# Development, Validation, and Application of the *Dynaface*® Helicopter/Ship Dynamic Interface Simulation Software Package

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## Keywords

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## Abstract

The importance of safely operating helicopters from moving ships in potentially-severe sea conditions is widely recognized. In many cases, particularly on small military and coast guard vessels, helicopter operability is maximized by the use of systems that assist with shipboard helicopter recovery and on-deck handling. Regardless of the level and type of aircraft securing provided, safe shipboard operation requires detailed understanding of the effects of ship motion on the embarked aircraft. It is necessary to determine the limits for safe operation in terms of operational and environmental conditions, the securing requirements if appropriate, the factors that compromise the safety of operation, and the long-term impact of shipboard loading on the design of aircraft and securing equipment. To assist with the analysis of the dynamic interface that exists between ships and embarked aircraft, Indal Technologies Inc. (ITI), a developer of helicopter handling equipment, has developed, extensively validated, and applied the *Dynaface*® aircraft/ship dynamic interface analysis simulation software package. This paper outlines the development and basis of the mathematical model, validation activity, and the various ways in which *Dynaface*® can be applied to enhance the analysis and ultimately the safety of shipboard aircraft operation. Sample analysis applications are presented and discussed. It is shown that the simulation package is suitable for supporting engineering analysis and design, simulation-based acquisition, operational planning, and incident investigation.

## Introduction

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 vessels, to the role of the helicopter as the primary weapons platform on many military ships. In order to fulfill diverse roles, shipboard helicopters must be operable in the greatest range of sea conditions possible. In many cases, particularly on small military and coast guard vessels, helicopter operability is maximized by the use of systems that assist with shipboard helicopter recovery and on-deck handling. These systems vary in complexity ranging from manually-applied chain lashings to completely autonomous systems that recover, secure, and traverse shipboard aircraft without strictly requiring any personnel on the ship deck. Regardless of the level and type of aircraft securing provided, safe shipboard operation requires detailed understanding of the effects of ship motion on the embarked aircraft. It is necessary to determine the limits for safe operation in terms of operational and environmental conditions, the securing requirements if appropriate, the factors that compromise the safety of operation, and the long-term impact of shipboard loading on the design of aircraft and securing equipment. To assist with the analysis of the dynamic interface that exists between ships and embarked aircraft, Indal Technologies Inc. (ITI), a developer of helicopter handling equipment, has developed, extensively validated, and applied the *Dynaface*® aircraft/ship dynamic interface analysis simulation software package[1]. This paper outlines the development and basis of the *Dynaface*® mathematical model, validation activity, and the various ways in which the *Dynaface*® software package can be applied to enhance the analysis and ultimately the safety of shipboard aircraft operation.

The component programs that form the *Dynaface*® package are identified by solid blocks in Figure 1. Elements in dashed blocks are linear

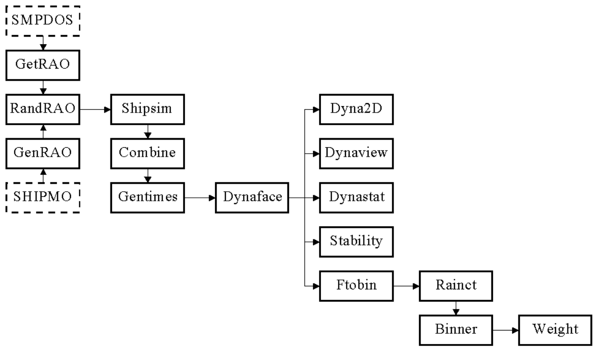


Figure 1: Structure of component programs in the *Dynaface* software package

frequency-domain programs that generate response amplitude operators (RAOs) characterizing ship motions that form the basic input to all forms of dynamic interface analysis for moderate to severe sea conditions. The other blocks in the first column in Figure 1 post-process the output data from SHIPMO[2] and SMP[3] into a form appropriate for use with the simulation package. The second column of programs generates time series and statistical data describing the continuous and peak ship motions at various shipboard locations as well as the magnitudes of equivalent acceleration parameters that provide effective indications of the severity of flight deck conditions as they affect shipboard helicopter operation[4]. The *Dynaface*® simulation program at the centre of the diagram forms the core of the package and consists of a 15-degree-of-freedom mathematical model and time-domain solution of the response of the helicopter to ship motions. Program blocks to the right of the central block provide statistical, animation, and other analytical treatments of the generalized displacement and force data that results from the *Dynaface*® simulation program.

Subsequent sections of this paper describe the development, validation, and application of the *Dynaface*® package.

