Real Time Ship Motion Criteria for Maritime Helicopter Operations

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Abstract

The traditional approach for defining ship/helicopter operating limits (SHOLs) provides statistical criteria which are adequate for general design and operational analysis studies, but not for time-domain simulation, nor for real time operator guidance at sea. Real time ship motion criteria offer a new way to define flight deck operating limits for maritime helicopters. The conceptual differences between real time criteria and SHOLs are described, and their applications are discussed. Flight deck certification trial data for high sea state operations are described and analysed, to examine relationships between ship motions and helicopter pilot control input. A ship motion correlation study examines trends between lateral and vertical motions, and is used in conjunction with helicopter performance data to select critical ship motion parameters. Representative real time criteria are developed for helicopter landings, by comparing vertical and lateral ship motions with the success or failure of attempted landings. A two-part definition of quiescence is introduced for real time applications, and illustrated by examining measured ship and helicopter parameters.

1 Introduction

Landing a helicopter on a moving ship at sea is a challenging task, which is further complicated by the contemporary naval practice of placing frigate and destroyer flight decks very far aft in the ship. In high sea states, contemporary frigates experience much greater vertical motion at the flight deck than older ships, on which the flight deck was typically located closer to the centre of the ship. As a result, some of the traditional, empirical ship motion indices used to define ship/helicopter operating limits (SHOLs), are no longer relevant. Also, the approach used for defining SHOLs provides statistical criteria which are adequate for general design and operational analysis studies, but they are not adequate for time-domain simulation and modeling, nor for real time operator guidance at sea.

The main focus for this paper is based on the two following recommendations from [1], which describes technical challenges for developing maritime helicopter ship motion criteria, we should: (i) develop a clear understanding of which ship motions limit which aspects of helicopter operation; and, (ii) develop real time ship motion criteria for operator guidance at the actual time of landing.

This paper introduces real time ship motion criteria, and examines their application to helicopter/ship operations. The conceptual differences between real time criteria and traditional SHOLs are summarized, and applications of both approaches are briefly discussed. The development of real time criteria for helicopter landings is illustrated, based on analysis of measured and observed ship and helicopter performance during flight deck certification trials in sea states 'high' 5 and high 6[1]. The most important ship motion parameters are identified by examining frequency- and time-domain characteristics of ship and helicopter parameters. Limit values are then defined for day and night operations, by comparing ship motions with the success or failure of attempted landings. A two-part definition of quiescence is introduced for real

[1] High sea state 6 has significant wave heights of 5 to 6 m, with a maximum expected height of approximately 10 m in every 200 encounters (15 to 45 minutes for typical ship speed and course combinations at 'flying stations').

time applications, and illustrated by examining measured ship and helicopter parameters.

2 Traditional SHOLs vs. real time criteria

Traditional SHOLs provide a statistical description of the ship motion environment in which experience shows that successful helicopter operations are expected to be possible. Typical SHOLs are expressed statistically, in a way which seems to make the most sense for the intended application.

For ship design and analysis, SHOLs are usually expressed as root-mean-square or significant amplitudes [2,3], which can then be combined with wave and wind environmental statistics [4,5,6], to calculate ship motions [2,7,8], and apply SHOLs to derive quantities such as the 'percent of time operable' [2]. This is a suitable process for evaluating relative performance of differences between ships, helicopters (defined by the SHOLs), flight deck locations, geographic locations, time of year (or season), etc., but is not a suitable way to evaluate absolute performance. In other words, this process cannot answer the question "can I land now ?".

In the operational environment, SHOLs are usually expressed as maximum ship motion amplitudes for performing the task in question, with an acceptable margin of safety. These limits are usually determined from flight deck certification or qualification trials, which are complex, challenging, expensive, and weather-dependent. In many cases, initial SHOLs have to be 'expanded' over time, as suitably demanding weather conditions were not encountered during the formal tests.

On Canadian Forces frigates and destroyers, 'hauldown' landings using the Indal Technologies Incorporated recovery assist, secure and traverse (RAST) system, have typical SHOLs of 20° to 25° for maximum roll angle, and 4° to 6° for maximum pitch angle. These maximum amplitudes can generally be related to design and analysis criteria, using the Rayleigh distribution, which describes both ocean wave and ship motion amplitude statistics [8]. This procedure was also used in footnote 1 to calculated the expected maximum wave height from a significant wave height.

