Simulation Tools Used in the Analysis of Aircraft Handling Systems for Safe Embarked Operation

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ABSTRACT

The importance of safely operating helicopters from ships in severe sea conditions is widely recognized. On military and Coast Guard vessels, helicopter operability is maximized by the use of systems that assist with shipboard helicopter recovery and on-deck handling. An aircraft securing and handling system (ASHS) must provide an efficient means to safely secure and straighten an aircraft on the flight deck, and traverse it to and from the hangar. These operations must be performed in severe sea conditions day or night. Regardless of the type of ASHS, safe shipboard operation requires detailed understanding of the effects of ship motion on the embarked aircraft. INDAL, the leading innovator of ASHS solutions, has extensive experience analyzing securing requirements and on-deck stability of manned and unmanned aircraft on moving platforms. The paper outlines the development and basis of the simulation tools used in the analysis of ASHS as well as providing an overview of available fully integrated ASHS.

INTRODUCTION

The importance of safely operating helicopters from moving ships in potentially-severe sea conditions is widely recognized. Critical applications exist ranging from search and rescue 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 rotorcrafts without requiring any personnel on the ship deck thus providing maximum safety to both equipment and personnel.

Even though operational requirements are similar for most shipboard helicopters, the physical characteristics of the required handling facilities are derived from features directly related to the interactions between the specific helicopter and ship characteristics. From helicopter/ship activities performed by INDAL Technologies, a business unit of Curtiss Wright Flow Control Company (INDAL), over the last 20 years two important findings can be highlighted:

- ship design is not, and will not be optimised for helicopter operations; and
- most helicopter designs are not, and will not be optimised for on-deck handling.

These conclusions mean that, to meet current and future naval operational requirements, more emphasis must be directed towards the design of securing and handling facilities that accommodate the interface conditions between the helicopter and the ship. Furthermore, optimisation can be applied to the design of the onboard facilities through better understanding of the deck conditions and their influence on the securing and handling requirements through the use of computer simulation.

Traditional approaches used for estimating the on-deck behaviour of an aircraft on small ships neglect important factors influencing the interface dynamics. Aircraft on ships experience loads generated by geometrically nonlinear and time dependent ship motion, non-linear suspension kinematics, nonlinear and intermittent tire contact and sliding, time and displacement dependent rotor forces, aerodynamic fuselage loading, and a variety of securing forces resulting from nonlinear passive and active type securing devices. Time dependence and nonlinearity of forces acting on an aircraft render static, quasi-static, and frequency domain approaches inadequate for understanding the true nature of the aircraft/ship dynamic interface.

Computer modelling capability that supersedes the limitation of traditional approaches requires a nonlinear time domain solution of the highly coupled equations of motion describing the characteristics of the aircraft/ship system. Such a simulation tool can be used to perform a wide variety of analyses aiding in the optimization of ASHS designs.

INDAL has developed, extensively validated, and applied the *Dynaface*® aircraft/ship dynamic interface simulation software package [1, 2] to expand the understanding of the dynamic interface of aircraft and UAVs fitted with either wheeled or skid-type landing gears. This is particularly important in the current global trend of reduced defence budgets and supporting aircraft operations on smaller and smaller ships where ship motion becomes increasingly severe. This paper outlines several types of fully integrated ASHS and the development and basis of the simulation program mathematical model, validation activity, and the various ways in which the simulation program can be applied to enhance the analysis ensuring the safety of shipboard aircraft operations and personnel.

AIRCRAFT SECURING AND HANDLING SYSTEMS

The challenge posed by the naval environment is that as the severity of sea conditions increases the difficulty to land and deck handle an aircraft/UAV increases. In a very basic system, once the aircraft is on-deck, chocks must be inserted and tie-down chains/straps applied in a choreographed routine well known to flight deck crews. If deck-handling of the aircraft is required, deck crews must use a tow-bar/tow tug in conjunction with a “running” lashing scheme. This involves removing the tie-downs from the aircraft, traversing the aircraft during a period of quiescence, and then reapply the tie-downs to the aircraft prior to the ship exiting quiescence. This time consuming and man-power intensive operation would be repeated until the aircraft is safely stowed in the hangar.