# *Dynaface*® Development

## Governing Dynamics

Figure 2 shows a typical embarked helicopter secured to the deck by a rapid securing device (RSD). The RSD is part of an ITI Aircraft/Ship Integrated Secure and Traverse (ASIST) system that secures the helicopter from a helicopter-mounted probe as shown in Figure 3[5]. The objectives of on-deck dynamic interface simulation are to mathematically represent the in-service aircraft and ship system with sufficient fidelity to gain insight into the dynamic interface behaviour yet also maximize simulation speed such that very large numbers of simulation cases can readily be investigated within the scope of a single dynamic interface study.

Figure 2: Image of a typical shipboard helicopter securing condition

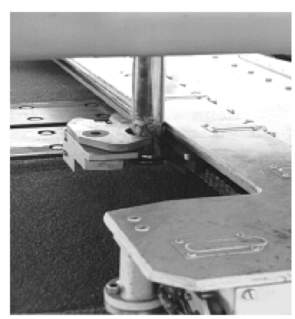

Figure 3: Image of the ITI ASIST securing system

*Dynaface*® includes a special-purpose 15-degree-of-freedom mathematical model of the aircraft/ship system. The degrees of freedom comprise three translations and three rotations for the ship, three translations and three rotations for the aircraft body, and one prismatic or revolute degree of freedom per suspension station depending on the suspension type. Forces acting on the aircraft portion of the system include deck reaction forces, securing forces, aerodynamic forces, inertial forces, and gravitational forces. A total of seven primary coordinate systems are used to derive the equations of motion: an inertial frame, a ship frame, an aircraft frame, a rotor tip path plane frame, and wheel frames corresponding to each suspension station (maritime aircraft normally have at least one steerable or castorable wheel). All suspension, external, and securing forces are modelled, analytically or empirically, depending on the quality and availability of data, and the resulting equipollent forces and moments are evaluated and applied through Newton-Euler equations. While the simulation is special-purpose to promote solution efficiency, it includes sufficient generality such that a large variety of aircraft and virtually all ships can readily be modelled. The simulation currently contains cantilever and leading/trailing arm suspension models having up to two wheels each that can be attached to the fuselage in either nose-wheel or tail-wheel configurations, up to two main rotors, and a large variety of securing devices. The model includes detailed representation of the oleo stiffness, damping, and friction characteristics; induced rotor forces; and a nonlinear tire model that supports complex tire behaviour including lift-off and touch-down, rolling due to suspension travel, brake slippage, and sliding.

Computationally, speed is maximized by removing physically impossible discontinuities from model characteristics, carefully controlling coupling between model degrees of freedom, and carefully matching the numerical integration with the equation structure. These considerations have led to a simulation that meets the objectives of accuracy and speed.

## Suspension Systems

Two widely used suspension station configurations implemented in the model are cantilever and leading/trailing arm suspensions shown schematically in Figures 4 and 5 respectively. Each adds one degree of freedom (linear or angular) to the model per station. The governing equations are developed in the aircraft frame with suspension stations treated as force producing devices.

Investigation has demonstrated that while the aircraft body and suspension stations are kinematically coupled, mass coupling is very weak. Consequently, treating suspension stations as force producing elements rather than tightly coupling the respective equations reduces the solution complexity and high frequency content and correspondingly improves speed performance without affecting accuracy.

The dominant passive suspension element is a gas oleo that generates stiffness, damping, and frictional forces in response to relative displacements, velocities, and transmitted forces and moments across the element. Oleo stiffness is modelled using the ideal gas law for the primary compression region and a stiff linear spring for extension. A continuous and differentiable transition between the two regions is achieved using a cubic polynomial. This is illustrated schematically in Figure 6 though the extent of the transition region is very much exaggerated for clarity. Complex oleos may involve additional stiffness stages that are appended to the oleo stiffness characteristic. The nonsymmetrical damper design and possible inclusion of pressure relief valves necessitates that a multistage damping model be used with a damping force in each region described as a nonlinear function of velocity for velocity-dependent hydraulic dampers or displacement in the case of oleos containing metering pins. The transition velocities between regions vary with time because the pressure relief valve actuation may depend on the total transmitted force. A modified friction model[6] is used to evaluate the oleo friction force

$$F_f = (\dot{q}/|\dot{q}|)\, F_{f\ max}\, (1 - \exp(-\alpha|\dot{q}|)) \qquad (1)$$

