (which also matches the model.)
- The model might better be served by a mitigation level that is less dynamic (pilots aren't likely to take away risk mitigation efforts as quickly as they implement them.) Additionally, modeling Effects of External factors as a ramp instead of a sinusoid would be more realistic.

System dynamics modeling is a great tool for improving comprehension of highly dynamic systems. Although it is more typically used in business and industrial systems modeling, using this approach to incorporate the many highly integrated variables in the ship helicopter DI helps to improve understanding and may help to validate and illustrate issues causing pilot feedback. A highly tuned model may enable conceptual analysis of pre-production LPI approaches and their probable impact on flight operations at sea and with higher fidelity after more extensive testing, the model may become as viable of a tool to improvement of the LPI as ship motion programs are for developing ship's particulars.

Furthermore, a system dynamics approach can assist designers, ship and flight engineers, policy makers and any non-aviators involved or responsible for components of the Dynamic Interface in fully visualizing and comprehending the field of complex issues involved in landing a helicopter a sea. By provoking more discussion, complex dynamic inter-disciplinary issues may arise for future cooperation, investigation and resolution.

# Chapter 4 – Summary and Conclusions

Although the sea is a challenging and complex frontier, technology exists to help mariners improve their "seaman's eye." This thesis presented two different methodologies as examples of ways to further understand these technologies to increase operational capabilities in the marine environment.

While LPIs and DDML systems have had a long history in literature, increased implementation would be highly beneficial to many industries beyond standing naval forces operating helicopters at sea. While most mariners would gain from an LPI type device, it is imperative that the operation and output of the device is easily understood and well defined. This can be accomplished either through open source style design or similarly straightforward comparison to a known benchmark.

A system dynamics approach may also help assess and define LPIs. Fully defining the entire dynamic system is important, but incorporating all of the variables and considerations into the design space is necessary when attempting to create a system improvement. The same approach may be helpful to validate or compare devices for system implementation considerations.

## Future Work

A mechanical tool/system that accurately measures ship motions should be created to replace current bubble inclinometers where LPIs are not feasible or needed. As LPIs emerge for implementation, they should be methodically evaluated and documented. If possible, comparisons between additional indicators should be attempted to gain further insight on pertinent motions to measure, preferred methods for measuring accuracy, optimized operational envelopes, and enhanced safety devices.

Additional study on using longer measurement periods in rough seas should be conducted to identify the possibility of predicting quiescent periods that may be more apparent when analyzing a longer time history (due to longer periods and more complex wave systems). Utilizing the current approach used by the U.S. Navy and U.S. Coast Guard, predictions and indications that are relevant for a relatively short time period (less than that needed to make an approach over the subject vessel's stern) are useful only for aiding the pilot's mental prediction of quiescent periods. These tools may not be useful as a pushbutton landing solution unless they can be developed to predict or indicate these periods with enough lead time to take action on their displayed information.

Another solution may be to readdress the aircraft approach style employed by U.S. naval combatants in order to reduce the duration of required landing periods. There have been informal suggestions within the U.S. Coast Guard to consider the Royal Navy's approach style (which reduces the required landing period to 10s or less) (Bolton 2002).