In order to ensure complete safety to both aircraft and on-deck personnel in severe conditions an all-in-one system is required that provides both securing and handling operations. INDAL has the unique capabilities to develop and analyze such systems. Unlike other handling systems (such as deck-lock and wire-based systems) which provide either aircraft recovery or on-deck handling operations, there are only three available systems that can truly be classified as providing complete aircraft securing and handling solutions in a single integrated system. They include INDAL’s; Recovery Assist, Secure and Traverse (RAST) system, Aircraft Ship Integrated Secure and Traverse (ASIST) system, and Twin Claw - Aircraft Ship Integrated Secure and Traverse (TC-ASIST) system. RAST and ASIST are both probe-based systems whereas TC-ASIST is considered a landing gear-based system. In a probe-based system a helicopter-mounted probe, normally mounted on a strong point below the aircraft’s centre of mass, and a shipboard securing device on the flight deck is used to secure to the probe. The landing gear-based system does not require aircraft installation of a probe but rather the shipboard securing device engages with the main landing gear wheel axles through wheel spurs. A brief overview of the various systems is made below.

RAST

The RAST system provides the capability to operate helicopters from ships in very high sea conditions (through sea state 5/6 conditions). A principle performance criterion of the RAST system is that it be capable of recovering and traversing the helicopter with deck motions of up to 31 degrees of roll, 9 degrees of pitch, and a heave rate of 6 metres per second. It is capable of securing the helicopter against these motions within two seconds of touchdown. A helicopter landing on a moving platform using RAST is shown in Figure 1(a).

(a) (b)

Figure 1: Helicopter landing on a moving platform with the aid of a) RAST and b) ASIST

In the employment of RAST, the “Recovery Assist” function assists the pilot to safely land the helicopter within the confines of a Rapid Securing Device (RSD). Recovery is accomplished by attaching a constant tension Recovery Assist (RA) cable from the ship to the helicopter. The pilot flies the helicopter down to the deck while tension on the RA cable guides the pilot during his descent, providing a stabilizing and centring effect. The result is a significantly reduced landing dispersion that ensures the probe will be located within the RSD.

The “Secure” function secures the helicopter, within two seconds of landing by “trapping” a retractable probe, projecting from the underside of the helicopter, in the jaws of the RSD. This is done without the use of on-deck crew.

The “Traverse” function moves the helicopter quickly and securely between the flight deck and the hangar. Straightening the helicopter prior to traversing into the hangar is a simple process by connecting the tail guide winch cables to the helicopter at a point near the tail wheel. The helicopter is held securely during the straightening operation, which is completed in less than two minutes.

There are currently 300 RAST systems in use onboard 200 ships.

ASIST

An improvement over the RAST system is ASIST, which is an integrated system combining the securing, straightening, and traversing functions in a single component, the RSD. A helicopter landing on a moving platform using ASIST is shown in Figure 1(b). ASIST provides continuous aircraft security from the moment of touchdown until it is ready to take off. The system provides safe recovery, securing, straightening, traversing, stowing, and launching of helicopters in severe sea conditions day or night.

ASIST operates without the need for personnel on deck during the landing, securing, straightening, and traversing sequences. It incorporates an electro-optical tracking system, which controls the traverse winch thereby allowing the RSD to follow the aircraft fore and aft during hover and landing. The tracking ability ensures minimum distance between the securing device and the probe at landing. Upon contact with the probe the RSD claw automatically moves laterally across the RSD to complete the probe capture sequence. After the probe is secured, the helicopter can be aligned by a combination of longitudinal and lateral forces applied through the RSD claw. The straightening, traversing, and launch operations are performed without attaching any cables to the aircraft.

Two recent developments related to ASIST that allow for increased capabilities are with the “rotatable” and “reconfigurable” versions of the RSD. The “rotatable” ASIST allows for a single system to operate with both nose- and tail-wheeled helicopters from the same platform. The “reconfigurable” ASIST allows for compatibility with any helicopter type to be operated from a single platform.

There are over 55 ASIST systems in use on over 40 ships.

TC-ASIST

While ASIST is a popular system for those navies that have probe-equipped helicopters, for some navies the option to install a probe on existing helicopters is difficult. In order to support non-probe installed aircrafts, INDAL has developed the TC-ASIST, a derivative of an already proven and successful ASIST system. The TC-ASIST is based on the ASIST system but employs a larger RSD as shown in Figure 2.