Consider a typical SHOL with a maximum ship roll angle of 20°. This means that, when the maximum ship roll angle is less than 20 degrees, over some unspecified observation period, then there is a high probability that there will be an opportunity to land safely. In real operations, the helicopter maintains relative position over the ship at high hover during large amplitude ship motions, and then descends to low hover and landing when the ship enters a 'quiescent period'. The concept of quiescence is explored more fully later in this paper.

Real time criteria are the maximum motions that can be safely tolerated at the time of performing an activity. For example, the SHOL for roll may be 20°, but the maximum acceptable roll at the actual time of transition from low hover to landing is much less, as shown later in this paper.

The relative velocity between helicopter and ship at touchdown is of critical importance for landing gear structural integrity, but it is not considered here, as flight deck vertical velocity alone is not a reliable indicator of relative velocity at touchdown [1].

3 Data Analysis

In the early 1990's, DRDC Atlantic, then called DREA, supported flight deck certification trials conducted by the Aerospace Engineering Test Establishment, AETE, for Sea King CH-124A helicopters operating on Canada's new Halifax Class frigates. The main purpose for these trials was to define operational capabilities of this new helicopter/ship combination. Operating limits were defined primarily in terms of relative wind envelopes, but special attention was also paid to determining operating limits associated with ship motions.

3.1 Summary of Data

Figure 1 shows measured ship motion and helicopter data for a two-minute 'test point'. The first four panels show ship roll angle, flight deck lateral acceleration (FDLA), pitch angle, and flight deck vertical acceleration (FDVA). The last three panels show pilot collective control input; helicopter engine torque (either port or starboard engine, whichever is greater for the test point), and radar altimeter, which is the vertical distance, or clearance, between the helicopter and flight deck. All seven panels are aligned with the horizontal time axis shown at the bottom.

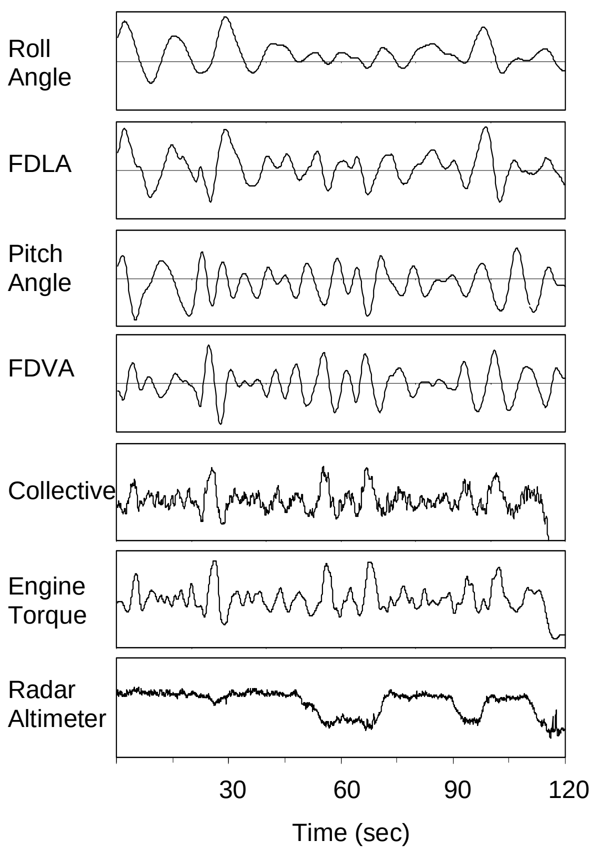

Figure 1: Example test point data.

The overall data set examined for this paper comprises 56 different test point cases, 38 in day time and 18 at night. All test points are for hauldown landings in sea states high 5 and high 6. The procedures and ship systems used for hauldown landings are described in [1]. The helicopter was at or near full load weight, and all flight control augmentation systems were functional. Each test point represents a different combination of relative wind direction (i.e. red or green, for port or starboard), and relative wind speed, and each test point has different ship speeds and courses. Considering the same test point (i.e. relative wind condition) in both day and night produces two test point cases, for a single test point.

3.2 Ship Lateral and Vertical Motion

In this paper, roll angle and FDLA are described as lateral motions; and, pitch angle and FDVA are described as vertical motions. As expected for a 'monohull' frigate on a nominally straight course, longitudinal accelerations and variation in yaw angle were not large, and so are not considered.

The separation of ship motions into lateral and vertical components is a common approach for assessing ship motion effects. This is largely due to their different frequency response characteristics. For monohull frigates and destroyers, lateral motions are 'narrow banded', with a pronounced peak in response amplitude at the ship's 'natural frequency', which is a function of hull form and centre of gravity. Conversely, vertical motions are 'broad-banded', and respond to the wave encounter frequency, which is a function of ship speed, course relative to the waves, and wave frequency. These trends are evident in Figure 2, and explored further in [9]. A full treatment of these topics can be found in contemporary seakeeping texts (e.g. [8]).

