Ship Flight Deck Motion Parameters for Ensuring Safety of Helicopter Operation

Dr. A. R. Tadros, Director of ASIST Engineering
Dr. R. G. Langlois, Senior Dynamicist
Mr. Michael LaRosa, Aerospace Engineering Analyst

Indal Technologies Inc., Mississauga, Ontario, Canada

February 7, 2003

Abstract

The importance of safely operating helicopters from moving ships in potentially severe sea conditions is widely recognized. Critical applications exist ranging from medical evacuation of personnel from civilian fishing vessels, cruise ships, and freighters to over-the-horizon reconnaissance and antisubmarine warfare for military vessels. To satisfy these diverse requirements, helicopters must be operable in high sea conditions in which the flight deck motions become extremely severe. The limits for embarked aircraft operation historically have been specified in terms of sea state (essentially a probabilistic description of the amplitude and frequency distribution of waves in a seaway) and angular displacements of the ship (typically roll and pitch angles). Similarly, acceptable landing windows during quiescent periods have been defined by limits on ship angular displacements. For example, operating limits currently may be stated as, "…limited to sea state 5 with landings occurring when ship roll is less than 8 degrees and ship pitch is less than 3 degrees."

The shortcomings of this approach for defining operating limits quickly become apparent. First, the severity of aircraft loading and therefore the risks associated with flight deck operations are not only related to angular displacements but rather accelerations at the flight deck. Second, deck conditions are influenced by numerous factors including hull design, flight deck location, ship operating conditions (including heading, speed, and loading), and environmental conditions. Appropriate motion limits must be independent of specific combinations of these factors and be physically measurable

in service. This requirement is heightened by the ever-increasing need to operate in severe/extreme sea states as well as the necessity for interoperability between ships. Helicopter launch, recovery, and on-deck securing and handling (if applicable) limits should be available that are aircraft specific but independent of the ship. For example, an aircraft approaching a ship should immediately be able to assess whether the current flight deck conditions are within the aircraft's safe operating limits. The current approach used for identifying aircraft- and ship-specific limits can result in unsafe operations.

Recognizing the limitations of conventionally-established parameters, and based on extensive experience analyzing the dynamic interface that exists between marine aircraft and ships, Indal Technologies Inc. (ITI), a developer of marine aircraft handling systems, has developed and applied the concept of equivalent acceleration for defining appropriate motion limits for the case where helicopter rotors are not turning and the expanded concept of T-factor for defining appropriate limits when the rotors are turning. These concepts combine factors affecting flight deck conditions into meaningful parameters. Analysis and experience have shown that these concepts are very effective for quantifying the severity of flight deck motions and for providing useful guidance to helicopter and ship operators, thereby maximizing the safety of helicopter operations.

This Lloyd's Register Safer Ship Award application presents the concept of equivalent acceleration and T-factor. It shows that loss of helicopter on-deck stability resulting in sliding, slewing, or toppling is directly related to these parameters. It also shows that ship operating conditions that produce high values of the conventional roll and pitch measures of the severity of flight deck conditions are very different from those indicated by the appropriate equivalent-acceleration-based parameters and the T-factor. Equivalent acceleration is discussed in the context of military and civilian examples, such as the recent incident involving a Super Puma helicopter on the West Navion drilling ship where the helicopter rolled over due to unexpected ship motion causing major damage to the aircraft and injury to the co-pilot. Examples such as this demonstrate that incorporating physically-meaningful equivalent-acceleration-based parameters into routine flight deck operations can significantly enhance safety. Failure to adopt appropriate parameters exposes flight and deck crew to potentially serious or life-threatening injuries as the result of unexpected aircraft motion. The potential consequences associated with the loss of aircraft and damage to ships are also significant.

1 Introduction

The capabilities of naval operations are substantially increased with the utilization of rotorcraft on board ships. Anti-submarine warfare and search and rescue capabilities are substantially improved by the presence of helicopters onboard. To realize such improved capabilities, helicopter operations must be possible in a wide range of environmental conditions from calm seas to severe weather conditions. Figure 1 shows a typical frigate-sized ship operating in moderate seas.

Figure 1: Typical frigate-sized ship

The approach for defining limits for safe embarked helicopter operations were, in the past, based on roll and pitch angles as well as the severity of the sea, identified by the sea state number. Even today, the naval community is still using this approach. The imposed limits, based on roll and pitch, vary depending upon helicopter; operational phase, such as launch, landing, and deck handling; and the availability and performance of a helicopter securing and/or handling system. For a typical frigate-sized ship and a moderate weight helicopter operating with a helicopter securing system, typical limitations during the on-deck evolution may be stated as follows:

- launch and recovery: limited to periods of quiescence having roll angles less than 8 degrees and pitch angles less than 3 degrees;
- straightening: limited to sea state 5 with roll and pitch angles limited to 20 degrees and 4 degrees respectively;
- traversing: limited to sea state 5 with roll and pitch angles limited to 25 degrees and 6 degrees respectively; and
- helicopter lashed beyond 31 degrees roll and 9 degrees pitch.

These limitations are typically developed so that an embarked helicopter does not slide, slew, topple, or exceed structural limits. Using roll and pitch angles as a means of specifying ship limits provides a quick and somewhat reasonable indication of the severity of ship motion since ship personnel can visually identify severe roll and pitch angles. However, flight deck conditions, and correspondingly the aircraft loading, are also influenced by accelerations. The severity of flight deck motion, based on accelerations, is difficult to discern quantitatively by on-board personnel without the aid of instrumentation.

Deck conditions are influenced by numerous factors that can generally be grouped into three categories:

- ship geometry;
- environmental conditions; and
- control inputs.

Ship geometry encompasses ship factors such as the ship displacement, underwater hull and appendage design, flight deck location, and specific loading conditions. Environmental conditions include such factors as significant wave height, modal period, wave spectrum, and wind conditions. Control inputs such as ship heading (relative to the principal wave direction), ship speed, steering, and the status of active/passive stabilization play a vital role in identifying the severity of deck conditions. Appropriate motion limits must therefore be independent of specific combinations of these factors and be physically measurable in service.

The currently usual approach used for determining ship motion limits for helicopter-embarked operations, by using only roll and pitch, typically apply to a single combination of helicopter and ship. However, as both defence and commercial funding sources are being reduced, shifting their emphasis to threats of national security, there has been an increasing trend to maximize the capabilities of both helicopters and ships. This requirement is being accomplished by allowing for interoperability of various helicopters and ships. Several navies around the globe have been steadily increasing the capabilities of their helicopters by allowing for embarked operations on several different types of ships. This trend will increase the potential for helicopter incidents onboard causing personal injuries and both helicopter and ship damage if the traditional method for evaluating the deck conditions continues to be used. Also, as navies tend to maximize the interoperability requirements, as well as allowing for helicopter operations to occur in ever-increasing sea conditions, physically-meaningful ship motion parameters are required that are independent of the ship. For example, by knowing the aircraft's safe operating limits, an approaching aircraft can quickly assess whether the flight deck conditions are within the predetermined aircraft limits. This cannot be strictly accomplished using the current angular-displacement-based limits.

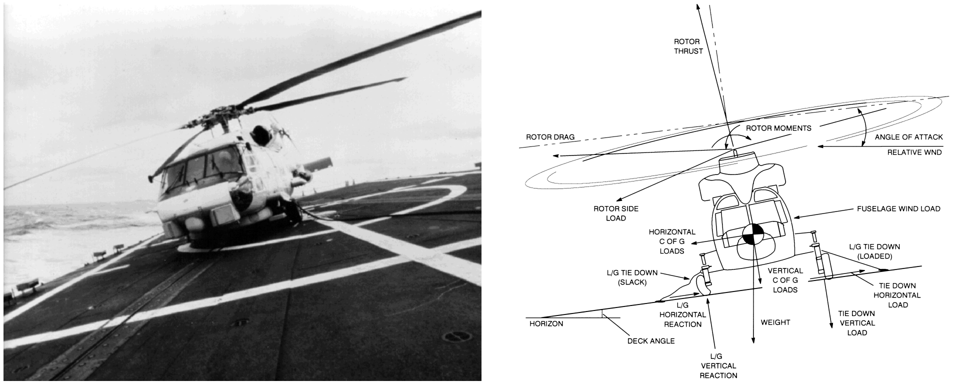

Figure 2: Typical embarked helicopter (left) and external loading (right)

A typical shipboard securing condition on a frigate-sized ship as well as the forces acting on an embarked helicopter are shown in Figure 2.