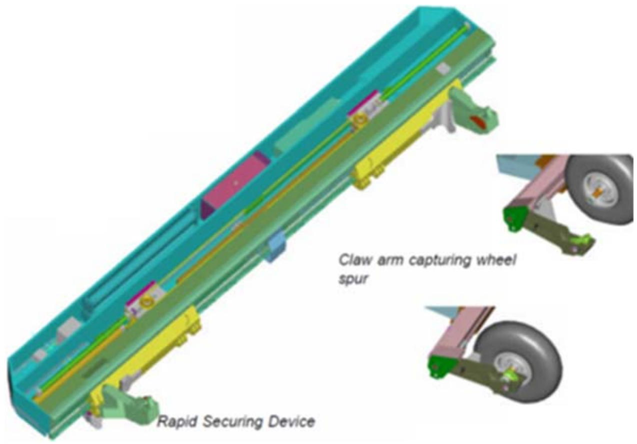

Figure 2: TC-ASIST system

The pilot, assisted by visual cues, flies the aircraft to a position over the designated landing area on the flight deck. The RSD, fitted with a pair of claw arms designed to capture and secure the wheel spurs of the aircraft, tracks the aircraft's position with the capture arms at a ready position at either end of the RSD. The claw arms are spring loaded and held in the down position until tire sensors contact each tire as the arms are brought in. Upon contact, spring force rotates the claw arm upwards until it contacts the wheel spur. Each claw arm acts independently, but they are mechanically interlocked to ensure simultaneous operation.

TC-ASIST provides smooth, controlled, and secure movement of the helicopter between the landing/take-off position and the hangar. After the helicopter is landed and secured, the helicopter can be aligned and centred over the deck track by combinations of fore and aft forces applied to the main landing gear by the RSD. The straightening operation is performed without attaching cables to the aircraft or the need for any personnel on deck, in a similar manner to the existing ASIST system.

There are currently 2 TC-ASIST systems in use on 2 ships.

***DYNAFACE*® MODEL DEVELOPMENT**

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 a very large number of simulation cases can readily be investigated within the scope of a single dynamic interface study.

The ship experiences spatial motion consisting of three translations (surge, sway, and heave) and three rotations (roll, pitch, and yaw). The ship motion is governed by the ship geometrical and inertial properties and excitation resulting from sea state and wind conditions. Recognizing that the mass of the aircraft is negligible compared with the mass of the ship, it is reasonable to neglect the influence of the aircraft dynamics on the ship motion. However, the converse of this statement is not true. Ship motion is typically the most significant excitation acting on the aircraft. Consequently the six degrees of freedom describing the ship motion may be considered as prescribed functions of time.

Dynaface® consists of a special-purpose 15-degree-of-freedom mathematical model of the aircraft/ship system. While the simulation is special purpose to promote solution efficiency, it includes sufficient generality such that a large variety of aircraft/UAVs and virtually all ships can readily be modelled. The simulation currently allows for analysis of both wheeled (containing prismatic oleo and leading/trailing arm suspension models having up to two wheels each that can be attached to the fuselage in either the nose or tail wheel configuration) and skid type landing gear systems (with or without ground handling wheels), up to two main rotors, and a large variety of possible securing devices; probe-based systems, tie-down cables, single force systems, harpoon/deck-lock type systems, pretensioned probe systems, and landing gear securing systems. The model includes detailed representations of the oleo stiffness, damping, and friction characteristics; induced rotor forces; and a detailed 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 maximised 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. The aircraft and ship configurations, environmental conditions, and simulation control parameters are specified in a set of input files. The simulation uses this information to describe the physical system. It then generates the time-varying prescribed ship motion and propagates a time-domain solution by numerically integrating the governing equations of motion for the system.

Governing Equations

A schematic illustration of the position and orientation of the rigid body representing the aircraft in the global space coordinate system is shown in Figure 3. The displacement vector from the origin of the space frame to the aircraft centre of mass is

$$\vec{r}_{cm} = r_x\vec{\imath} + r_y\vec{\jmath} + r_z\vec{k} \tag{1}$$

where $\vec{r}_{cm}$ is defined in the inertial coordinate system. The linear velocity and acceleration can then be found by differentiating the displacement vector and velocity vector respectively.

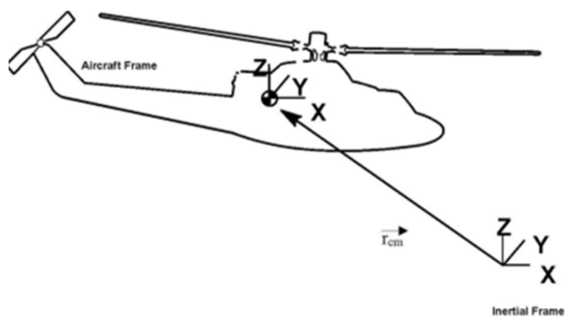

Figure 3: Schematic illustration of the aircraft body in the global coordinate system

Newton's law is used to relate the equipollent forces $\vec{F}_{eq}$ acting on the aircraft to the linear accelerations of the aircraft centre of mass expressed in the inertial space coordinate system.

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

where *m* is the mass of the aircraft. Equation 2 is solved for the linear accelerations. These are numerically integrated twice resulting in the linear velocities and displacements of the aircraft expressed in global coordinates.