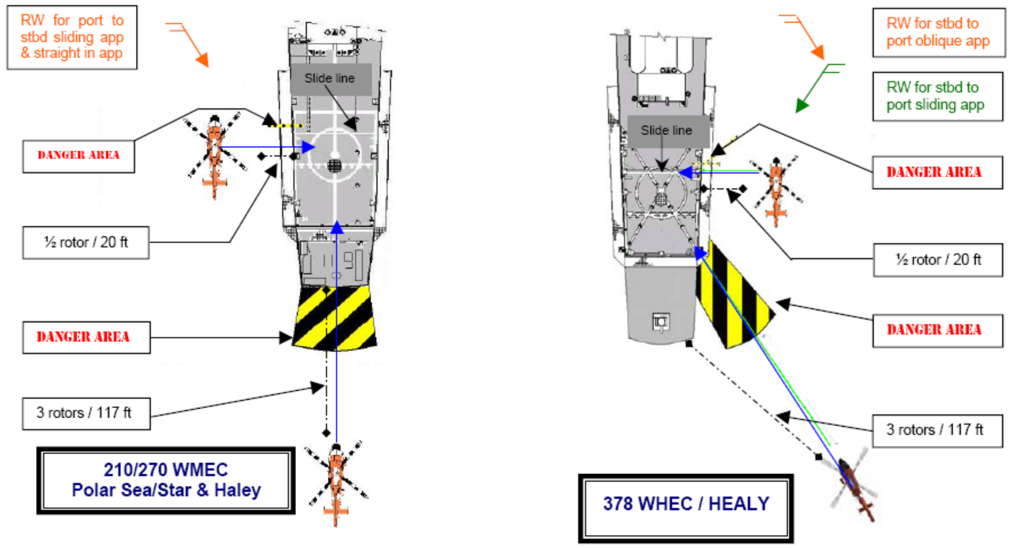


**Figure 48 – A Comparison of the Current USCG Approach to that of the Royal Navy (Waters 2003)**

This approach style also reduces the time that the aircraft is subject to airwake from the superstructure, introduces more flexibility into flight operations (allows pilots to takeoff or land from either port or starboard directions), and requires no change in wind or motion limits or ship visual landing aids. "The sliding method for shipboard recovery provided a safer means transitioning the helicopter from approach termination point to safe on deck aboard a pitching flight deck," (Waters 2003).

This approach may be more attractive to the Coast Guard than the Navy as the Coast Guard regularly operates helicopters in heavier sea conditions and with larger ship motions and would greatly benefit from shorter more efficient operations. Additionally, on many classes of Coast Guard cutter, using the current approach requires pilots to fly over a fantail area in their approach to the flight deck. Most cutters' fantails are complicated with storage for small boats, towing capstans, gasoline barrels, and damage control equipment which makes for a very uneven surface for rotor forces to reflect off of and presents serious hazards to the ship and helicopter if the aircraft were to crash short of the flight deck. With the RN approach, the helicopter flies up alongside the ship, instead remaining over the water which also preserves an option to easily fly out of the approach in case of emergencies (Waters 2003).

Again, as modeled in the system dynamics approach, a shorter required landing period reduces the stress on the pilot, overall risks of crash during landing execution, and allows a more accurate and effective implementation of an LPI. Additional development of the system dynamics model should include more accurate and complete descriptions of the human factors involved during a pilot's approach on a ship at sea. Improved models for stress levels, risk and environmental factors should be implemented including a more thorough treatment of the affect of a LPI on the pilot.

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# Appendix

## Documentation for Vensim Dynamic Model

(01) Actual Risk Level=

MIN(ABS(Input),1)

Units: dimensionless [0,1]

Risk is a measure of the probability of an unsafe landing. This is real time measure of how unsafe the current landing situation is relative to an average landing. ex. if Actual Risk Level is .3, than this landing has a 30% probability of an unsafe landing evolution, if Actual Risk Level is 1, if the landing is attempted, it will fail. Given landing helicopters on ships w/o injury is a regular practice, a realistic value is assumed between 2-8%, meaning a 92-98% success rate for shipboard landing is appropriate. This will oscillate with real time wave heights and wind strength (best modeled by a sin wave). Risk level cannot be larger than 1 or less than 0.

(02) Average Mitigation Adjust time=

5

Units: seconds

Average Mitigation Adjustment time is the average time it takes a pilot to make adjustments to the risk mitigation level.

(03) "Average P. Risk Adjust. Time"=

3

Units: seconds

Average Perceived Risk Adjustment Time is the average time it takes to perceive risk changes while flying.

(04) Current Risk Level=

MAX(Actual Risk Level-Risk Mitigation Level,0)

Units: dimensionless [0,1]

Current Risk measures the impact of Risk Mitigation actions on total risk level. Current Risk Level cannot be larger than 1 or less than 0.

(05) Difference between Perceived Risk and Risk Mitigation=

Perceived Risk-Risk Mitigation Level

Units: dimensionless

This is a measure of the difference between perceived risk and the affect of actions taken to mitigate the risks. Dimensionless

(06) Difference in Perceived and Actual Risk=

Actual Risk Level-Perceived Risk

Units: dimensionless

Equal to the difference between Actual Risk Level and Perceived Risk levels. Dimensionless

(07) "Effect of External Factors (wind/waves)"=

MIN(ABS(Input 0),5)

Units: Sea State/Sea State [0,5]

External factors represent weather conditions and sea state that generally don't change instantly (i.e. sustained conditions, not instantaneous wave height and wind speed.) Here it is simplified to a normalized sea state. That is, the average sea state for flight operations is sea state 2. A value less than 1 represents a sea state less than the average. A value greater than one represents a sea state greater than the average. This input might change during the simulation to indicate a change in weather conditions (ramp input) or sudden storm (step increase.)

The maximum sea state is 10, so a normalized value beyond 0 or 5 is not valid.