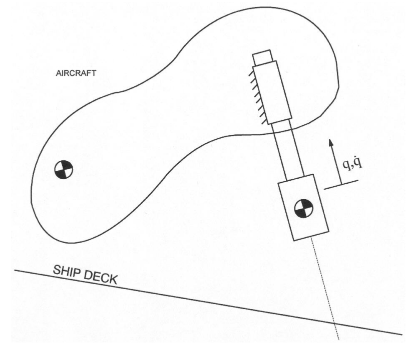


Figure 4: Schematic representation of cantilever suspension

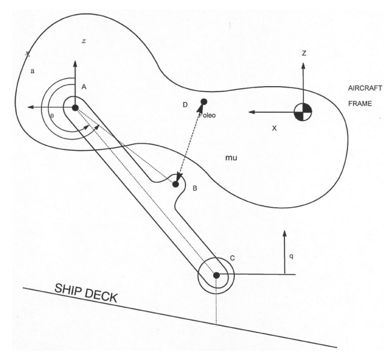


Figure 5: Schematic representation of a trailing arm suspension

where $\alpha$ is the decay rate of the modified friction model, $q$ is the suspension station configuration coordinate, and $F_{f\ max}$ is the maximum possible oleo friction force comprised of oleo seal and normal force contributions

$$F_{f\ max} = F_{f\ seal} + \mu F_N \tag{2}$$

Leading/trailing arm suspensions include additional friction resulting from angular motion through at least three joints, each introducing friction that is related to the joint reaction force. Suspension test results indicate that in some cases frictional contributions to the total suspension force are similar in magnitude to the stiffness contribution. Consequently, suspension friction must be modelled very accurately to achieve dynamic results that are representative of the in-service aircraft.

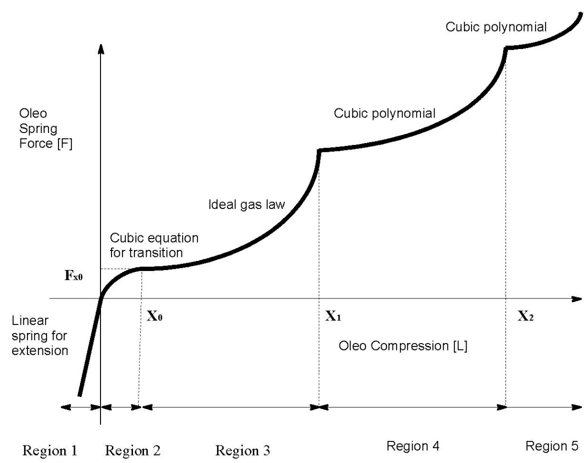


Figure 6: Schematic representation of the oleo stiffness model

Tire forces are calculated assuming vertical compression and tire design-dependent stiffness in the longitudinal and lateral directions[7] and a multi-stage cubic stiffness in the vertical direction. Linear viscous damping is assumed in all three component directions. However, additional complicating factors exist in evaluating tire forces. These relate to the tire contact condition. First, when the tire loses contact with the deck, the tire 'contact' point tracks the projected touchdown point. In this way, residual tire deformation is released when a tire lifts off and does not exist initially upon touchdown. This is illustrated schematically in Figure 7. Second, tire sliding occurs when the resultant of the longitudinal and lateral forces exceeds the instantaneous allowable frictional force. Third, suspension kinematics in the case of leading/trailing arm suspensions couple the tire contact point to suspension compression. Fourth, under severe securing conditions, the wheel brake slip limits can be reached leading to brake slippage and tire rolling. The inter-relationships between these phenomena motivate the need for a sophisticated tire model specifically designed for the dynamic interface problem.

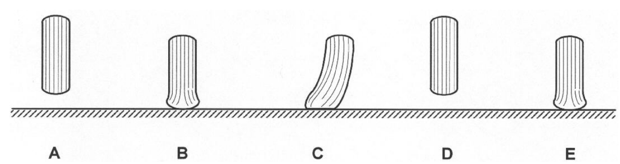


Figure 7: Schematic representation of tire behaviour during intermittent tire contact

## Aerodynamics

Aerodynamic forces acting on the aircraft result from aerodynamic drag and rotor induced forces and moments. Aerodynamic drag is calculated based on the equivalent frontal and side areas of the aircraft fuselage and the relative wind speed. The rotor thrust is modelled using a constant thrust value during the descent phase of the touchdown transient followed by decaying rotor thrust as the pilot reduces the rotor collective to its minimum. This optional decreasing thrust can be triggered by the first wheel contact with the deck. In the case of maritime aircraft, even with the rotor at its minimum collective, ship motion generates an angle of attack of the rotor disc relative to the apparent wind. This effect is highlighted by the flow visualization presented in Figure 8. Testing has demonstrated that the rotor-induced thrust can reach 30% of the aircraft weight for the case where the rotor collective is at its minimum. Consequently, potentially large rotor forces and moments can be developed. These are evaluated continuously throughout the simulation based on helicopter manufacturer rotor data and the instantaneous wind conditions and angle of attack. Testing in this area has been performed at the National Research Council of Canada Institute for Aerospace Research in collaboration with ITI[8]. Further experimentation is currently underway. The complexity of air flow over and around ships is a growing field attracting considerable research effort[9].