The rotational motion of a body in space can be described using a set of XYZ Euler angles (θ_x, θ_y, θ_z) where θ_x, θ_y, and θ_z are the roll, pitch, and yaw angles respectively. Rotations about the x, y, and z coordinate axes are summarized by Equations 3 through 5 respectively.

$$[R_x] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \tag{3}$$

$$[R_y] = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \tag{4}$$

$$[R_y] = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The order of transformation from the local coordinate system to the global is defined as roll followed by pitch followed by yaw where the global to local transformation matrix is defined as:

$$[T]_{g\ to\ l} = \left[[R_x] \quad [R_y] \quad [R_z] \right]^T \tag{6}$$

The angular velocity of the body expressed in local coordinates can be expressed in terms of the time derivatives of the XYZ Euler angles and the Euler angles themselves. Alternatively, the angular velocity of the body can be expressed in the global coordinate system.

In solving forward dynamics problems using Newton-Euler equations, it is common for the angular velocities in the local coordinate system to be known. These are obtained from numerical integration of angular accelerations expressed in local coordinates determined using Euler's equation. From these it is necessary to extract the time derivatives of the Euler angles. These are required so that they can be numerically integrated to obtain the Euler angles at the next time step. The time derivatives of the Euler angles can be evaluated from the local angular velocities and the Euler angles themselves.

Euler's equation is used to solve for the absolute angular accelerations of the aircraft expressed in the aircraft frame $\vec{\dot{\omega}}$ from the vector of equipollent moments acting on the aircraft and the angular velocities of the aircraft [3]

$$[I]\{\dot{\omega}\} = \{M_{eq}\} + \{M_{gyr}\} \tag{7}$$

where $[I]$ is the inertia matrix for the aircraft, $\{\dot{\omega}\}$ is the vector of angular accelerations expressed in the aircraft coordinate system, $\{M_{eq}\}$ is the equipollent moment vector, and $\{M_{gyr}\}$ is the vector of gyroscopic moments. The angular accelerations of the aircraft in the local coordinate system are numerically integrated to obtain angular velocities in the local coordinate system. From these, the time derivatives of the Euler angles which are numerically integrated to obtain the Euler angles for the next time step.

In addition to the fuselage, the aircraft is comprised of suspension stations. Two suspension station configurations that are in common use are vertical oleo suspensions and pintle-arm suspensions. The physical contact between an unsecured aircraft and ship occurs through the tires (for wheeled aircrafts) that generate longitudinal, lateral, and vertical forces or skid tubes (for skid type aircraft). Tires may also slide along the deck or lift off the deck during the simulated period of motion, wheel brakes may slip, and wheel steer angles may vary.

Directly generated external forces resulting from gravity, aerodynamic drag, and rotor forces generated either as the result of rotor angle of attack or rotor thrust are applied directly to the aircraft. Further, securing devices can apply passive or active forces to the aircraft at the securing points. Figure 4 provides a schematic representation of typical forces acting on an aircraft.

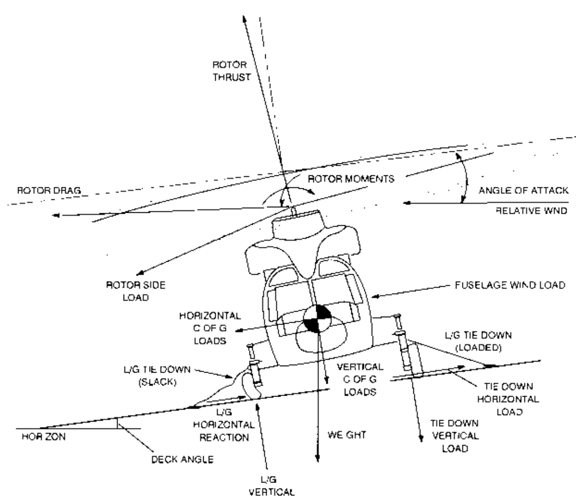

Figure 4: Identification of forces acting on a secured aircraft

Suspension Station

Two widely used suspension station configurations implemented in the model are cantilever and leading/ trailing arm suspensions. Each adds one degree of freedom (linear or angular) to the model per station.

The dominant 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 5 though the extent of the transition region is very much exaggerated for clarity. Complex oleos can be modeled using additional stiffness stages that are appended to the oleo stiffness characteristic.