To allow for such helicopter/ship interoperability to occur safely, operational limits must be established, using a simple measure of ship motion severity that includes the influence of all relevant factors, that is easily quantifiable. Continued use of angular displacement measures jeopardizes the safety of personnel, leads to increased risk of loss or damage to equipment including aircraft and ships, limits potential operability, and requires that safety-critical decisions be made blindly without accurate quantitative assessment of the severity of deck conditions. ITI's experience with analyzing the ship/helicopter dynamic interface has led to the development of a more appropriate set of parameters that better identify conditions of severe ship motion. These parameters are based on equivalent acceleration for the case where the helicopter rotors are not turning and the expanded concept of T-factor for defining appropriate limits when the rotors are turning. These two concepts have been shown to provide a very effective way of quantifying the severity of ship motion into meaningful parameters thus allowing for improvements of existing helicopter/ship operations and at the same time maximizing safety.

2 Conventional Parameters

When operating in severe conditions, that may approach the limits of safe helicopter operations, it is critically important to be able to quantify deck motion severity relative to aircraft and pilot capabilities during launch, recovery, and aircraft handling while on the deck. Historically, for a particular combination of helicopter and ship, acceptable deck conditions have been specified using primarily the ship roll angle and ship pitch angle.

Detailed mathematical modelling and transient computer-based dynamic analysis of the behaviour of embarked helicopters in response to ship motion has been used by ITI to comprehensively explore the securing requirements of helicopters while on-board [1, 2, 3, 4, 5]. Analysis results consistently show very poor correlation between the severity of deck angular displacements and corresponding destabilizing forces acting on the helicopter and therefore the securing requirements. To support analysis presented in this document, a sample operational scenario is considered where a moderately-sized helicopter is embarked on a typical frigate operating in upper sea state 6 conditions at a moderate speed and with a unidirectional sea approaching from 60 degrees off the bow. The helicopter is assumed to be secured to the ship by a single-point passive securing system such as the ITI Aircraft/Ship Integrated Secure and Traverse (ASIST) system[6] illustrated in Figure 3. Analysis confirms that the helicopter/ship system satisfies a strict securing definition that ensures that the helicopter neither slews, slides, nor topples. However, the analysis also shows very weak correlation between the conventional roll and pitch measures and single point securing forces. The correlation coefficients between the magnitudes of roll and pitch angles and the horizontal and vertical components of the single-point securing forces are presented in Table 1. The low correlation coefficients indicate poor correlation thereby motivating the need to establish better measures of deck motion severity as it affects helicopter operation.

Figure 3: ASIST system RSD

The results discussed in this section reflect in-service experience where unexpected helicopter slewing and sliding occur even though the deck conditions are considered to be within acceptable limits based on angular displacements.

In one incident, after the final flight of the day, an aircraft was prepared for movement into the hangar. It was then determined that the best ship

Table 1: Correlation between roll and pitch angular displacements and securing force components for a typical severe helicopter securing condition

	horizontal force	vertical force
roll angle	0.53	0.38
pitch angle	0.31	0.31

heading available produced occasional slow 10 degree ship roll amplitudes with a frequency of 10 to 15 seconds. A 12-person movement team was assembled for a progressive chains move and the aircraft was moved forward into the hangar in approximately 4 foot increments as the position of the deck padeyes (securing points) allowed. As the final chains were being attached, the ship rolled to port and the aircraft tail swung, allowing a blade flap to impact the port track of the hangar door.

In this case, damage was limited to the trailing edge flap and no personnel were injured. However, it was considered a fortunate coincidence that it was the flap that touched the hangar door track and not a main rotor blade. A 12,000 pound aircraft sliding inside a relatively small hangar provided great potential for major aircraft damage as well as serious injury to personnel trying to secure it. Use of appropriate parameters that accurately reflect the securing requirements could have identified the potential hazard.

3 Equivalent Acceleration

3.1 Concept and Derivation

Ship motions are usually evaluated at the ship origin which is typically the intersection of a vertical line through the centre of mass of the ship and the undisturbed free sea surface. Refer to the ship and aircraft coordinate systems identified in Figure 4. While ship displacements may provide an indication of some aspect of the severity of the ship motion, it is the total linear acceleration at the flight deck that directly affects helicopter securing. Therefore, acceleration-based parameters that consider the effect of the instantaneous forces acting on the helicopter, called ‘equivalent accelerations’ are derived in this section and include:

- horizontal equivalent acceleration;
- vertical equivalent acceleration; and
- equivalent acceleration ratio.

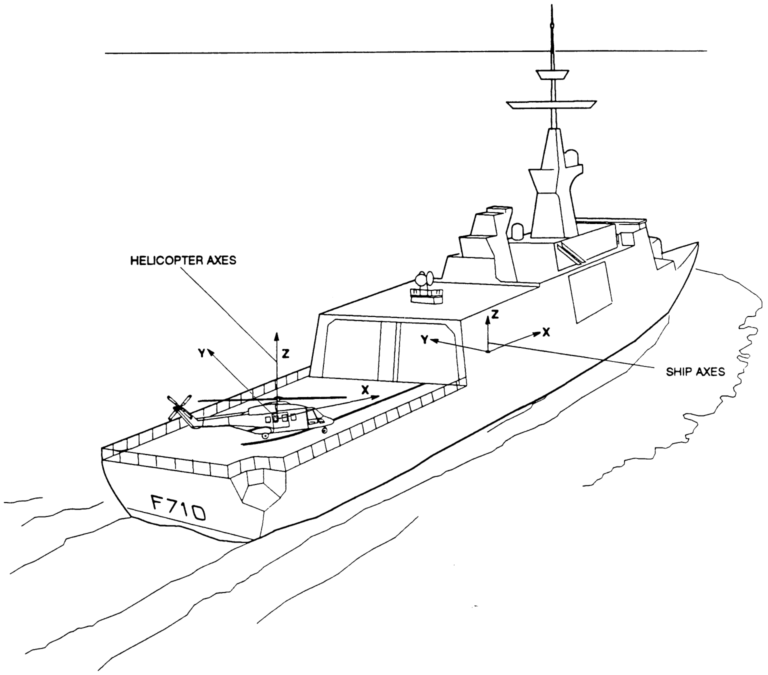

Figure 4: Primary ship and helicopter coordinate systems

Increased horizontal equivalent acceleration indicates increased horizontal loading on the aircraft in the plane of the deck. Reduced vertical equivalent acceleration indicates reduced contact force between the aircraft and the deck, and correspondingly reduced potential for developing frictional force to oppose aircraft sliding. Consequently, the ratio of horizontal equivalent acceleration to vertical equivalent acceleration generally quantifies the tendency of a conventional unsecured aircraft to slide as the result of ship motion when the ratio exceeds the deck coefficient of friction.

The concept of equivalent acceleration, in its simplified planar form, is illustrated schematically in Figure 5. The total acceleration at the flight deck is comprised of the linear acceleration resulting from ship kinematics and from the instantaneous component of the acceleration due to gravity. Equivalent acceleration effectively combines the effects of both the deck inertial acceleration and angular displacement of the ship as it affects the aircraft/ship dynamic interface.

Derivation of equivalent acceleration is based on the free-body diagram of an unsecured object sitting on the deck as illustrated in Figure 6.