3.3 Ship Motions and Pilot Controls

Four pilot control inputs are considered; collective, lateral cyclic, longitudinal cyclic, and pedal. The relationship between ship motions and helicopter engine torque is summarized, following [9], and radar altimeter data are used to evaluate 'altitude-keeping'.

Figure 2 compares energy spectra for pilot control input with ship motions, in a four-row by two-column matrix of panels. Each panel shows normalized spectral density, $S(\omega)$, as a

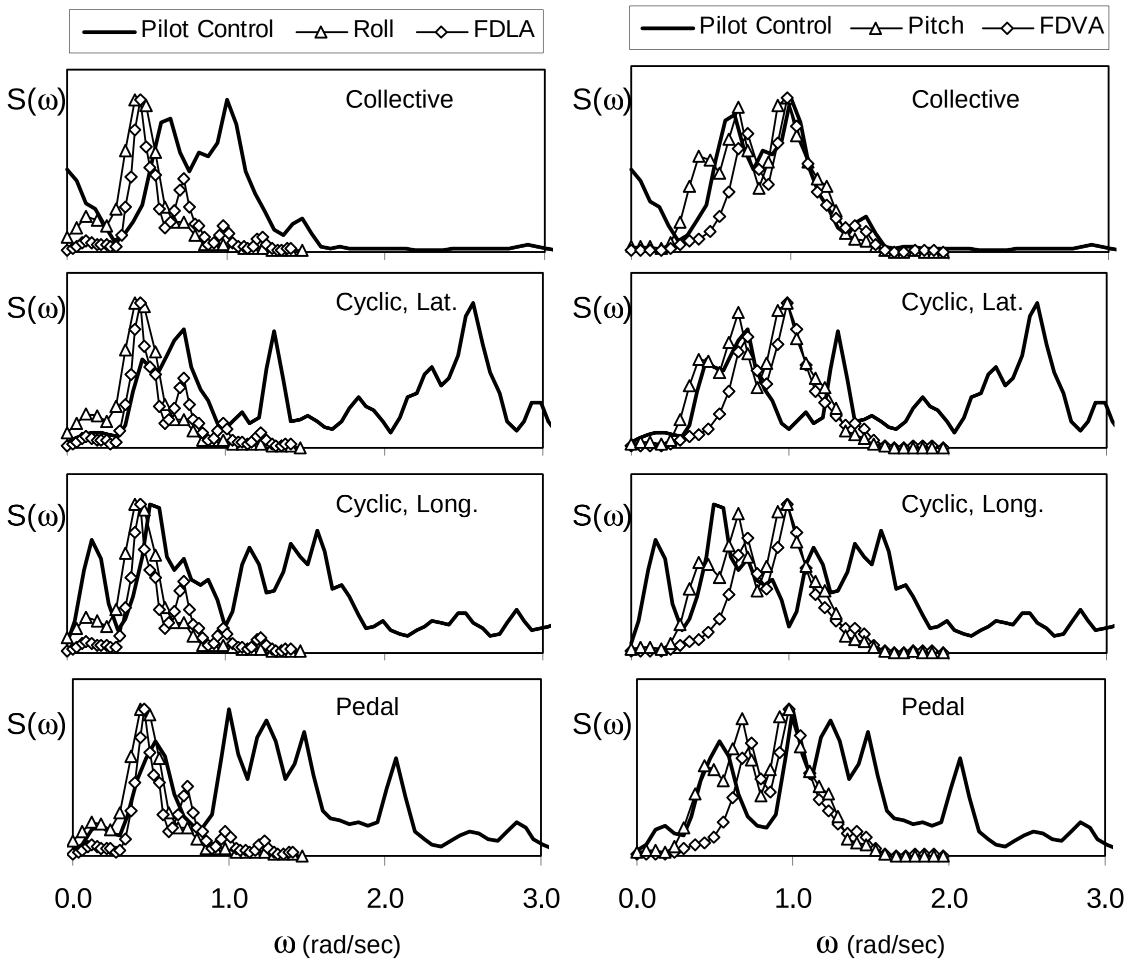

Figure 2: Spectral density plots for pilot controls (annotated on each panel) with ship lateral motions on the left, and ship vertical motions on the right, for data from Figure 1.

function of frequency, ω (rad/sec). The panels are arranged with each of the four pilot controls on subsequent rows, as annotated in each panel. Ship lateral motions are shown in the left hand column, and vertical motions are shown in the right hand column.