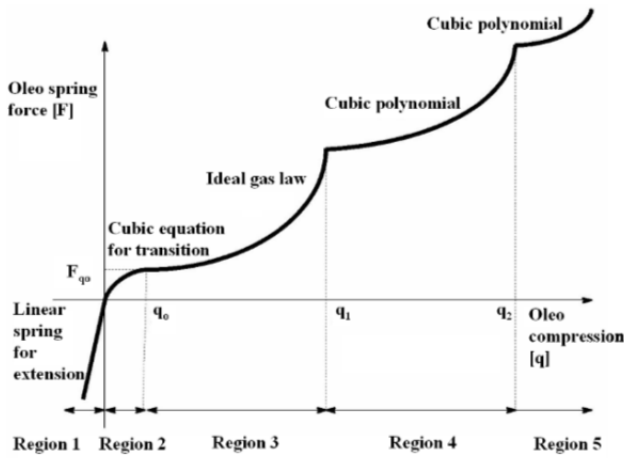

Figure 5: Schematic representation of the oleo stiffness model

The non-symmetrical 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 [4] is used to evaluate the oleo friction force. 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.

Tires

Tire forces are calculated assuming vertical compression and tire design-dependent stiffness in the longitudinal and lateral directions [5] and a multistage 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 6. Second, tire sliding occurs when the resultant of the longitudinal and lateral forces exceeds the instantaneous friction capacity. 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.

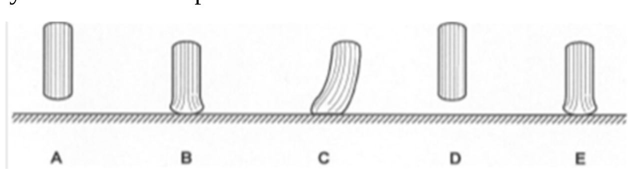

Figure 6: Schematic representation of tire behaviour during intermittent tire contact

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.

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 [6]. 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.

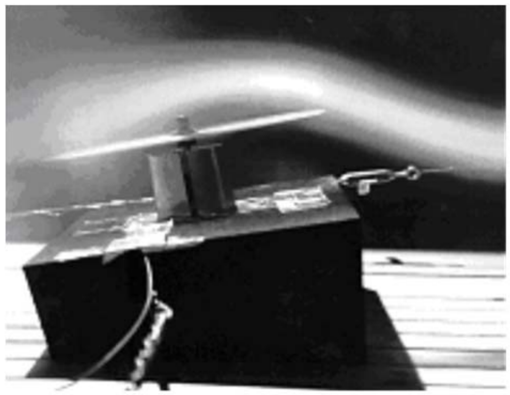

Figure 7: Visualization of air flow over a typical frigate flight deck

Skid Type Aircraft

The typical structural elements of a skid landing gear and associated nomenclature are defined in Figure 1. It is observed that the two main structural elements are the skid tubes and the cross-tubes. The cross-tubes provide the compliance in the landing gear and typically provide little damping to the system unless fitted with external damping devices. The skid tubes serve the primary function of providing a large contact area with the ground and consequently minimize contact pressure.

Dynaface® includes two skid landing gear stiffness models [7]. The first is a linear model that makes assumptions about the linearity of the landing gear stiffness and the relative rigidity of the skid-tubes. As a result, the associated input data requirement is simple and the simulation run speed is fast. The second alternative models the cross-tubes and skid-tubes using a general three-dimensional finite element analysis supporting beam elements. While more complex than the linear model, the input file remains fairly simple and this model provides considerable versatility in the range of landing gear that can be represented. The simulation speed, though slower than the linear model, is not prohibitive in this transient dynamic simulation due to the use of the finite element model strictly as a stiffness force producing device without implicitly including the high frequency vibration modes associated with full flexible body dynamic analysis and the corresponding numerical stiffness.

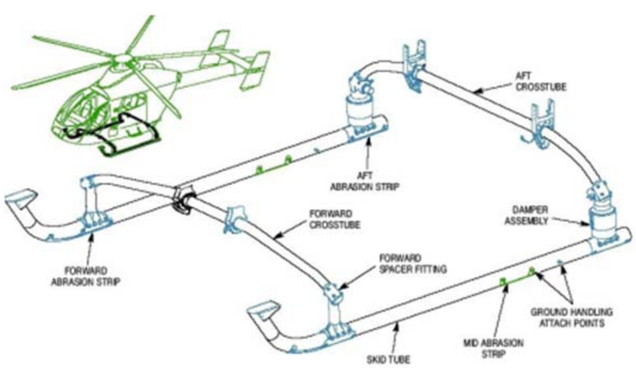

Figure 8: Skid landing gear nomenclature (adapted from [8])

Validation

Development of the simulation program has emphasized the importance of accurately predicting the interface parameters between an embarked helicopter and ship. The input data source to some extent influences the relative importance of verification and validation at the simulation component level. During development, each component of the simulation program 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. During landing gear design and tuning, designers routinely conduct an extensive experimental drop test program whereby a large volume of data is collected. 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 9 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 9.