First the kinematic acceleration of the point of interest p on the ship is determined. The relationship governing the absolute acceleration of a point p attached to a rigid ship is given by

$$\vec{a}_p = \vec{a}_o + \vec{a}_{p/o} = \vec{a}_o + \vec{\omega} \times \vec{\omega} \times \vec{r}_{p/o} + \vec{\alpha} \times \vec{r}_{p/o} \tag{1}$$

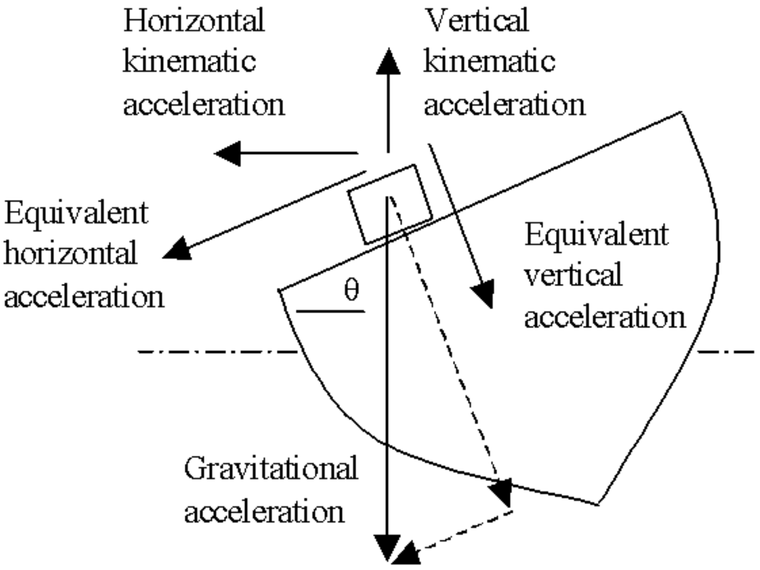

Figure 5: Schematic planar representation of the concept of equivalent acceleration

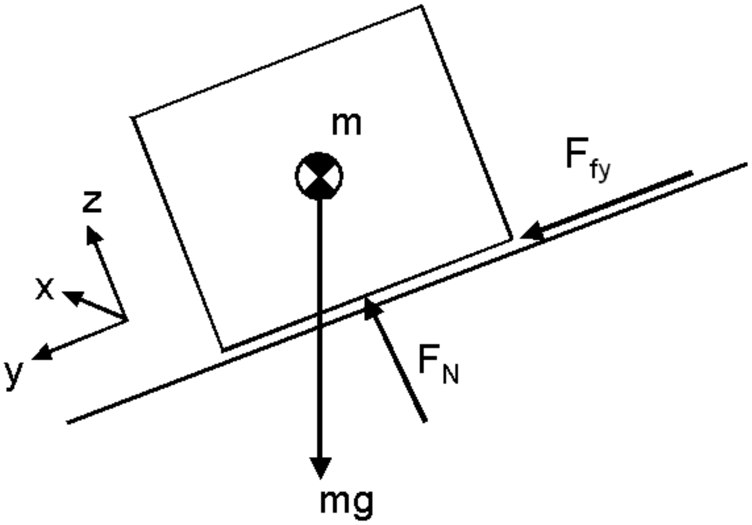

Figure 6: Free-body diagram of an unsecured object sitting on the deck

where

$\vec{a}_p$ is the kinematic acceleration of the point at which the equivalent acceleration is required, expressed in the ship-fixed coordinate system;

$\vec{a}_o$ is the kinematic acceleration of the reference point (often the ship centre of mass or centre of rotation), expressed in the ship-fixed coordinate system;

$\vec{\omega}$ is the angular velocity vector of the ship, expressed in the ship-fixed coordinate system;

$\vec{\alpha}$ is the angular acceleration vector of the ship expressed in ship-fixed coordinates and can be obtained by numerically differentiating the ship angular velocity vector $\vec{\omega}$; and

$\vec{r}_{p/o}$ is the relative position vector directed from the reference point where the total linear kinematic acceleration vector was measured expressed in the ship-fixed coordinate system.

Using the known acceleration, Newton's law is applied to the free body in the form

$$\sum \vec{F} = m\vec{a} \tag{2}$$

Evaluating the left and right hand sides of Equation 2 in three dimensions yields

$$\left\{ \begin{array}{c} F_{fx} \\ F_{fy} \\ F_N \end{array} \right\} + [T_{spsh}] \left\{ \begin{array}{c} 0 \\ 0 \\ -mg \end{array} \right\} = m \left\{ \begin{array}{c} a_x \\ a_y \\ a_z \end{array} \right\} \tag{3}$$

where F_{fx}, F_{fy}, and F_N are the longitudinal, lateral, and vertical components of the directly applied external forces; $[T_{spsh}]$ is the rotational transformation matrix from the inertial frame to the ship frame; m is the mass of the body; g is the acceleration due to gravity; and the acceleration vector on the right-hand side is the vector of kinematic accelerations evaluated for the particular point p on the ship. The rotational transformation matrix $[T_{spsh}]$ can be defined using any convenient set of parameters. In this case the XYZ set of Euler angles $(\theta_x, \theta_y, \theta_z)$ rotating the inertial coordinate system into the body-fixed coordinate system is used[1]. A vector expressed in the inertial space frame $\vec{R}_{sp}$ can be transformed to an equivalent vector expressed in the ship frame $\vec{R}_{sh}$ using the rotational transformation matrix from the space coordinate system to the ship coordinate system defined by the XYZ Euler angles

$$\vec{R}_{sh} = [T_{spsh}]\,\vec{R}_{sp} \tag{4}$$

---

[1] This set of angles is also often referred to as the set of Bryant angles.

where

$$[T_{spsh}] = \begin{bmatrix} \mathrm{c}\,\theta_y\,\mathrm{c}\,\theta_z & \mathrm{c}\,\theta_x\,\mathrm{s}\,\theta_z + \mathrm{s}\,\theta_x\,\mathrm{s}\,\theta_y\,\mathrm{c}\,\theta_z & \mathrm{s}\,\theta_x\,\mathrm{s}\,\theta_z - \mathrm{c}\,\theta_x\,\mathrm{s}\,\theta_y\,\mathrm{c}\,\theta_z \\ -\mathrm{c}\,\theta_y\,\mathrm{s}\,\theta_z & \mathrm{c}\,\theta_x\,\mathrm{c}\,\theta_z - \mathrm{s}\,\theta_x\,\mathrm{s}\,\theta_y\,\mathrm{s}\,\theta_z & \mathrm{s}\,\theta_x\,\mathrm{c}\,\theta_z + \mathrm{c}\,\theta_x\,\mathrm{s}\,\theta_y\,\mathrm{s}\,\theta_z \\ \mathrm{s}\,\theta_y & -\mathrm{s}\,\theta_x\,\mathrm{c}\,\theta_y & \mathrm{c}\,\theta_x\,\mathrm{c}\,\theta_y \end{bmatrix} \tag{5}$$

and c and s are abbreviations for the trigonometric cos and sin functions respectively.

Equation 3 can be solved for the ratio of the reaction forces to the mass such that

$$\frac{1}{m}\begin{Bmatrix} F_{fx} \\ F_{fy} \\ F_N \end{Bmatrix} = [T_{spsh}]\begin{Bmatrix} 0 \\ 0 \\ g \end{Bmatrix} + \begin{Bmatrix} a_x \\ a_y \\ a_z \end{Bmatrix} \tag{6}$$

The left-hand side has dimensions of acceleration and is defined as the equivalent acceleration vector such that

$$\begin{Bmatrix} a_{eq\ x} \\ a_{eq\ y} \\ a_{eq\ z} \end{Bmatrix} = [T_{spsh}]\begin{Bmatrix} 0 \\ 0 \\ g \end{Bmatrix} + \begin{Bmatrix} a_x \\ a_y \\ a_z \end{Bmatrix} \tag{7}$$

thereby removing the dependency on mass. Individual components of the equivalent acceleration vector result directly from Equation 7 and are called the longitudinal equivalent acceleration ($a_{eq\ x}$), lateral equivalent acceleration ($a_{eq\ y}$), and vertical equivalent acceleration ($a_{eq\ z}$). Components can further be combined to produce the horizontal equivalent acceleration $a_{eq\ h}$

$$a_{eq\ h} = \sqrt{a_{eq\ x}^2 + a_{eq\ y}^2} \tag{8}$$

and the equivalent acceleration ratio $a_{eq\ ratio}$

$$a_{eq\ ratio} = \frac{a_{eq\ h}}{a_{eq\ v}} \tag{9}$$

Equation 6 highlights how equivalent acceleration parameters relate to forces acting on an unsecured object on the ship deck. Equivalent acceleration components when multiplied by the body mass yield corresponding applied force components.

In terms of practical implementation of this method, it should be noted that all of the parameters on the right hand side of Equation 1 can be obtained directly or indirectly from instrumentation readily available on the ship. Alternatively, a convenient option is to locate a triaxial accelerometer on the ship in the vicinity of the flight deck to measure the kinematic equivalent acceleration directly.