(08) FINAL TIME = 1200

Units: second

The final time for the simulation.

(09) Fractional Increase in Stress due to Hover Time=

Hover Time/Max Hover Time*Landing Period Indicator Fractional Effect

Units: dimensionless

Fractional Increase in Stress due to Hover Time is equal to

Hover Time normalized by max hover time, modified by the fractional effect of the landing period indicator. Values less than one represent hover times less than the average max hover time, while values greater than one represent hover times longer than the average max hover time.

(10) Hover Time= INTEG (

Hover Time Accumulation Rate,

0)

Units: seconds

Hover time is the total hover time a pilot needs prior to making

a landing on a ship at sea. This is constantly increasing value that will have a strong affect on Stress Level.

(11) Hover Time Accumulation Rate=

1

Units: seconds/seconds

Hover Time Accumulation Rate is simply a way of adjusting Hover

Time from 0-T where T is the total time necessary to hover prior to landing. It increases Hover Time at the rate of 1 second per second .

(12) INITIAL TIME = 0

Units: second

The initial time for the simulation.

(13) Input=

0.02+STEP(Step Height,Step Time)+

(Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)+

RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+

Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+

STEP(1,Noise Start Time)*0

Units: dimensionless

Input is a dimensionless variable which provides a variety of test input patterns, including a step, pulse, sine wave, and random noise.

(14) Input 0=

1+STEP(Step Height 0,Step Time 0)+

(Pulse Quantity 0/TIME STEP)*PULSE(Pulse Time 0,TIME STEP)+

RAMP(Ramp Slope 0,Ramp Start Time 0,Ramp End Time 0)+

Sine Amplitude 0*SIN(2*3.14159*Time/Sine Period 0)+

STEP(1,Noise Start Time 0)*0

Units: dimensionless

Input is a dimensionless variable which provides a variety of test input patterns, including a step, pulse, sine wave, and random noise.

(15) Landing Period Indicator Fractional Effect=

1.5

Units: dimensionless [0.24,1.5]

Landing Period Indicator Effect refers to the ability of the pilot to use the landing period indicator as a rapid and accurate source of information on safe landing periods. The direct effect is that the indicator would reduce hover time by accurately predicting for the pilot when to land (which eliminates or reduces the pilot's own observance time) and would also innately help the pilot correlate the motions and risk, reducing the information delay in adjustment times. In essence, a good fractional effect would be 0.5 (halves necessary hover time and adjustment time) while a poor effect (1.5) would illustrate an inaccurate indicator that may distract the pilot and indicate unsafe landing periods during calm periods, extending the total hover time. A value of 1 means the indicator has no effect on the hover time (and thus no effect on the stress level or time to adjust perceived risk.) The limit of the fractional effect of the device is assumed to be from 0.24-1.5.

(16) Max Hover Time=

300

Units: seconds

Max Hover time is on average, the maximum time a helicopter hovers before landing. It is assumed to be constant and is used to normalize total hover time.

(17) Mitigation Adjustment Rate=

Difference between Perceived Risk and Risk Mitigation/Time to adjust Risk Mitigation

Units: 1/seconds

Mitigation Adjustment Rate is equal to the Difference between Perceived Risk and current Risk Mitigation Levels divided by the Time to adjust Risk Mitigation

(18) Noise Start Time = 5

Units: seconds

Start time for the random input.

(19) Noise Start Time 0 = 5

Units: seconds

Start time for the random input.

(20) "P. Risk Adjustment Rate"=

Difference in Perceived and Actual Risk/"Time to adjust P. Risk"

Units: 1/seconds

Perceived Risk Adjustment Rate is dependent on the difference between perceived and actual risk and is divided by the time to adjust perceived risk.

(21) Perceived Risk= INTEG (

"P. Risk Adjustment Rate",

0.02)

Units: dimensionless [0,1]

Perceived Risk is equal to the cumulative Perceived Risk Adjustment Rate over time. Initial value is .02 or 2%. Perceived Risk cannot be larger than 1 or less than 0. This is defined as the perceived probability of an unsuccessful landing.

(22) Pulse Quantity=0

Units: dimensionless*seconds

The quantity to be injected to actual risk, as a fraction of the base value of Input. For example, to pulse in a quantity equal to 50% of the current value of input, set to .50.

(23) Pulse Quantity 0=
0
Units: dimensionless*seconds
The quantity to be injected to effect of external factors, as a fraction of the base value of Input. For example, to pulse in a quantity equal to 50% of the current value of input, set to .50.