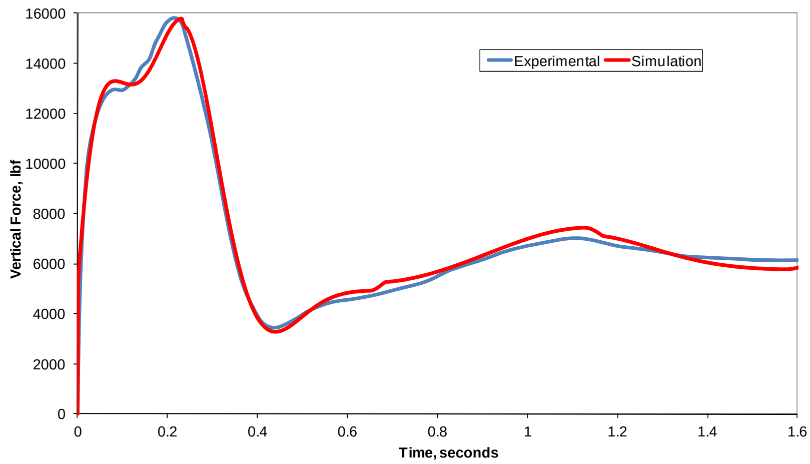

Figure 9: Comparison between experimental and simulated drop test data for a typical cantilever main landing gear suspension

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 10 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 10, nominal aircraft parameters and a steady wind were assumed thereby likely accounting for the differences observed. 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.

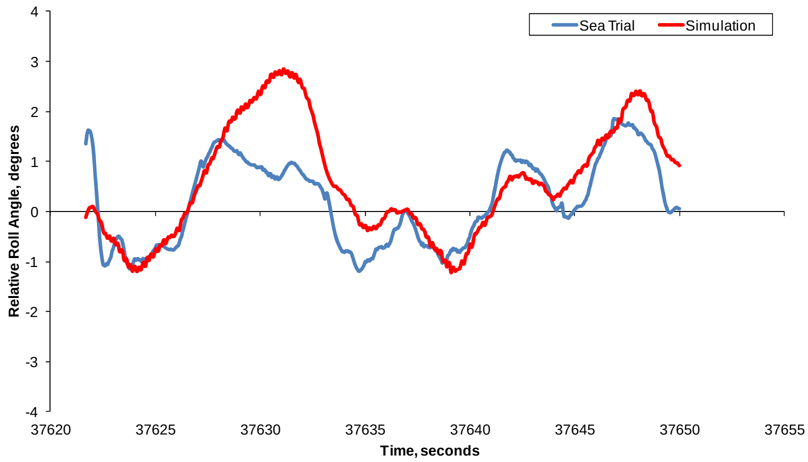

Figure 10: Comparison between measured and simulated sea trial data for a typical medium-sized tail dragger helicopter operating on a typical frigate in severe sea conditions

SECURING REQUIREMENTS

The performance of a helicopter securing system must account for the dynamic interface conditions between the helicopter and the ship to meet the fundamental requirement for securing. Since helicopter securing reflects safety aspects regarding personnel during on-deck helicopter operations, a quantitative definition of helicopter securing was developed as follows. For a helicopter to be considered "secure", two criteria must be satisfied:

- excessive motion must be prevented; and
- aircraft sliding must not occur.

While it is widely known that a variety of conditions affect the securing requirements for a helicopter on a moving platform, the effects of ship design have been discussed extensively in Reference [9], and the effect of sea conditions and ship operating conditions have been addressed to some extent in Reference [10]. The interface parameters of a secured helicopter (landing gear reactions, helicopter movements relative to the deck, and securing loads) vary considerably depending on the underlying principle upon which the securing system is based.

All securing systems can be classified in one of two categories – passive and active, as described below. The two securing principles are illustrated schematically in Figure 11.

a) 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 a passive securing system include; tie-downs, RAST, ASIST, and TC-ASIST.

b) Active securing systems are those in which a mechanical/hydraulic device, fitted to the helicopter and attached to the ship, continuously applies a constant 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 of such systems include; deck-lock and wire-based systems.