Equivalent acceleration parameters have been applied by ITI for identifying the severity of flight deck conditions. Experience suggests that they provide a valuable measure and often predict conditions that would not be expected to be severe if one erroneously considered only angular displacement parameters. Consider the two peak motion parameters for a typical frigate operating in severe sea conditions presented in Figure 7. The upper plot of roll angle suggests that the most severe conditions occur at headings of ±120 degrees relative to the principal wave direction. The lower plot presents the peak equivalent acceleration ratio. The peak values occur at headings of ±45 degrees. Clearly, in this example, erroneous conclusions about the severity of ship motion at headings of ±120 degrees would be drawn based on the traditional roll measure of flight deck motion while the actual most severe conditions occur at headings of ±45 degrees.

A topic related to shipboard helicopter securing is that of motion induced interruptions (MIIs) where the focus is on estimating the frequency with which humans would be interrupted by the need to change stance or otherwise stabilize themselves to prevent sliding or tipping as the result of ship motion. Graham et al [7] proposed a set of linear force estimators that are linearized parameters suitable for predicting MIIs. In the current work, it is recognized that helicopter securing is required for operation in all but the most benign ship motion conditions. In this case, the flight deck motion parameters of interest are important for quantifying the severity of securing conditions and establishing appropriate operating limits rather than calculating the probabilities of sliding and toppling. Further, small angle approximations and ignored second-order effects associated with linear force estimators may not be appropriate in the extreme ship motion conditions where the peak single amplitude roll angle can approach values greater than 30 degrees and the pitch angle can similarly exceed the conventional limits accepted for small angle approximations. In the helicopter/ship application, it is therefore most appropriate to work with the fully nonlinear equivalent acceleration parameters.

3.2 T-Factor

The concept of equivalent acceleration developed in Section 3.1 is strictly applicable for the case where the aircraft rotors are not turning and therefore not developing lift. Although the fuselage drag forces are relatively small when compared with the gravitational forces, the main rotor induced forces, when the rotors are turning, are significant and therefore can have a profound effect on the contact forces between an aircraft and ship deck, and correspondingly on the ability of the aircraft tires to develop frictional forces to oppose aircraft sliding.

To investigate appropriate modifications to the definition of equivalent acceleration to account for turning rotors, a series of wind tunnel experi-

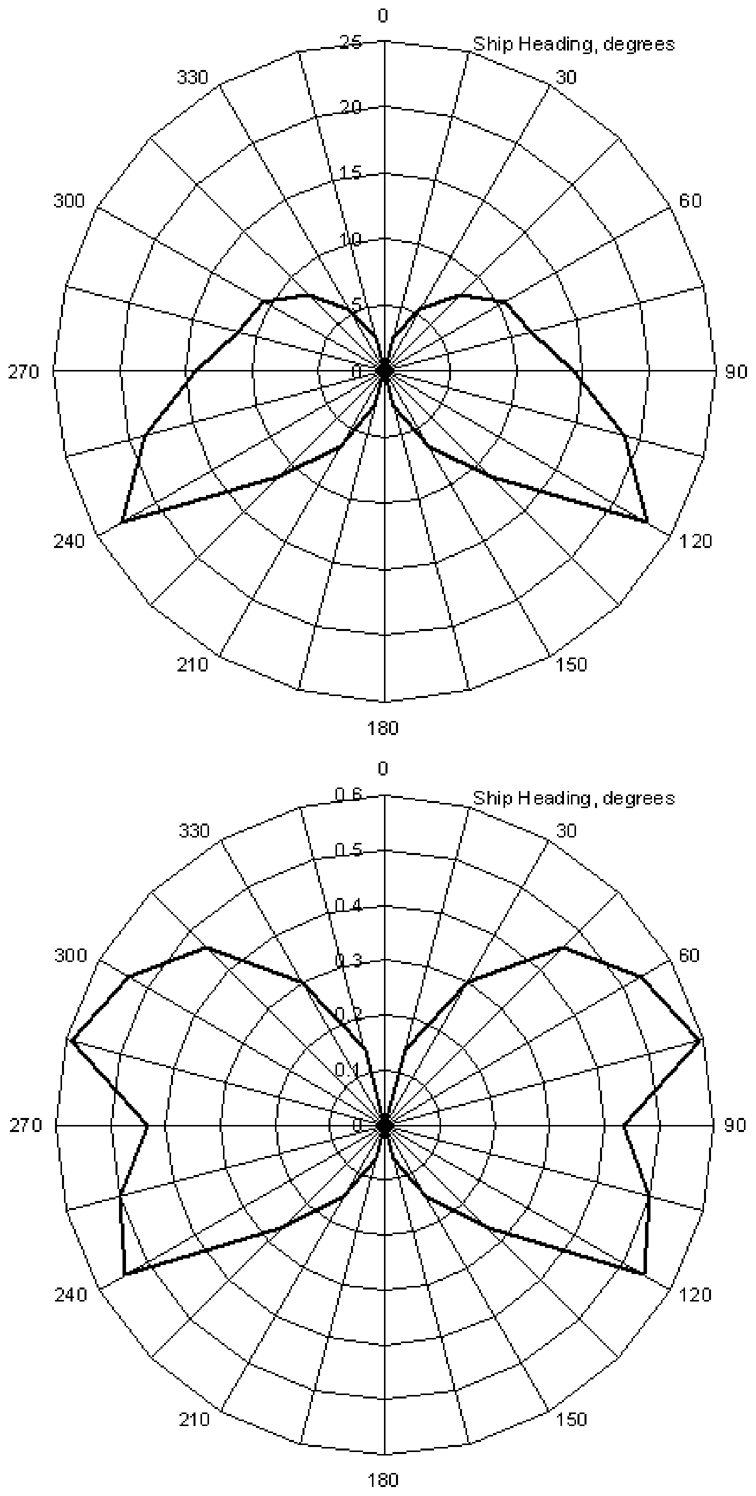

Figure 7: Typical frigate peak roll angle in degrees (upper) and peak equivalent acceleration ratio (lower) for operation in severe sea conditions as a function of ship heading and ship speed

ments were conducted jointly by ITI and the National Research Council of Canada[8]. For these experiments, a model was constructed to represent the cross-section of a typical frigate at the flight deck and a typical rotor. The model was oriented in the wind tunnel such that scaled wind speeds could be generated approaching the frigate from the starboard beam direction[2]. Qualitative data regarding the air flow over the flight deck and quantitative data reflecting induced aircraft loading was gathered for a range of wind speeds. Figure 8 indicates the flow field around the rotor. It is clear that the angle of attack formed between the rotor disk and the dominant local wind results from both the roll angle of the ship and the local distortion in the ambient air flow due to the presence of the ship. Though the rotor collective may be set at its minimum value (often close to zero), the angle of attack induces lift as well as other components of rotor force and moment. From the perspective of equivalent acceleration parameters, the lift component is the most important. In fact, for a 30 knot beam wind, it was found that the induced lift could exceed 25% of the aircraft weight. Figure 9 shows how the nondimensionalized induced lift varies with the ship roll angle that approximates the main rotor angle of attack. The traces in Figure 9 show both simulated and experimentally-measured values. The experimental data increases up to a ship roll angle of approximately 20 degrees beyond which the induced lift no longer increases and in fact decreases somewhat.

The experimental data from the series of experiments were used to develop the following empirical relationship for the thrust ratio a_t that is formed by the ratio of the induced lift to the aircraft mass for ship roll angles up to 20 degrees

$$a_t = \frac{F_L}{m} = \frac{G}{4}\,\frac{|\theta_{roll}|}{20} \tag{10}$$

where F_L is the induced lift force, m is the aircraft mass, θ_{roll} is the ship roll angle measured in degrees, and the thrust ratio has units of G. For ship roll angles in excess of 20 degrees, the thrust ratio was conservatively considered to remain constant with a magnitude of $\frac{G}{4}$. This relationship is based on an apparent beam wind speed of 30 knots - typical of upper sea state five conditions on the open ocean. Equation 10 reflects linear variation of induced rotor thrust with rotor angle of attack (approximately equal to the roll angle) up to a maximum $0.25\,G$ at 20 degrees.

It is observed that positive thrust ratio corresponds to reduction of the contact force between the aircraft and deck, unlike the vertical component of equivalent acceleration that indicates increased contact force. Consequently, for the case of rotors turning, the equivalent acceleration ratio must be mod-

---

[2] Dynamic interface analysis conducted by ITI has consistently shown that the beam component of apparent wind is the most severe from the perspective of helicopter on-deck operations.