## Securing Systems

The dynamic interface simulation model provides capability to simulate a wide variety of existing and proposed passive and active securing devices that

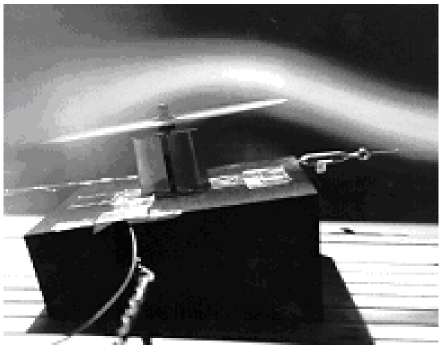

Figure 8: Flow visualization of air flow over a typical frigate flight deck

may operate independently or in combination. Passive securing systems are those in which one or more structural members fitted to the helicopter and fixed to the ship react the helicopter loads, restraining the helicopter from excessive movement and transferring the loads into the ship's structure. Securing is limited only by the strength of the securing member(s) and the supporting structure. Examples of systems falling into this category are the ITI Recover Assist Secure and Traverse (RAST) system, the ITI ASIST system, landing gear securing devices, and non-pretensioned lashing cables. Active securing systems are those in which a mechanical/hydraulic device, fitted to the helicopter and attached to the ship, continuously applies a force in an effort to create sufficient friction to prevent tire sliding. Securing is limited by the magnitude of the force, the extension of the securing element(s) under load, the landing gear capacity, the tire deflection limits, and the deck coefficient of friction. Examples include a variety of hydraulically-controlled pretensioned link systems and tensioned lashing cables.

## Solution Strategy

The objective of the computer simulation is to propagate the dynamic solution for the aircraft motions and securing forces forward in time. The general approach that is adopted for this purpose is described in the following procedure.

1. Evaluate the prescribed ship motion (displacements and velocities) at the current simulation time.

2. Evaluate internal forces developed by suspension stations and securing devices and express them as equipollent forces and moments based on the prescribed ship motion and aircraft state vector known from the previous time step.

3. Evaluate externally applied forces resulting from gravity, aerodynamic drag, and rotor forces and express them as equipollent forces and moments.

4. Evaluate the time derivative of the system state vector. The derivatives of velocities are determined using Newton's law for aircraft linear velocities, Euler's equation for aircraft angular velocities, and the suspension station governing dynamic equations for the relative wheel velocities. The time derivatives of the configuration coordinates are simply set equal to the corresponding velocities known from the previous time step.

5. Numerically integrate the composite derivative vector using an adaptive time step integration algorithm to yield the displacements and velocities at the next time step.

This procedure is repeated for the duration of the simulation or until user-specified limits are exceeded. Limits that are checked include relative aircraft angular motions, axial oleo forces, vertical tire forces, and lateral tire deflections.

The solution can also be run with subsets of the 15 available degrees of freedom to facilitate specialized types of analysis such as validating suspension models and simulating helicopters with gagged oleos.

The formulation is implemented in ITI's proprietary simulation software package *Dynaface*®. Based on descriptions of the ship, aircraft, and operating environment, the model predicts generalized displacements and generalized forces as a function of time. These generalized output values include aircraft relative angular displacements, securing forces, landing gear reaction forces, suspension forces, tire deflections, induced aerodynamic forces and moments, and animation data.

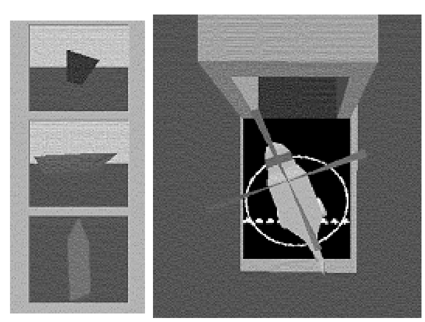

Figure 9: Sample animation frame indicating one of several optional graphical post-processing options

# *Dynaface*® Validation

Development of the *Dynaface*® simulation has emphasized the importance of accurately predicting the interface parameters between an embarked helicopter and ship. To achieve this, the simulation model input data consists of a combination of theoretical aircraft design data, experimentally-measured suspension data, empirical tire data, and externally-calculated or measured rotor data. In all cases, the information source was selected based on optimizing the quality of the input data. Therefore, the input data source to some extent influences the relative importance of verification and validation at the simulation component level. However, during development, each component of the *Dynaface*® simulation was both verified and validated at the component level and once assembled into the full simulation. Validation activity comprised a combination of comparisons with analytical solutions, comparisons with other simulation results, comparisons with jig suspension drop test data, and comparisons with both land-based and sea trial full vehicle experimental data.