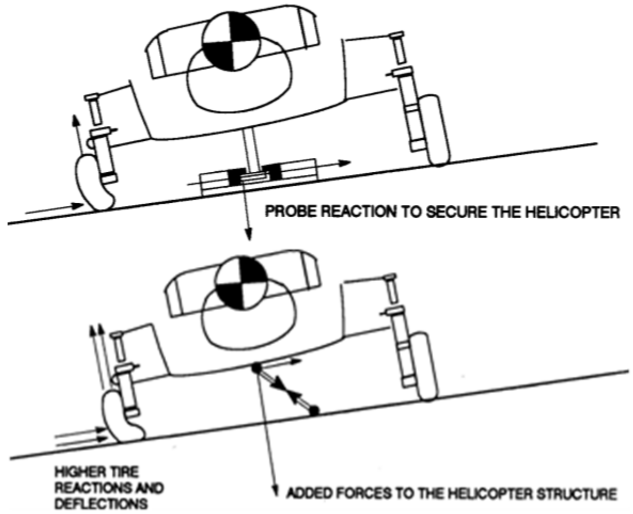

Figure 11: Schematic representation of passive (upper) and active (lower) securing principles

The selection of securing principle not only affects securing loads, as indicated above, but also directly influences how the second part of the securing definition is satisfied. Consider the schematic illustrations in Figure 12. The left sketch corresponds to an aircraft secured by a single point passive system such as INDAL's probe system as pictured in Figure 13. The right sketch corresponds to a single point constant tension link (deck-lock) system. In the case of the passive system (left sketch), the probe, which is generally mounted in the aircraft close to the centre of mass, forms a fixed point of rotation between the helicopter and ship. Consequently, the only mode by which sliding can occur is aircraft yaw about the fixed point of rotation. For this to occur, all tires must become saturated such that they cannot generate sufficient friction to produce the frictional moment about the fixed point of rotation required to resist aircraft relative yawing. In the case of a single constant tension link (right figure), the securing system essentially acts as a constant-tension spring between a point generally close to the centre of rotation of the helicopter and the ship. As this system does not form a fixed point of rotation, two instability modes are possible that can result in sliding and correspondingly failure to satisfy the securing definition. The first instability mode is pure translation of the aircraft; the second is pure rotation (in yaw) of the aircraft.

Dynamic analysis studies consistently show that sliding manifests itself as a combination of the two modes such that the aircraft yaws about an instant centre of rotation. This is the situation illustrated in Figure 12 where rotation occurs about the main gear located in the lower left of the sketch (the same rationale applies to both nose and tail gear aircraft). The result is that loss of securing can occur when only two landing gears (rather than three in the case of a single passive probe system) reach their frictional saturation limit.

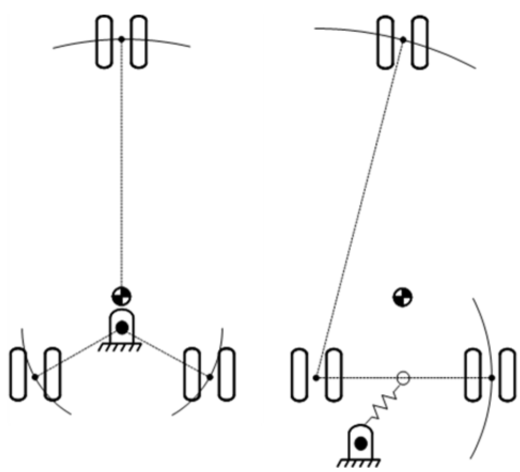

Figure 12: Schematic representation of fixed point of rotation created by a single point passive securing system (left) and the usual instability mode associated with single point constant-tension securing systems where yaw tends to occur about an instant centre of rotation located at a main landing gear (right)

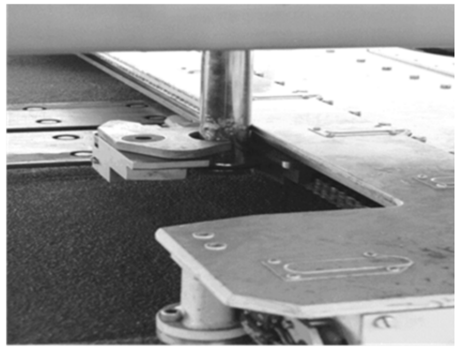

Figure 13: INDAL's passive ASIST securing system securing an intermediate-sized helicopter

AIRCRAFT RESPONSE ANALYSIS

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 maximise simulation speed such that a very large number of simulation cases can readily be performed such that a variety of on-deck scenarios can be investigated during a single study.

While the forces acting on the helicopter are a function of the helicopter characteristics and the deck conditions, the securing forces are largely affected by the method of the securing as discussed below. Model complexity arises from the nonlinearity and range of behaviours associated with the various force-producing elements in the model.