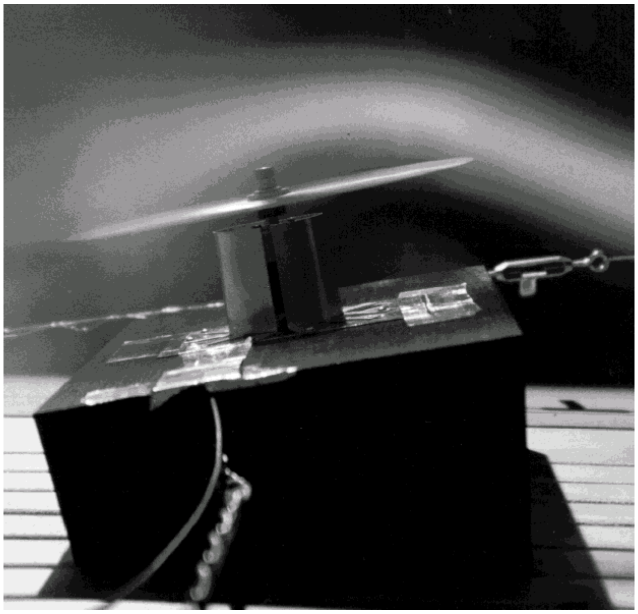

Figure 8: Wind tunnel visualization of air flow over a ship flight deck in the presence of a turning helicopter rotor.

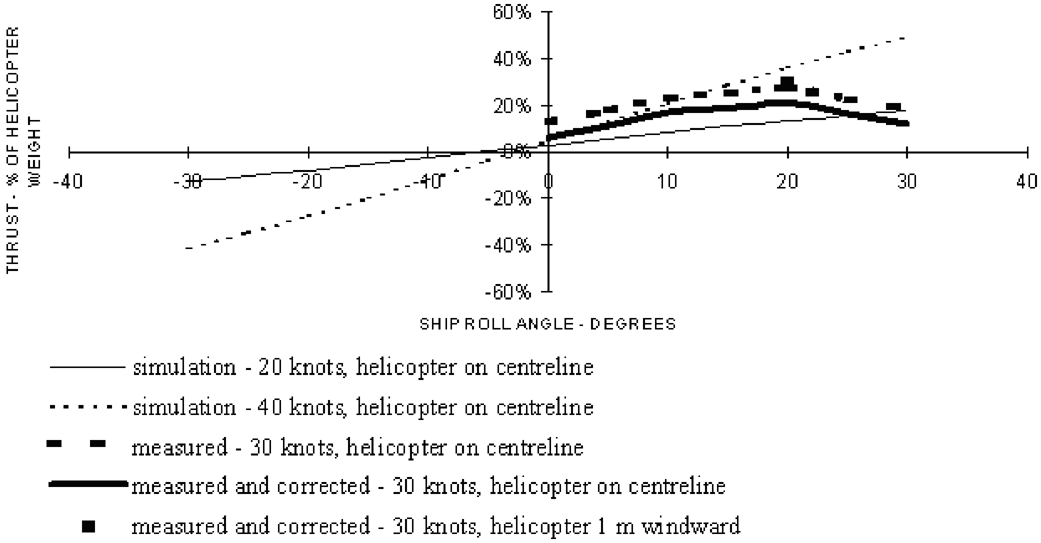

Figure 9: Variation of induced rotor lift with ship roll angle (approximately equal to the angle of attack)

ified to reflect the total vertical force ratio resulting in the following relationship

$$\mathrm{T-factor} = \frac{a_{eq\ h}}{a_{eq\ v} - a_t} \tag{11}$$

where T-factor (Tendency of an Aircraft on-Deck with Rotors On to Slide) is a new ratio that quantifies the potential for aircraft sliding.

The equivalent-acceleration-based parameters often indicate severe securing conditions for ship operating conditions that are not indicated by conventional displacement measures. By including the effect of wind, the T-Factor can provide an effective means for defining the severity of operating conditions for the case where the rotors are turning. The T-Factor can also be used as a comparative parameter for evaluating the expected relative securing requirements, stability issues related to an unsecured helicopter, landing gear reaction forces for various helicopters, and potential severity of time periods in a trace of ship motion based on consideration of helicopter securing.

The effectiveness of the T-Factor for identifying severe aircraft securing conditions is demonstrated in Figure 10. The plot shows the variation with time of the horizontal and vertical components of the single-point securing force. The frigate motion corresponding to this plot was simulated using the standard ship motion program *SMP*[9] and *ShipSim*[10]. Figure 10 also shows the variation of the T-Factor with time. While the simulation duration in this case was 30000 seconds to insure statistically meaningful results, only the 200-second segment containing the maximum securing forces is shown. The arrows on the plot indicate the peak values of the radial securing force, vertical securing force, and T-Factor. It is evident that the T-Factor successfully identifies the ship motion corresponding to the most demanding securing requirements.

4 Sample Application

It was previously shown that for a typical severe helicopter securing condition the ship roll and pitch angles did not correlate well with the vertical and horizontal securing forces. Table 2 provides the correlation coefficients between the horizontal and vertical components of equivalent acceleration, the equivalent acceleration ratio, and the T-factor to the horizontal and vertical securing force components for the same typical severe helicopter securing condition previously considered. From these results it is apparent that much better correlation is possible between the equivalent acceleration and T-factor parameters than was possible using angular displacement measures alone (refer to Table 1). The improved correlation achieved by the T-factor over the equivalent acceleration ratio is consistent with the fact that the helicopter rotors were turning in the representative case considered. This correlation

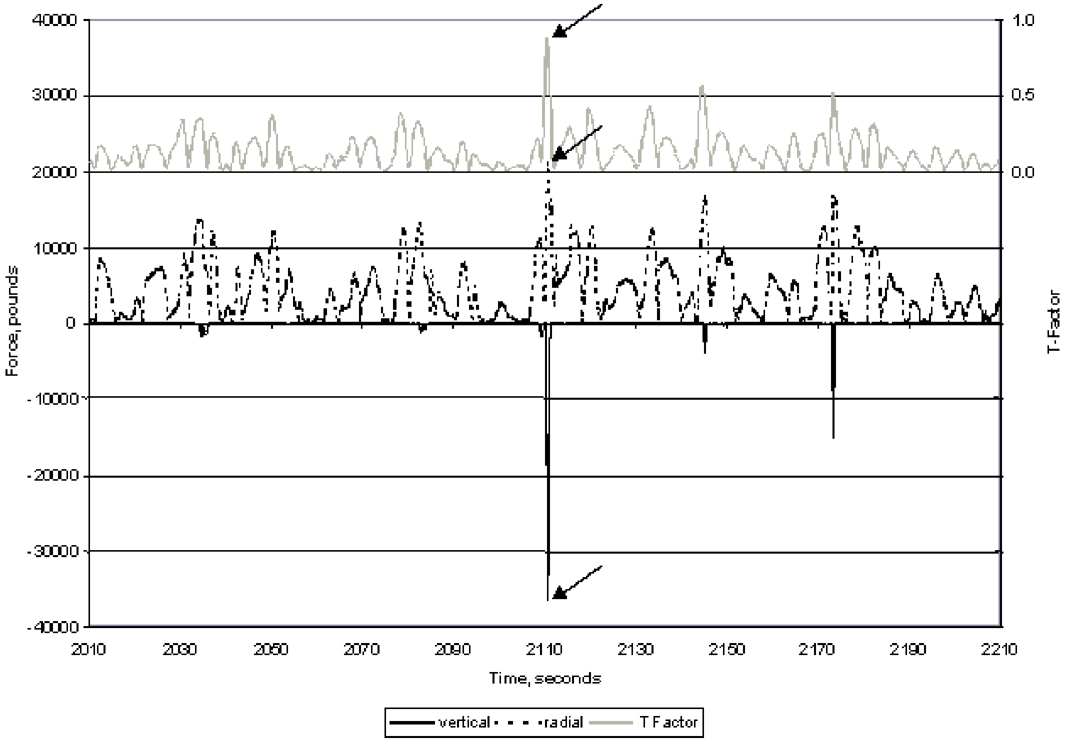

Figure 10: Variation of radial and vertical securing forces and T-Factor with time

data is visually presented and expanded to include the complete range of ship headings in this section.