The most complex element in the complete simulation is the landing gear model. For this reason, extensive validation activity focussed on this element of the model. During landing gear design and tuning, designers routinely conduct an extensive experimental drop test program whereby a large volume of data is collected. The experiment involves mounting the full-scale landing gear in a device that allows the landing gear to translate downward from its fully-extended condition with a predetermined initial sink speed. The landing gear then experiences the touchdown transient and settles to its static condition. This type of experiment is performed for a range of initial sink speeds and a range of helicopter weights. The ground reaction force and suspension compression are two variables that are usually measured with respect to time in these tests. This data provides an excellent opportunity for validating the landing gear and tire elements of the simulation. The data also provides a means for validating the landing gear models of specific aircraft prior to using them for dynamic interface analysis. Figure 10 shows a sample drop test validation result for a cantilever main landing gear suspension, where the simulated and measured ground force is plotted versus time. Drop test validation of this type has been performed for a large number of aircraft having both leading/trailing arm and cantilever type suspensions and has shown excellent agreement between measured and predicted responses similar to what is seen in Figure 10.

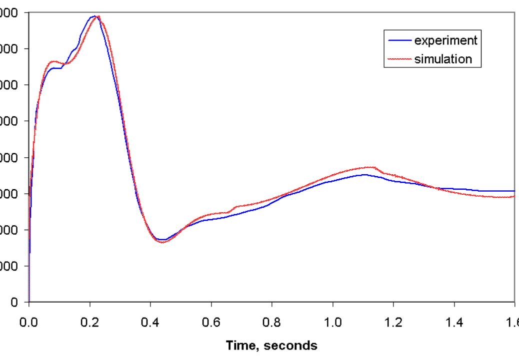


Figure 10: Comparison between experimental and simulated drop test data for a typical cantilever main landing gear suspension

The most direct, and arguably most comprehensive, validation of the complete simulation results from comparing the simulated aircraft response with the measured aircraft response during an actual sea trial. Figure 11 shows such a comparison for a medium-sized tail dragger helicopter operating on a typical frigate in severe sea conditions. The plot compares the simulated and measured relative roll angle between the aircraft and ship in response to measured ship motion. The comparison shows that the simulation captures the behaviour of the actual shipboard aircraft though some differences do exist. This does not reflect a limitation of the simulation but rather highlights the difficulty associated with attempting to perform detailed validation using existing data collected in a relatively uncontrolled environment. Two main difficulties exist with most available sea trial data. First, ship and helicopter measurements are rarely perfectly synchronized; and second, the exact aircraft configuration and prevailing environmental conditions are often not available. The response of an aircraft depends significantly on the inertial properties of the aircraft, its orientation on the ship, and the exact wind conditions (as a function of time) to which it is subjected. As this data was not available for the sample case presented in Figure 11, nominal aircraft parameters and a steady wind were assumed thereby likely accounting for the differences observed in Figure 11. An unrecorded wind gust could easily account for the differences between the measured and simulated values in the area of 37630 seconds. While sea trial data is representative of actual operating conditions, in the dynamic interface analysis application, unless very carefully-conducted dedicated sea trial experiments are performed, the most rigorous validation data is obtained from experiments conducted in carefully-controlled environments.

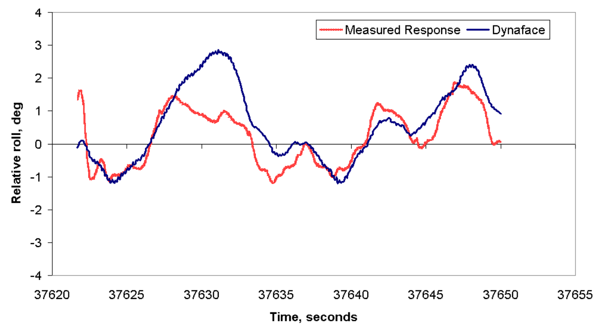


Figure 11: Comparison between measured and simulated sea trial data for a typical medium-sized tail dragger helicopter operating on a typical frigate in severe sea conditions

# *Dynaface*® Application

*Dynaface*® was developed as a versatile analysis tool. Since it's initial development, significant experience has been gained with its use. This section describes the process of individual helicopter input file development from data typically provided by aircraft manufacturers. It also describes the process involved in performing several important types of dynamic interface analysis for which the *Dynaface*® package is well suited.