The spectra shown in Figure 2 are for the test point shown in Figure 1, which has relative wind of 'green' 15° at 35 knots (i.e. the relative wind direction is 15° off the starboard bow, at a relative speed of 35 knots), at a ship speed of 16 knots.

Figure 2 suggests two trends: (i) spectral shapes for collective are similar to those for ship vertical motion, but not for ship lateral motions; and, (ii) the spectral shapes for other pilot controls are considerably more complex.

The first trend is examined in detail in [9], which shows that spectral shapes for vertical motion, pilot collective input, and helicopter engine torque are consistently similar, for both day and night operations. This trend is not evident between ship lateral motion and helicopter parameters.

With respect to the second trend, Figure 2 suggests that both vertical and lateral ship motions are directly associated with all pilot controls in the range of ship motion frequencies, but pilot controls appear to be significantly affected by other factors, such as buffeting from wind turbulence [10], at frequencies above 1.5 rad/sec.

The low frequency peak shown in Figure 2 for ship lateral motions appears to be reflected in pedal control, and may be an influence on both lateral and longitudinal cyclic. Similarly, the relatively low frequency peak in ship vertical motions appears to be reflected in all pilot controls, but the higher frequency peak is only evident in pedal. This last feature is likely directly associated with the collective control input - in order to maintain constant heading of the helicopter when increasing collective, the pilot must also increase pedal control input.

This paper does not explore the complex relationships between ship motions and pilot control input for lateral and longitudinal cyclic, and for pedal. Such an effort requires a multi-disciplinary approach, with specialists in flight operations, aerodynamics, flight control systems, and helicopter performance. However, the following observation provides some perspective, with respect to defining real time ship motion criteria. Every single 'event of interest' in the 56 test point cases, is directly associated with relatively large, lateral and/or vertical ship motions. These events include: comments by the test pilots and flight test engineers; 'marginal' altitude-keeping; and, all unsuccessful landing attempts. A marginal altitude-keeping event occurs when altitude changes by more than +/- 1 m, while the helicopter is at nominally constant altitude. At low hover, this represents from 1/2 to 2/3 of the typical clearance between the ship and helicopter. Figure 1 shows a high-hover marginal event at about 25 seconds, and low hover marginal events at 55 and 70 seconds.

For now, the complex relationships between ship motions and pilot cyclic and pedal controls are temporarily put aside. On the other hand, it is probably critical to develop a more complete understanding of these relationships before developing a methodology relating ship motions to pilot workload, via helicopter control and performance parameters - a task for future consideration.

3.4 Ship Motion Correlation

Figure 3 shows real time ship motion data for five test point cases, arranged in a five-row by two-column matrix of panels. Each row represents a different test point case, with labels A_D, A_N, B_D, B_N, and C; where subscript D denotes daytime flights, and N is for night.

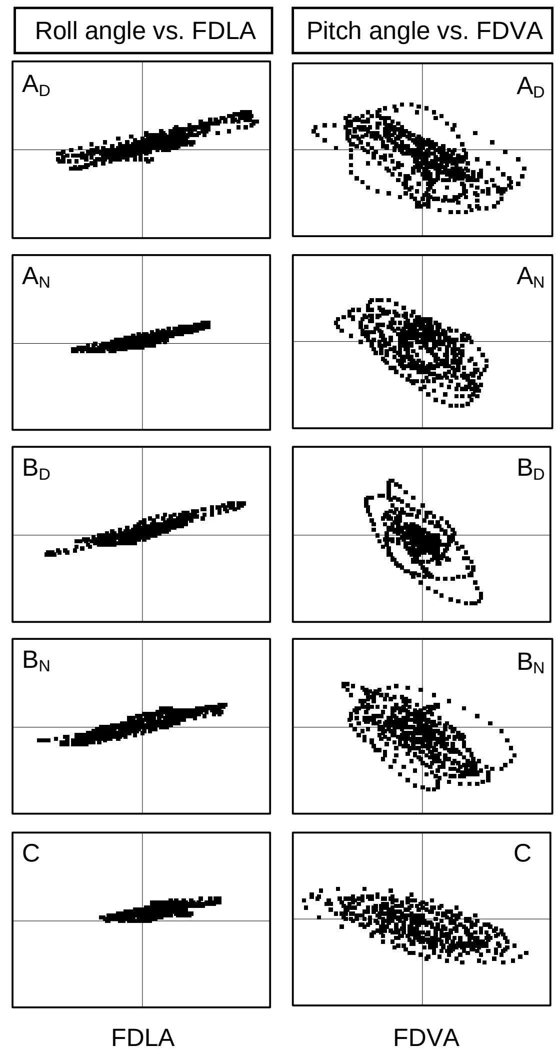

Figure 3: Scatter plots for 5 test point cases, with Roll Angle vs. FDLA on the left, Pitch Angle vs. FDVA on the right, all data normalized by SHOLs.