Take for example the polar plots of Figures 11 and 12, which show the relationship between the securing forces of a typical moderate weight aircraft and the ship roll and pitch angles respectively for a typical frigate operating in upper sea state 6 conditions. The magnitudes of the ship roll and pitch angles are indicated by the circumferential lines labelled on the 0 degree ship heading axis, whereas the magnitude of the nondimensionalized securing loads are indicated by the circumferential lines labelled on the 180 degrees ship heading axis. Looking at Figure 11, it quickly becomes apparent that the peak roll angle, occurring in quartering seas, does not produce the most severe helicopter securing loads which occur in seas off the bow. In fact, the peak securing loads occur at relatively small ship roll angles potentially within the traditionally-used angular displacement limits. Although Figure 12 shows that the ship heading producing the peak pitch angle also has the largest value of the helicopter securing forces, the next largest pitch angle does not correspondingly produce the next largest securing force. Since large values of ship pitch typically occur in head seas, this does not effectively correlate

Table 2: Correlation between equivalent acceleration parameters and securing force components for a typical severe helicopter securing condition

	horizontal force	vertical force
horizontal equivalent acceleration	0.59	0.45
vertical equivalent acceleration	0.18	0.33
equivalent acceleration ratio	0.62	0.60
T-factor	0.64	0.65

to the large values of the helicopter securing loads which occur at different headings.

The correlation between helicopter securing forces and ship motion are better identified using equivalent acceleration parameters as shown by Figures 13 through 16. For example, Figure 13 shows that the equivalent acceleration ratio correlates well with vertical probe loads, where both the vertical securing loads and the equivalent acceleration ratio follow the same pattern. On the other hand, the horizontal securing loads are better correlated to the horizontal equivalent acceleration as shown by Figure 14. Again, both the horizontal securing loads and horizontal acceleration have the same shape. A smaller correlation exists with the minimum vertical equivalent acceleration and vertical securing loads in Figure 16. Note that for the minimum vertical equivalent acceleration plot, it is the smaller values that correlate with the high vertical securing loads (i.e. negatively correlated).

5 Widespread Applicability

The previous section showed that the use of ship roll and pitch angles alone does not predict the most severe condition as it relates to helicopter operations. However it was also shown that using equivalent acceleration parameters provides a much better indication of the induced helicopter loads and stability issues that can occur, even with relatively small magnitudes of ship angular displacements. The use of equivalent-acceleration-based parameters would provide a set of helicopter-specific parameters that can be used to characterize the flight deck without knowing details about ship conditions and operations. This is especially beneficial for allowing the increased interoperability potential of various helicopters on a single ship and capability to operate in extreme sea conditions by providing a quantitative description of the deck conditions for each phase of helicopter embarked operations such as landing, launch, and deck handling. Plots can be created and displayed identifying the ship heading and ship speed combinations that have the potential

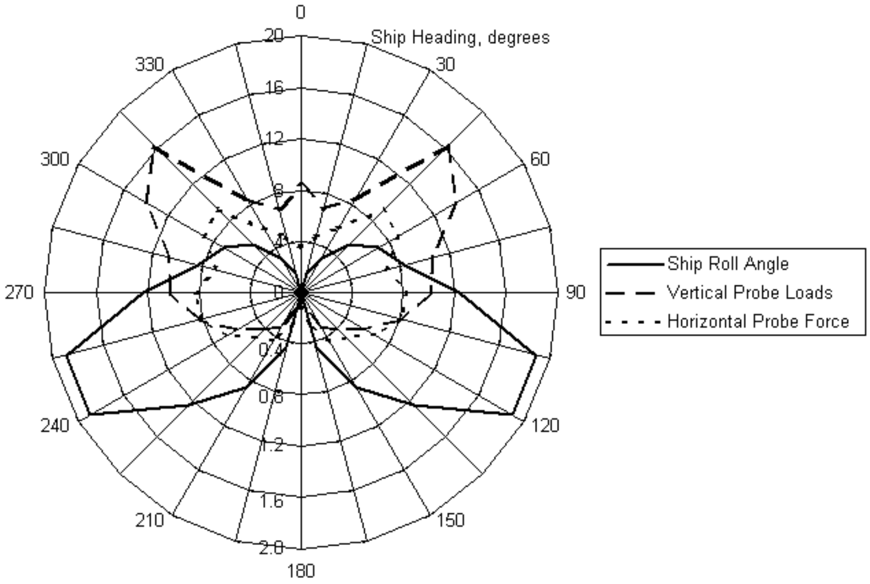

Figure 11: Relationship between ship roll angle and securing forces

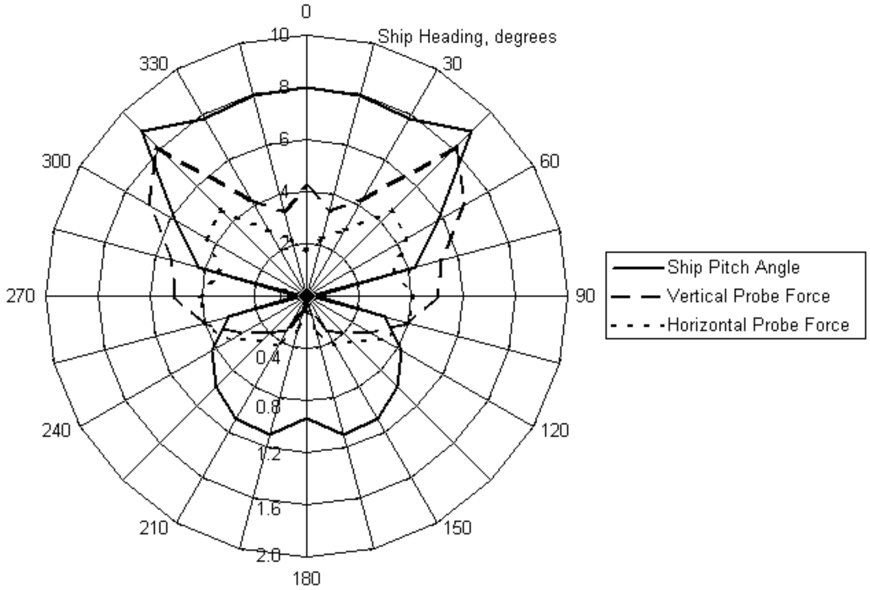

Figure 12: Relationship between ship pitch angle and securing forces

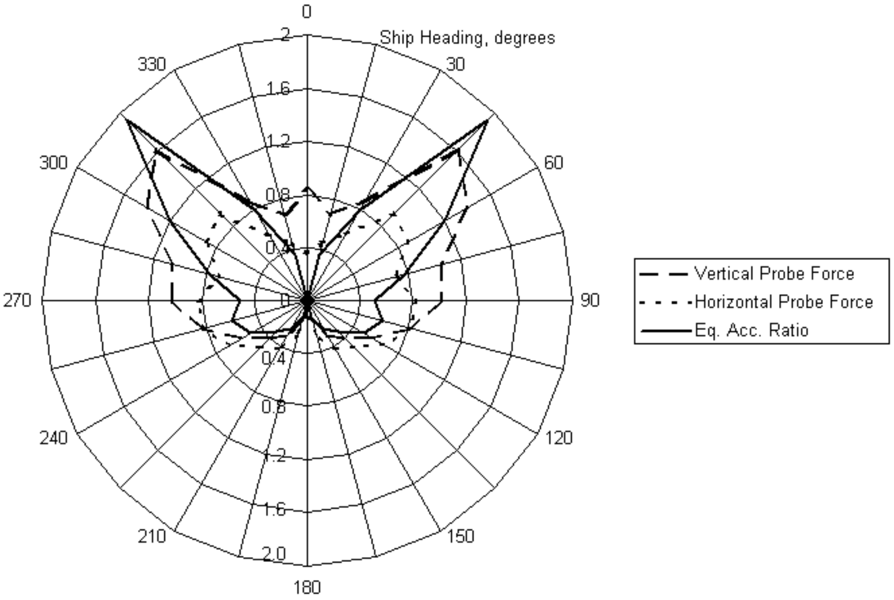

Figure 13: Relationship between ship equivalent acceleration ratio and securing forces