## Model Development

In using the simulation, the aircraft and ship configurations, environmental conditions, and simulation control parameters are specified in a detailed set of input files. The simulation uses this information to describe the physical system. Ship motion, which is the dominant excitation for the aircraft/ship system is either input as experimentally measured sea trial data or developed from linear frequency-domain response amplitude operators (RAOs). The simulation then generates the time-varying prescribed ship motion and propagates a time-domain solution by numerically integrating the governing Newton-Euler equations of motion for the system. An exhaustive set of optional results; including aircraft relative angular displacements, securing forces, landing gear reaction forces, suspension forces, tire deflections, induced aerodynamic forces and moments, and animation data; are saved in a selected subset of 23 available output files. Simulation results are post-processed by a suite of utility programs or animated using either two- or three-dimensional animation software tools.

## Securing Analysis

Securing analyses are typically performed to identify helicopter securing requirements as a function of helicopter configuration, ship operating conditions in terms of ship heading and speed, and environmental conditions including sea state, wind speed, and wind direction. Typical helicopter parameters that can vary throughout an analysis include: aircraft weight, rotor status, brake status, nose/tail wheel orientation, aircraft alignment with respect to the ship's centreline, aircraft location on the ship such as on the flight deck or in the hangar, and type of securing system. Also, the type of helicopter embarked operation can vary; possibilities include: free-deck analysis, on-deck securing, aligning for hot refuelling and rearmament, straightening, traversing, and hangaring. Consideration of all permutations can lead to a vast number of simulation runs for which *Dynaface*® is well suited due to the speed at which it is able to perform the simulation runs. Figure 12 shows a typical polar plot of how securing force requirements vary with significant wave height and ship heading.

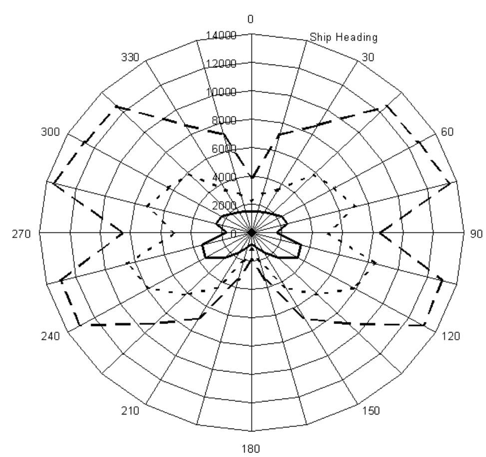


Figure 12: Sample result indicating the variation of peak securing loads with ship heading and significant wave height (4 m for inner trace, 5 m for middle trace, and 6 m for outer trace)

Upon selecting the helicopter configurations, ship operating conditions, and environmental conditions that will vary throughout the analysis, *Dynaface*® is typically run for short time periods (40 seconds) around the occurrence of a peak ship motion event. As indicated earlier, the user is able to select from 23 output files including: landing gear forces, securing forces, suspension forces, deflections, and velocities, tire forces and deflections, aircraft displacements, velocities, and accelerations, and aerodynamic forces and moments. Depending on the type of securing analysis being performed, the complete set of *Dynaface*® output files need not be outputted. For a typical securing analysis, the critical data to be extracted from a simulation runs are the securing loads, landing gear loads, aircraft relative displacements, and change in tire contact position to identify whether the aircraft has slid or slewed. A statistical analysis can be performed to identify the maximum, minimum, and frequency of occurrence of each parameter. These loads and displacements can then be compared against specified design limits and used to develop helicopter operating envelopes as a function of ship heading and speed. Figure 13 shows a typical helicopter operating envelope indicating the ship heading and speed combinations where the aircraft without a securing system has slid on-deck.

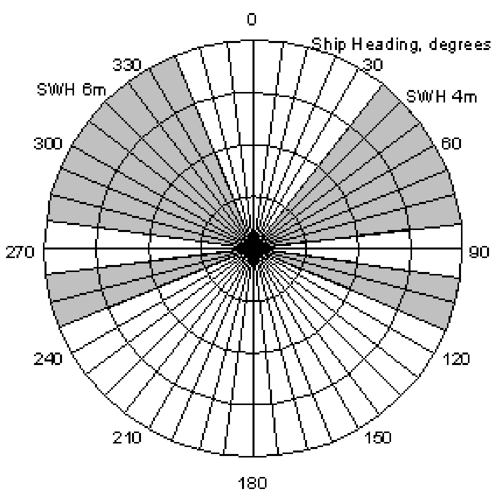


Figure 13: Ship headings where an unsecured heavy aircraft does not satisfy a securing definition in seas characterized by both 4 metre (right) and 6 metre (left) significant wave heights

*Dynaface*® can be used early in the design cycle to address helicopter/ship compatibility issues such as identifying whether a securing system is required. If a securing system is required based on the expected theatre of operation, simulations can be conducted using *Dynaface*® to compare the relative performance of various helicopter securing and handling systems. Alternatively, for a given helicopter and ship combination, *Dynaface*® could be used to safely expand current operations. For example, most helicopter/ship operations are limited to sea state 5 conditions. *Dynaface*® can quickly identify specific ship heading and speed combinations that will not exceed helicopter limits in higher sea states therefore expanding current capabilities.