Panels in the left hand column of Figure 3 show roll angle vs. FDLA, and those in the right hand column show pitch angle vs. FDVA. The ship motion data in each panel are normalized by their respective, real daytime SHOL values (FDLA does not have a SHOL value defined, and so the FDVA value is used). In all panels, the scales for all vertical and horizontal axes vary from -1 to 1, with angular motions plotted on the vertical axes, and linear accelerations on the horizontal axes.

These five test point cases represent challenging ship motion conditions, including situations where attempted landings were successful, marginal, and unsuccessful. Test point A has relative wind of 'green 15° at 35 kn', with ship speed of 16 kn; B is green 15° at 30 kn, ship speed 7 kn; and, C is red 15° at 55 kn, ship speed 24 kn. More details on these five test point cases were reported in [9]. Test point case A_D was used for Figures 1 and 2.

Table 1 shows linear Pearson correlation coefficient values, *r*, for the test point cases shown in Figure 3. The first five rows of this table contain *r* values for the five cases, and the last two rows contain their averages and standard deviations. The first three columns of numerical data show correlation for roll angle with pitch angle, FDLA, and FDVA; and the last three columns show correlation for pitch angle with roll angle, FDLA, and FDVA.

Table 1: Correlation between ship motions.

	Correlation for Roll with...			Correlation for Pitch with...		
	Pitch	FDLA	FDVA	Roll	FDLA	FDVA
A_D	0.22	0.89	-0.22	0.22	0.38	-0.61
A_N	0.34	0.89	-0.28	0.34	0.50	-0.56
B_D	0.49	0.94	-0.24	0.49	0.55	-0.59
B_N	0.19	0.92	-0.29	0.19	0.33	-0.63
C	0.12	0.74	-0.14	0.12	0.57	-0.65
ave.	0.27	0.88	-0.23	0.27	0.50	-0.61
S.D.	0.15	0.08	0.06	0.15	0.09	0.03

In many cases, a significance test based on the '*p-level*' statistic is used, for which statistical significance is accepted for $p < 0.05$ (i.e. a 5% or less chance that the observed correlation is random). In this case, where time series data are being analysed, the large '*N*', or number of data samples, gives very small *p-level* ($p < 0.001$, for all parameters), and so this measure of significance is not useful.

Another statistical concept is that the square of the correlation coefficient, r^2, is a measure of the extent that variability of one parameter can be explained by (not necessarily caused by), variability of a second parameter. In this case, we set a minimum value of 50% for 'explained variability' to represent statistical significance, for which $r \geq 0.71$ is the acceptance criterion. Using this statistic, the only significant correlation is between roll angle and FDLA. All other correlations amongst these ship motions, including between pitch angle and FDVA, are not significant.

The lack of significant correlation between pitch angle and FDVA is probably the most important result This suggests that using pitch angle to represent ship vertical motion in an environment with high FDVA, such as on a frigate flight deck, is not appropriate - FDVA should be used. The high correlation between roll angle and FDLA suggests that either parameter could be used to represent lateral motion. As shown later, the traditional selection of roll angle is appropriate.

Flight deck accelerations reported here are ship-referenced, as measured by strap-down accelerometers. The contribution of gravity due to roll in FDLA is partially responsible for the high correlation between FDLA and roll angle; however, it is appropriate to retain this gravity component, as FDLA is a direct measure of the lateral deck accelerations, and hence forces, that will act on the helicopter once it has landed. Similarly, FDVA represents the vertical deck forces acting on the landed helicopter.

3.5 Ship Motions, Collective and Torque

Table 2, from [9], summarizes correlation for pilot collective control input with ship motions, and with helicopter engine torque, Q_{MAX}, for the same five test point cases considered in the previous section. Q_{MAX} is for either the port or starboard engine, whichever is greater during the test point case

Using $r \geq 0.71$ as the acceptance criterion: the correlation between FDVA and collective is statistically significant in all cases; the correlation between pitch angle and collective is rarely significant; and, the correlation between ship lateral motion (roll and FDLA) is not statistically significant. The correlation between collective and torque is highly significant in all cases.