(24) Pulse Time=5
Units: seconds
Time at which the pulse in Input occurs.

(25) Pulse Time 0=
150
Units: seconds
Time at which the pulse in Input occurs.

(26) Ramp End Time=1e+009
Units: seconds
End time for the ramp input.

(27) Ramp End Time 0=1e+009
Units: seconds
End time for the ramp input.

(28) Ramp Slope=0
Units: 1/seconds
Slope of the ramp input, as a fraction of the base value (per second).

(29) Ramp Slope 0=
0

Units: 1/seconds

Slope of the ramp input, as a fraction of the base value (per second).

(30) Ramp Start Time=5

Units: seconds

Start time for the ramp input.

(31) Ramp Start Time 0=

100

Units: seconds

Start time for the ramp input.

(32) Risk Mitigation Level= INTEG (

Mitigation Adjustment Rate,

0.02)

Units: dimensionless [0,1]

Mitigation Level represents the fraction of risk avoided by risk mitigation actions taken. Dimensionless. Initial value is .02 or 2%. Mitigation Adjustment Rate cannot be larger than 1 or less than 0. This is defined as the result of the actions taken to mitigate an unsuccessful landing.

(33) Risk of Crash=

MIN(Current Risk Level*Stress Level, 1)

Units: dimensionless [0,1]

Risk of Crash represents the probability of an unsuccessful landing, measured by current risk level of the operation multiplied by stress level of the pilot. This is dimensionless. Risk of Crash cannot be larger than 1 or less than 0.

(34) SAVEPER =

TIME STEP

Units: second [0,?]

The frequency with which output is stored.

(35) Sine Amplitude=

0

Units: dimensionless

Amplitude of sine wave in Actual Risk Level (fraction of mean).

(36) Sine Amplitude 0=

0

Units: dimensionless

Amplitude of sine wave in Effect of External Factors (wind/waves) (fraction of mean).

(37) Sine Period=

50

Units: seconds

Period of sine wave in Actual Risk Level. Set initially to 50 seconds.

(38) Sine Period 0=

50

Units: seconds

Period of sine wave in Effect of External Factors (wind/waves). Set initially to 50 seconds.

(39) Step Height=

0

Units: dimensionless

Height of step input to Actual Risk, as fraction of initial value.

(40) Step Height 0=

0

Units: dimensionless

Height of step input to Effect of External Factors (wind/waves), as fraction of initial value.

(41) Step Time=

5

Units: seconds

Time for the step input.

(42) Step Time 0=

5

Units: seconds

Time for the step input.

(43) Stress Level=

Stress Level Lookup Table("Effect of External Factors (wind/waves)"*Fractional Increase in Stress due to Hover Time *Perceived Risk )

Units: dimensionless [0.24,2]

Stress Level is a factor of external factors, hover time required and landing period indicator fractional dependability. As any of these variables go up, stress level goes up corresponding to the specified lookup table. Stress level has been defined such that 1 is an average stress level, 2 is a max stress level, and 0.24 is the minimum stress level possible while piloting a helicopter.

(44) Stress Level Lookup Table(

[(0,0)-

(100,2.1)],(0,0.24),(0.02,0.3),(0.035,0.5),(0.05,0.8),(0.06,1),(0.247706

,1.39079),(0.6,1.6),(2,2),(2.2,2),(3,2),(100,2))

Units: dimensionless

Stress Level Lookup table\!\!\!

(45) TIME STEP = 0.0625

Units: second [0,?]

The time step for the simulation.

(46) "Time to adjust P. Risk"=

"Average P. Risk Adjust. Time"*Stress Level*Landing Period Indicator Fractional Effect

Units: seconds [0,?]

The time to adjust perceived risk is assumed to equal the average time to perceive risk multiplied by the current stress level and the fractional effect of the Landing Period Indicator.

(47) Time to adjust Risk Mitigation=

Average Mitigation Adjust time*Stress Level

Units: seconds [0,?]

Average Time to adjust risk mitigation is a constant multiplied by current stress level to give actual time to adjust risk mitigation.

# Vitae

LT Brook Sherman was born in Sun Prairie, WI. He graduated from the U.S. Coast Guard Academy with a BS in Naval Architecture and Marine Engineering and was commissioned an Ensign in 2001. LT Sherman's first assignment was to the USCGC HARRIET LANE (WMEC 903) out of Portsmouth, VA as the Damage Control Assistant and Assistant Engineer Officer. Prior to his graduate studies, LT Sherman was selected and served as a Naval Exchange Officer, serving as the Navigator of USS STOUT (DDG 55).