## Fatigue Analysis

The continuous nature of shipboard helicopter loading, variability of loading conditions, potential magnitude of securing forces, and anticipated number of load cycles often motivates detailed fatigue analysis of securing system elements and aircraft structure to which the aircraft portion of a securing system is mounted and through which shipboard securing loads are transmitted.

The first essential step in any any fatigue methodology is quantification of the dynamic loading acting on the securing device (if present), the landing gear, and consequently on the aircraft structure. The dynamic loading is dependent on three main factors: aircraft and securing system design in terms of geometrical, inertial, and stiffness parameters; sea conditions; and operational factors such as ship heading and speed relative to the principal sea direction. Detailed nonlinear transient dynamic simulation of the aircraft response to environmental conditions is ideal for this step in the overall process as it provides a means of exploring the full parameter space prior to detailed design of the securing and aircraft systems. Extended periods of time-domain data is generated by *Dynaface*® to ensure statistically representative loading and this data is subsequently post-processed using rainflow counting of load cycles leading to fatigue spectra[10]. Due to the potentially-large amount of simulation involved in considering all permutations of aircraft configurations; phases of on-deck operation including securing, manoeuvring, traversing, and hangaring; and ship operating conditions; it is often possible to base fatigue analysis on a reduced set of representative operational cases with associated probabilities of occurrence. Figure 14 shows a typical fatigue loading result indicating the number of loading cycles per hour of operation as a function of ship heading in a particular sea state.

Once the dynamic loading has been established using dynamic interface simulation, the remainder of the analysis can be performed analytically, experimentally, or using a combination of both approaches. As an example, a methodology combining dynamic interface analysis, detailed structural analysis and validation, and full-scale static and fatigue testing was developed and implemented to structurally substantiate the installation of the ITI RAST securing system in an existing Kaman SH-2G(A) Super Sea-

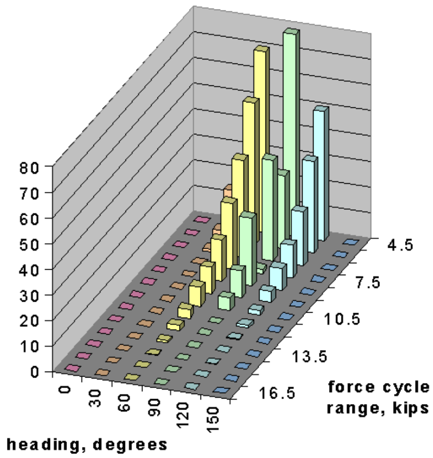


Figure 14: Sample result indicating securing device radial loading per hour of operation in sea state 5 conditions

sprite helicopter[11].

## Clearance Analysis

Shipboard aircraft are typically fitted with equipment and instrumentation ranging from cargo hooks to sonar domes and an expansive set of antennae. As the result of ship motion and the corresponding reaction of the aircraft suspension, relative motion develops between the aircraft and ship. Static and quasi-static analyses are insufficient to address these issues and do not take into account the complete kinematics of the both the aircraft, in terms of landing gear suspension and tires, and the ship. It is consequently important to investigate clearance issues between aircraft-mounted and ship-mounted equipment through the use of transient dynamic analysis to avoid any potential interferences.

Throughout the life expectancy of a helicopter, upgrades are typically made to expand and modernize the helicopter's capabilities and thus may include changes to aircraft components such as radar domes, landing gears, etc. These changes may create clearance problems between the aircraft and existing ship-mounted equipment. *Dynaface*® is able to identify any clearance problems that may arise by allowing the user to specify critical aircraft locations and corresponding ship locations as points of interest. Throughout the simulation, *Dynaface*® outputs the relative position of these points in each component direction. If interferences do exist, appropriate action can be taken to rectify the problem early in the design cycle.

Another common application is to ensure that while an aircraft is being traversed through the hangar door and into the hangar that the relative motion does not allow contact between the aircraft and doorframe. This is done by specifying several points on the helicopter where the potential for contact exists. *Dynaface*® is then run and the results analyzed to determine if aircraft contact with the hangar is made. This is most useful when a new helicopter is being considered to operate from an existing ship where decisions need to be made as to the necessity of upgrading the hangar. Alternatively, operating procedures can be changed to increase the level of aircraft securing to minimize the relative motions.