Table 2: Correlation for pilot collective input with ship motions and helicopter engine torque.

	Correlation for Collective with...				
	Roll	FDLA	Pitch	FDVA	Q_{MAX}
A_D	0.21	0.46	-0.66	0.85	0.94
A_N	0.29	0.51	-0.69	0.85	0.93
B_D	0.46	0.21	-0.58	0.76	0.83
B_N	0.43	0.28	-0.25	0.72	0.91
C_D	0.26	0.65	-0.74	0.83	0.94
ave.	0.35	0.37	-0.55	0.80	0.90
S.D.	0.11	0.18	0.20	0.06	0.05

4. Defining Real Time Criteria

The first step in defining real time criteria is to select the appropriate ‘critical’ ship motion parameters, and the second is to define appropriate limit values for each critical parameter, based on real time performance.

4.1 Selecting Critical Parameters

The ship motion parameters which are critical for any particular activity are dependent on both the activity being performed, and the characteristics of the host ship. In this case, the activity is landing a helicopter, and the host ship is a ‘monohull’ frigate. A similar exercise for a multi-hulled SWATH[2] or trimaran, or for high-speed hovercraft or hydrofoil, would produce very different results, but the same process is appropriate for any motion-sensitive task.

Based on previous sections, FDVA is clearly a critical parameter for pilot collective input and helicopter engine torque. Similarly, roll angle is critical, although most of the substantiation for this statement is not made until the next section. Pitch angle is not critical for helicopter landings, at least not for the amplitudes experienced in these trials. It should be possible to define ship pitch angle limits for hovering, to ensure clearance of rotor blades from the hangar, but this is not done here.

[2] small waterplane area, twin hull.

4.2 Real Time Limit Values

Figure 4 defines representative, real time limit values as vertical, dashed lines, for roll angle and FDVA. The figure is arranged in a two-row, two-column matrix of panels. The left column shows roll angle, normalized by the daytime SHOL value for roll, and the right column shows FDVA, normalized by the daytime SHOL for FDVA. The top row shows day operations, and the bottom row shows night operations. The curves shown in each panel are Rayleigh distribution probability of exceedence, POE. The POE curves were calculated from the standard deviation for each motion, averaged over the test point cases from which the data points were obtained. The scales for all axes are from 0 to 1; with POE on vertical axes, and normalized ship motions on horizontal axes.

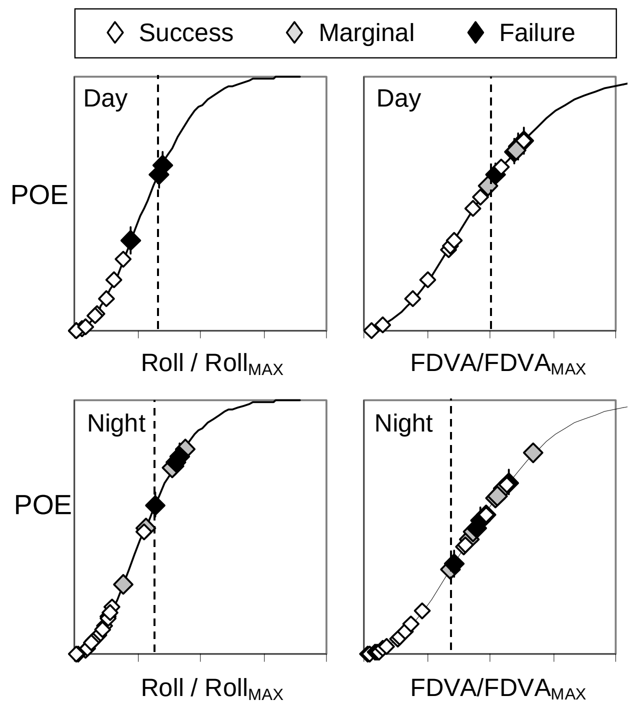

Figure 4: Real time limits (dashed lines), for roll angle in left hand panels, FDVA in right panels; daytime in top panels, and night on bottom panels

Data points from thirty-six test point cases (18 day, 18 night) are plotted on the POE curves, for the helicopter at low hover, while attempting to land. The remaining twenty test point cases had relatively low ship motions.

The data symbols define the result of each landing attempt: open symbols show success, grey-filled symbols show a 'marginal' condition (+/- 1 m altitude-keeping), and solid symbols show failure, where either the pilot or shipboard Landing Safety Officer initiated a wave-off, after which the helicopter returned to high hover. In some cases, marginal data points were followed by a successful landing, and in others, they were followed by a wave-off. In all cases, marginal and failure events are associated with peaks in ship motion, within approximately two seconds.