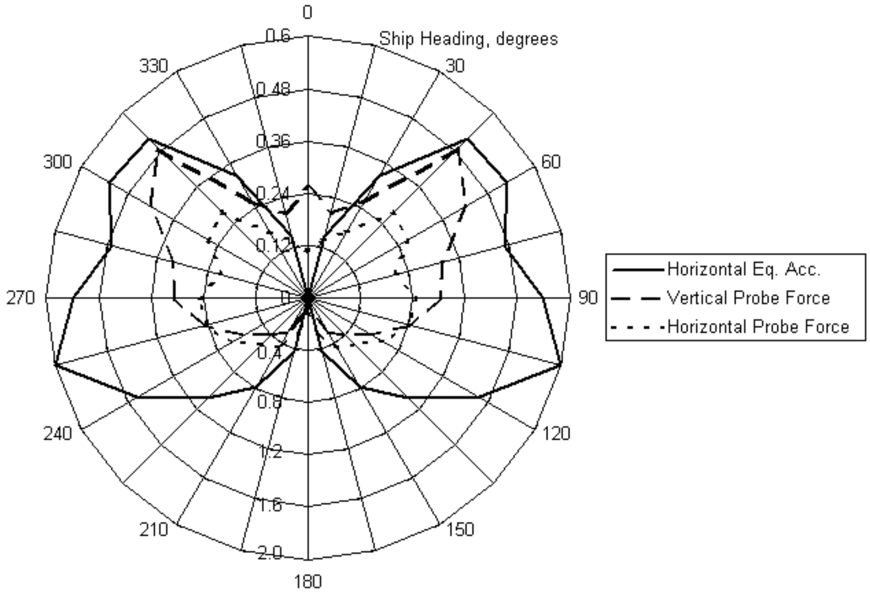

Figure 14: Relationship between ship horizontal equivalent acceleration and securing forces

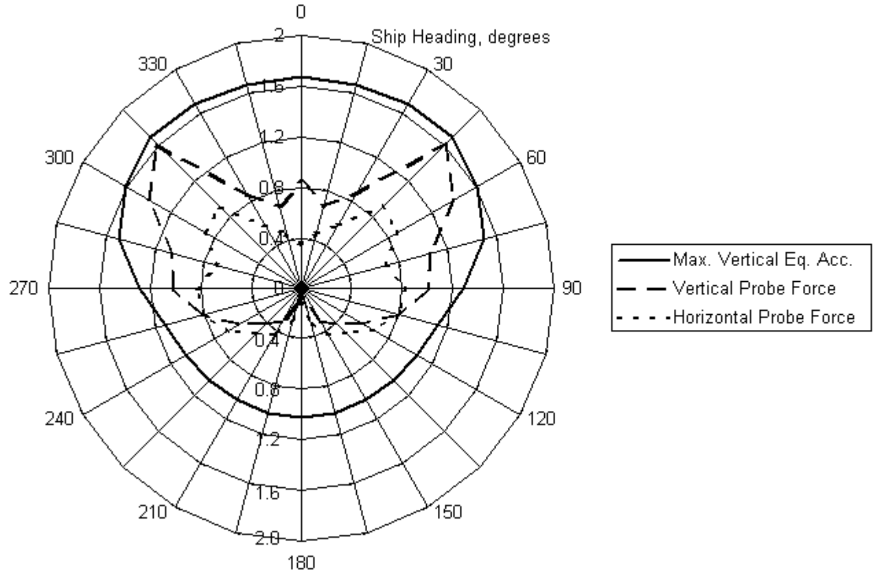

Figure 15: Relationship between ship maximum vertical equivalent acceleration and securing forces

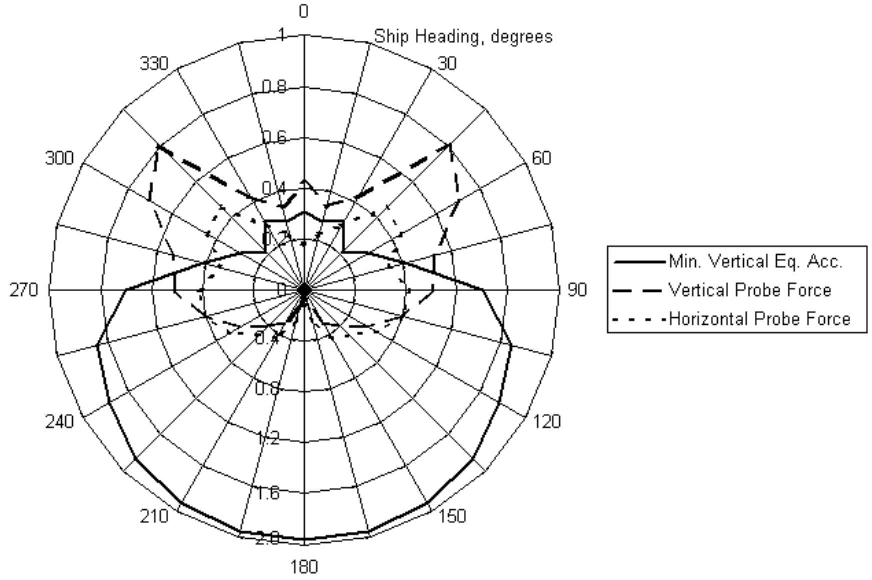

Figure 16: Relationship between ship minimum vertical equivalent acceleration and securing forces

Figure 17: Photograph of the West Navion drilling ship

of placing the helicopter in an adverse situation.

One recent example, where using equivalent-acceleration-based parameters would have helped explain a helicopter incident, occurred on the *West Navion* drilling ship in November 2001 at the Assynt Prospect, West of Shetland. A Super Puma helicopter, carrying several passengers, had landed on the helideck of the West Navion (a 253 metre long drill ship having a displacement of approximately 101000 tonnes) under normal operating conditions in moderate sea and wind conditions. The West Navion drilling ship is shown in Figure 17. The photograph also shows the forward and high location of the helideck. Throughout this time the vessel was maintaining a fixed heading into a 35-knot wind, with the helicopter rotors turning, while the bow-located helideck (approximately 35 metres above the waterline) was experiencing 3.0 to 3.5 metre heave motion. These conditions at the time the incident occurred were within the acceptable motion limits for operation on drill ships of this type (2.5 degrees for roll and pitch angles and 4 metres for heave motion). The passengers had disembarked and the helicopter was being refuelled. During this time, the ship lost heading control and rotated away from its original commanded heading. After the helicopter was refuelled, the Commander indicated to the co-pilot that he was ready to receive the 12 passengers for transportation back to Aberdeen, who were waiting below the helideck. The co-pilot had relayed this permission to one of the helicopter landing officers and as the first passenger had made it up to the first flight of stairs, the helicopter had rolled onto its starboard side shattering its rotor blades. Fortunately, the co-pilot was the only injured party; suffering a serious leg injury from the rotor debris while the aircraft was badly damaged. Figure 18 shows the Super Puma rolled over on its starboard side on the helideck of the West Navion drilling ship. It is important to note

Figure 18: Super Puma rolled over on the West Navion drilling ship

that during this incident, no helicopter restraints were used other than the netting laid on the helideck. The helicopter was only tied down to the deck after the aircraft had rolled over as indicated by the lashings in Figure 18.

Although the investigation is still ongoing by the UK Air Accidents Investigation Branch (AAIB), initial conclusions by the AAIB are that the most probable cause of the incident was that following the ship's loss of heading, the combination of the roll, pitch, and heave of the ship, the wind direction, and wind induced rotor forces caused the Super Puma to turn over onto its side. The AAIB is currently blaming a software problem with the ship's dynamic positioning system as being the root cause for the heading loss of the West Navion. Several items, as they relate to helicopter/ship operations discussed in this investigation, that were pointed out as a result of this incident include:

- a need to have a better understanding of the dynamic stability and operating envelopes of the Super Puma; and
- improving the pilot's ability to react to changing deck conditions by having instrumentation placed in the helicopter and external to the helicopter to indicate the severity of the deck motion and ship heading independent of the ship.

As indicated above, the limits of ship motion based on roll, pitch, and heave, as well the wind speed, were within the specified limits at the time the incident occurred. The ship was initially heading into the wind when the helicopter landed but rotated towards beam on to the weather when the dynamic positioning system failed. Large values of equivalent acceleration ratio and T-factor parameters are typically found to occur in seas off the bow and the magnitude of these parameters are primarily dependent on the sea conditions and location of the flight deck as discussed in previous sections. In the case of the West Navion, the flight deck is located some 35 metres above the waterline and approximately 125 metres forward of the ship's centre of mass. The further away the flight deck is from the ship's centre of mass, the higher the magnitude of the equivalent-acceleration-based parameters even for relatively small values of ship angular displacement. Though the ship experienced relatively small angles of roll and pitch, the helicopter had tilted several times before over turning. The ship motion may have initially caused the helicopter to lose stability, but the increasing helicopter angle relative to the ship, as it was tilting, would have produced high wind induced rotor loads causing the eventuality. This unsafe condition would have been detected if the T-factor were used to indicate the deck conditions.