## Parameter Optimization

A wide variety of sensitivity analysis and optimization is possible using the simulation package. Opportunities range from selecting the ideal placement of securing elements on the aircraft to considering how maritime aircraft can be better designed to be more compatible with shipboard operation from an on-deck securing perspective.

An example of the type of detailed sensitivity analysis that is possible is described in References [12] and [13]. In those studies, potentially-important helicopter geometrical and inertial parameters were considered for several aircraft to determine how sensitive helicopter securing requirements were to each parameter and to investigate how the sensitivity of securing requirements to helicopter design varies with aircraft size. A sample result is shown in Figure 15.

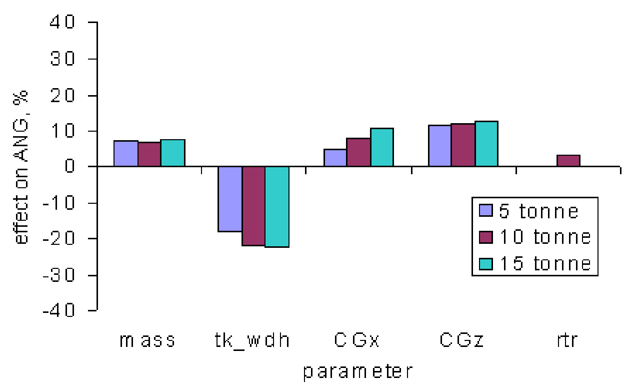


Figure 15: Sample result indicating how the aircraft relative roll angle sensitivity varies with aircraft design parameters and aircraft gross weight

As indicated previously, the simulation is flexible and can be used to support sensitivity and optimization analyses tailored to the specific objectives and requirements of the user.

### Incident Investigation

While emphasis is most often placed on analysis to prevent potential accidents involving shipboard aircraft, accidents do occasionally occur and the resulting consequences can be severe including the loss of helicopter and ship personnel, loss of the helicopter, and damage to the ship. Accurate dynamic interface analysis capability is essential for incident investigation as there may be multiple factors that contribute to an incident. The *Dynaface*® package has been applied and is well-suited for this purpose as part of the overall investigation.

Over the past few years, there have been several incidents involving helicopters embarked on ships in both military and civilian/commercial contexts. Although the exact conditions may not be known at the time of an incident, *Dynaface*® requires a minimal amount of information to be able to reproduce the incident with some level of confidence. The types of information surrounding the incident that should be easily available and input to *Dynaface*® include: the approximate aircraft weight, rotor status, brake status, aircraft on-deck alignment, aircraft location on the ship, ship heading and speed, approximate wind speed and direction, and method of securing. The more difficult task is to identify the ship motion at the time of the incident. *Dynaface*® is able to input experimental ship motion if measurements were taken and recorded, or alternatively sinusoidal motion could be used based on the observations of the ship's six degrees of motion made by witnesses. Once the incident is reproduced, the cause can quickly be determined. For example, a helicopter rollover may be caused by the combination of several factors such as no securing system, the ship at an unfavourable heading, the rotor turning, the aircraft lightly loaded, and unfavourable wind speed and direction. Another incident may involve a helicopter contacting the hangar door during traversing. Once the situation surrounding the incident has been identified, appropriate action can be taken to prevent the incident from recurring. This may include restrictions on ship heading and speed or the use of a more favourable securing and handling system.

## Conclusion

This paper has presented the mathematical framework and modelling approaches used in the *Dynaface*® simulation package; an overview of validation activity; and sample dynamic interface applications. The objective was to comprehensively introduce *Dynaface*® and indicate its range of applicability.

The simulation has been used by ITI and other international organizations to model a variety of existing maritime aircraft ranging in size from very small unmanned air vehicles to large helicopters. Specific aircraft modelled include various configurations of the Sea King, Sea Hawk, H-92, Super Puma/Cougar, NH-90, Dauphin, Super Seasprite, Lynx, EH-101, Bell 212, and Bombardier CL-327. These aircraft have been operated on a variety of ships ranging from lively cutters, to frigates, to larger stable platforms. Extensive experience with the model over the past fifteen years has demonstrated that *Dynaface*® provides a valuable analysis capability that can be directly applied to support engineering analysis and design, simulation-based acquisition, operational planning, and incident investigation. Ultimately, experience is demonstrating that the simulation is fulfilling its intended purpose of promoting the safety of shipboard helicopter operation.

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