Only one failure event is plotted to the left of a limit line; this is for roll angle, in daytime (top, left panel). This is the only event during the flight deck trials where a large amplitude motion in roll angle *towards* the relative wind direction caused (or was directly associated with) a wave-off. This is in direct conflict with the common assumption, which is used here, that limit values are symmetric with respect to motion axes. For roll, this is a port/starboard symmetry; for FVDA, it is up/down symmetry. This is a reminder that the almost universal assumption of symmetry for both ship motion and for an activity's tolerance to ship motion, is often not appropriate.

Comparison of day and night data shows that the real time limit value for roll angle is unchanged, and that for FDVA is reduced. In practice, SHOLs are reduced at night, to compensate for reduced visual cueing. The similarity between day and night real time limits for roll suggests that the relationships between ship motions, visibility, pilot cueing, and performance should be investigated in detail.

There were no occasions, day or night, when a successful landing was performed when ship roll exceeded the limit shown in Figure 4. Conversely, there were occasions, in both day and night, when the helicopter did successfully land when FDVA exceeded the limits; however, these landings were always associated with high levels of pilot collective input, and high amplitude transients in engine torque. Thus, it is apparent that the pilots were consistently able to stay away from the flight deck during large amplitude roll motions, but not during large amplitude FDVA.

Large pitch angles were encountered during the flight tests, but they were only associated with marginal and failure events when they were accompanied by high FDVA, or some other limiting event, such as heavy spray. On one occasion, pilot comments indicated that heavy spray was a major problem, but this test case was assessed as unsafe, and was not flown (i.e. the helicopter stayed on the flight deck).

5 Quiescent Periods in Real Time

In general, a quiescent period is any interval of time when all ship motions are within limits for performing a particular activity. This does not imply that a quiescent period will be long enough to accomplish the activity.

It is simple to define when the deck is 'out of limits', but it is not so simple to define when it is back, 'in limits'. If only the motion amplitude is considered, the 'state' of the deck can oscillate between quiescent and not-quiescent, as the periodic ship motions pass through zero, from one large motion peak, and towards another. In order to address this problem, a two-part definition is used: (i) the state is not quiescent when at least one limit is exceeded; and, (ii) in order to change state from not-quiescent to quiescent, each motion which has exceeded its limit, must experience a subsequent motion peak below its limit.

In practice, it is prudent to apply a threshold on the second condition, so that the state is not considered quiescent when the 'next' peak is only slightly lower than the limit. In the following example, a threshold of 0.80 is used, so that:

1. the state is not quiescent when at least one limit is exceeded; and,

2. in order to change state from not-quiescent to quiescent, each motion which has exceeded its limit must experience a subsequent motion peak below 0.80 of its limit.