Currently, helicopter operators have placed restrictions on ship motion levels. Roll and pitch motions have been reduced to 1 degree and heave motion has been reduced to 2 metres. Although steps have been taken to mitigate the risks by reducing the linear and angular limits, this may not necessarily prevent this incident from occurring again as high values of equivalent acceleration and T-factor can occur for even small values of ship angular displacements. By identifying ship heading and speed combinations where safe helicopter embarked operations can occur would eliminate any potential loss of aircraft stability.

The highly nonlinear and time-dependent nature of the helicopter and ship interface makes it impossible to determine analytically the most severe helicopter conditions, as the exact conditions are not known. For this reason, the need to conduct simulations over a wide range of conditions can only be accomplished through dynamic interface simulations. Having identified the various equivalent-acceleration-based parameters that are predictive of severe conditions for both the ship and helicopter, the peak values and their times of occurrence can be extracted from extended time histories of ship motion, whether they were generated experimentally or simulated using a variety of ship motion prediction software. Helicopter simulations can then be performed for short time periods centred in time on potentially severe ship motion events to identify whether a helicopter slides, slews, topples, or exceeds structural limits.

By conducting detailed dynamic interface analysis of the helicopter, the result can be used to define appropriate ship motion limits based on equiv-

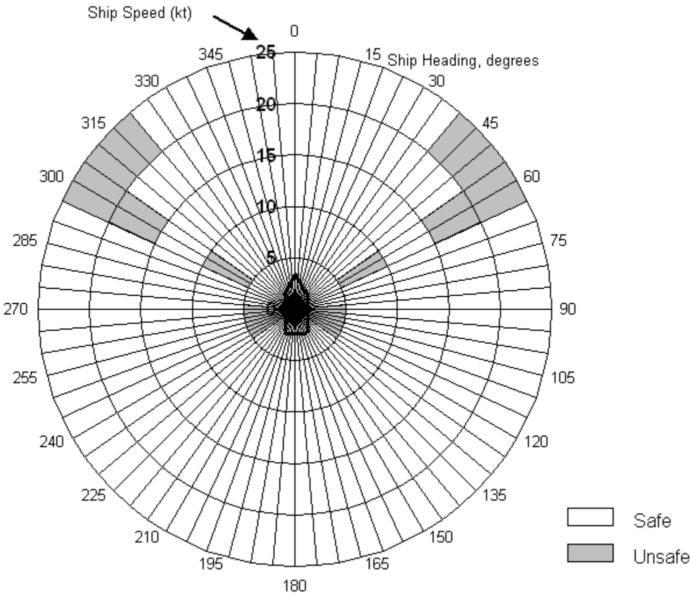

Figure 19: Typical safe operational envelope based on analysis of equivalent acceleration

alent acceleration for each phase of embarked operations. Alternatively, operating envelopes can be created that identify areas, based on ship heading and speed, where the helicopter can be safely operated without exceeding the equivalent acceleration and T-factor limits. For example, the shaded regions of Figure 19 indicates the specific ship heading and speed combinations that would cause the helicopter to be placed in an unsafe situation. Should, for whatever reason, the ship need to operate within the shaded regions, the appropriate action can be taken such as lashing the aircraft to the deck or the helicopter can take-off and wait until the ship motion returns to levels below the predetermined allowable limits. These type of plots can be created for each phase of helicopter embarked operations including launch, recovery, and deck handling with different ship motion limits for each phase.

In a commercial sense, such as with the West Navion drilling ship, restrictions on ship heading and speed may not impose a significant change to current operations. However, in a military application, where helicopters routinely operate from small frigates to conduct a variety of missions from search and rescue to antisubmarine and antiterrorist warfare, this may not be favourable. Developing operating envelopes by identifying limits for safe operation, using equivalent acceleration parameters and the T-factor, may only be appropriate as part of normal operations. It is understood that although there may be ship heading and ship speed combinations that can potentially place the aircraft at risk, this is likely not to occur frequently depending on the length of time spent on that heading and speed combination. However, unlike in commercial applications, a certain level of risk is allowed for military flight operations depending on the perceived threat. In these situations quantitative measures are therefore necessary for helicopter operations. By continuously displaying values of the equivalent-acceleration-based parameters and T-factor, appropriate crew members can be made aware of potentially severe helicopter conditions while still operating within the shaded regions of operation envelopes.

6 Conclusion

Equivalent acceleration ratio and T-factor parameters provide an effective means for quantifying helicopter tendency to slide. The parameters are easily computed in simulation and easily measured in service at sea. They therefore provide an effective and practical method for quantifying the severity of deck motion conditions. Failure to accurately assess the severity of deck conditions, as is inevitable when using displacement measures such as roll and pitch angles alone, produces a false impression of the risk associated with aircraft operations. In turn, this can lead to unsafe conditions resulting in serious and potentially life-threatening injuries to personnel, strong potential for loss or extensive damage to aircraft and shipboard equipment, reduced overall operability and associated risks and costs, and lack of understanding about the true motion condition of the flight deck. Further, great potential for developing interoperability limits for aircraft and ships within a fleet rely upon using proven parameters such as the equivalent acceleration ratio and T-factor. Proper equipment and indicators for both ship deck operation and helicopter pilots is achievable using currently available technologies. In fact, constant recording of the equivalent acceleration ratio and T-factor could provide useful data for analysis of accidents similar to that of the West Navion.

Acknowledgement

The authors wish to acknowledge the many and varied individuals who have directly and indirectly contributed to this work. The authors also wish to thank Indal Technologies Inc. for supporting this research activity.

References

[1] R. G. Langlois and A. R. Tadros. State-of-the-art on-deck dynamic interface analysis. In *Proceedings of AHS Forum 55*, Montreal, Canada, May 1999. American Helicopter Society, MIRA Digital Publishing.

[2] R. G. Langlois, LaRosa M., and A. R. Tadros. Parametric investigation of the sensititvity of shipboard helicopter securing requirements to helicopter configuration. In *Proceedings of the Canadian Society for Mechanical Engineering Forum 2002*, Kingston, Ontario, Canada, May 2002. CSME, CSME.

[3] R. G. Langlois, A. R. Tadros, and B. Lumsden. Investigation of the relationship between helicopter geometrical and inertial parameters and shipboard securing requirements. In *To appear in Proceedings of AHS Forum 58*, Montreal, Canada, June 2002. American Helicopter Society, MIRA Digital Publishing.

[4] A. R. Tadros, R. G. Langlois, and M. LaRosa. Investigation of ship fight deck motion limits for safe embarked helicopter operation. In *Proceedings of the International Powered Lift Conference 2000*, Arlington, Virginia, USA, October-November 2000. American Helicopter Society, MIRA Digital Publishing.

[5] R. G. Langlois and A. R. Tadros. *User's Manual for the Aircraft/Ship Dynamic Interface Simulation Dynaface Release 5.0.* Indal Technologies Inc., Mississauga, Ontario, Canada, January 1998. ITI Report No. 99/419.

[6] Indal Technologies Inc. ASIST product description. 3570 Hawkestone Road, Mississauga, Ontario, Canada L5C 2V8.

[7] R. Graham, Baitis A. E., and Meyers W. G. On the development of seakeeping criteria. *Naval Engineers Journal*, May 1992.

[8] S. J. Zan. A wind tunnel investigation of loads for an on-deck helicopter rotor in beam winds. Technical Report Report No. LTR-A-007, National Research Council of Canada Institute for Aerospace Research, Ottawa, Canada, April 1997. Prepared for Indal Technologies Inc. under contract P115858.

[9] Applebee T. R. Meyers, W. G. and A. E. Baitis. *User's Manual for the Standard Ship Motion Program SMP.* David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland, September 1981. Report No. DTNSRDC/SPD-0936-01.

[10] L. Vernooy and R. G. Langlois. *User's Guide for the ShipSim 4.2 Ship Motion Simulation Program*. Indal Technologies Inc., Mississauga, Ontario, Canada, August 1999.

Info

curtisswrightds.com

Email

ds@curtisswright.com