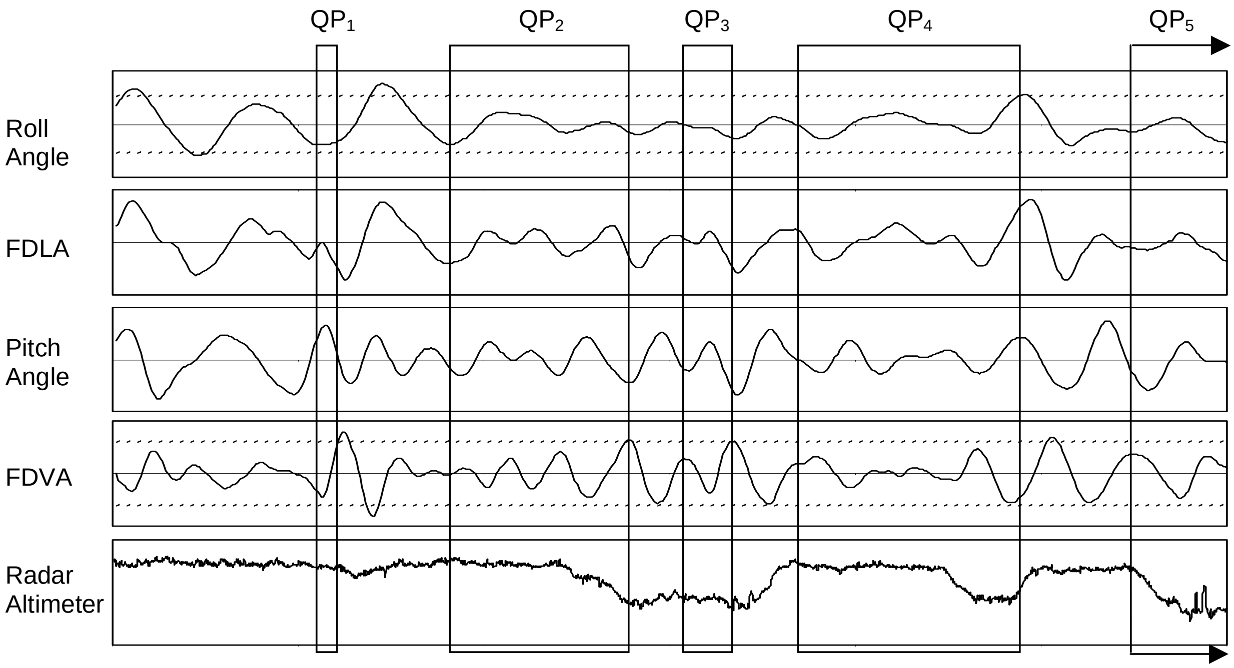

Figure 5: Quiescent periods for motions from Figure 1 (case A_D); the deck is quiescent within the rectangles.

These quiescent period concepts are illustrated in Figure 5, which shows the ship motion and radar altimeter data from test point case A_D, shown previously in Figures 1, 2 and 3. The horizontal, dashed lines show limit values for roll angle and FDVA.

In Figure 5, the deck is quiescent within each rectangle, and not quiescent outside of these regions. Five quiescent periods (QP) are shown, QP_1 through QP_5. The last quiescent period, QP_5, continues past the end of the test point. As evident from the radar altimeter data, the end of QP_1 precedes a marginal altitude-keeping event at high hover, the end of QP_2 precedes a marginal event at low hover, the end of QP_3 precedes a wave-off due to vertical motion, the end of QP_4 precedes a wave-off due to lateral motion, and the helicopter lands during QP_5. The durations of the first four quiescent periods are, respectively; 2.6, 19.0, 4.8, and 24.2 seconds.

The sequence of high-amplitude FDVA peaks between the ends of QP_2 and QP_3 is a recurring pattern. When this type of sequence occurs at low hover, the first peak exceeding the limit is often tolerated, but the second peak exceeding the limit usually precedes a wave-off. This accounts for most of the daytime marginal points for FDVA, in Figure 4.

As suggested by the consistently high correlation shown earlier between roll angle and FDLA, the relative trends for these two parameters with respect to the start and end of quiescent periods, are virtually identical. This is not the case for pitch angle and FDVA. For example, the large pitch angle amplitudes at the beginning of this time series (the left edge of the figure), are not reflected in FDVA, nor in radar altimeter data. Note that, this lack of criticality of pitch angle amplitude for helicopter landings does not mean that pitch angular motion is not important. On the contrary, pitch *angular acceleration* is critical, since it is the primary contribution to FDVA.

6. Simulation and Operator Guidance

The two-parameter criteria set used to define real time limit values, and to illustrate concepts associated with quiescence, may be adequate for design and analysis studies, but is not sufficient for time-domain modeling and simulation, nor for operator guidance at sea. Any and all ship motions, and related phenomena such as heavy spray and green-water on deck, have the potential to limit the performance of motion-sensitive tasks. All available information should be used, but the main difficulty lies in obtaining suitable performance data for defining real time limit values, or in measuring the correct quantity (as for relative velocity at touchdown [1]).

7. Concluding Remarks

The concept of real time ship motion criteria has been introduced, and described with respect to traditional SHOLs.

Roll angle amplitude and FDVA are critical motion parameters for helicopter landings.

Real time roll angle and FDVA limits have been developed for helicopters landing on monohull frigates, by comparing motions with the success and failure of operational performance. Real time FDLA limits can be developed following the same approach.

Pitch angle amplitude is not a critical parameter for helicopter landings, but pitch angular acceleration is critical.

Pitch angle amplitude limits should be developed to ensure blade rotor clearance for the hovering helicopter.

Defining additional real time limit values for time-domain simulation and operator guidance at sea will require suitable operational performance data.

A two-part definition has been introduced for the state of quiescence (i) the state is not quiescent when at least one limit is exceeded; and, (ii) in order to change state from not-quiescent to quiescent, each motion which has exceeded its limit, must experience a subsequent motion peak below 0.80 of its limit.

Recommendations for future work have been made to:

- develop a better understanding of the combined effects of ship motions, aerodynamics and control parameters on pilot control input;
- investigate the relationships between ship motions, visibility and pilot visual cueing; and,
- quantify asymmetric ship motion criteria.

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