A dynamic interface analysis study was conducted using a heavy helicopter secured to a typical frigate up to upper sea state 6 conditions (characterised by 6.0-metre significant wave height and an apparent wind speed of 35 knots from the beam). The securing definition (described earlier) was applied in post-processing the results and the resulting operational envelopes are presented in Figure 14. Shaded areas in red indicate ship headings (relative to the principal wave direction) and ship speeds where the securing definition is *not* satisfied. The results indicate that for the helicopter/ship combination considered, the heavy aircraft fitted with the probe system can be considered secure for all combinations of ship heading and ship speed in sea states 5 (right-hand side of plots) and 6 (left-hand side of plots). However, the operational envelope for the constant tension link secured aircraft is limited to ship headings from 0° to ±45° and from ±135° to 180° in sea state 5 and from 0° to ±30° and from ±150° to 180° in sea state 6. As all other parameters remained constant, this difference can only be attributed to the securing principle. The envelopes are a function of the system simulated, however the tendencies are generally applicable.

Ship limits in terms of ship angular displacements (mainly roll and pitch) are typically used by several Navies to indicate operating limits. The results for the probe-based system is are shown in Figure 15 while the results of the constant tension system are shown in Figure 16. The green points identify the ship roll and pitch values corresponding to those cases where the securing definition was satisfied. The red points identify the ship roll and pitch values corresponding to those cases where the securing definition was *not* satisfied. The solid blue line represents the predicted boundary between safe and potentially unsafe ship roll and pitch values. The ship roll and pitch limits, identified by the dashed box, is defined as providing the maximum combination of ship roll and pitch angles.

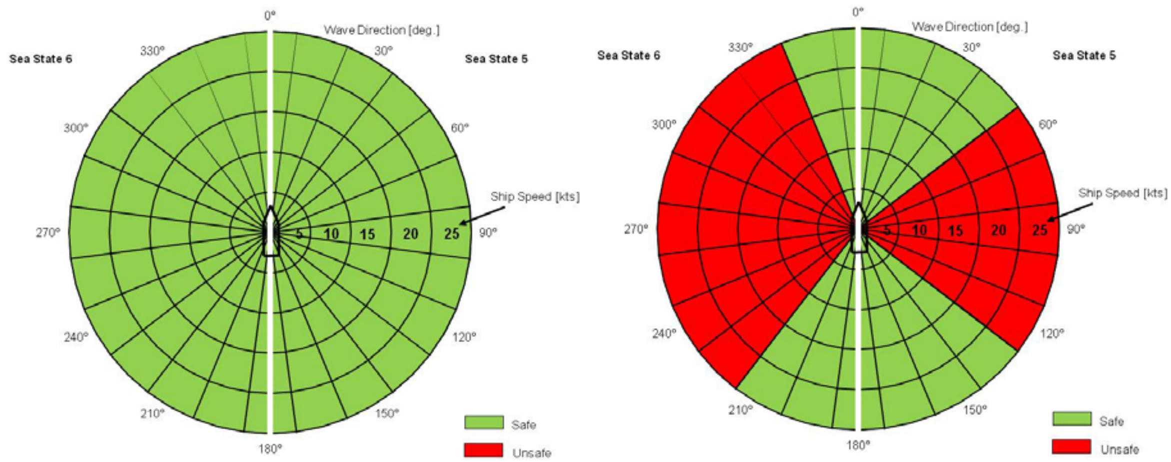

Figure 14: Ship headings and speeds where the securing definition is not satisfied for a) probe-based system and b) constant-tension system in sea states 5 and 6

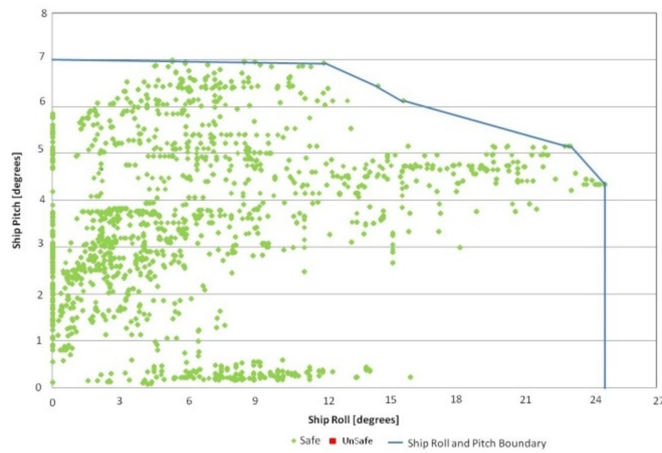

Figure 15: Ship roll and pitch limits up to sea state 6 when using a probe based securing device

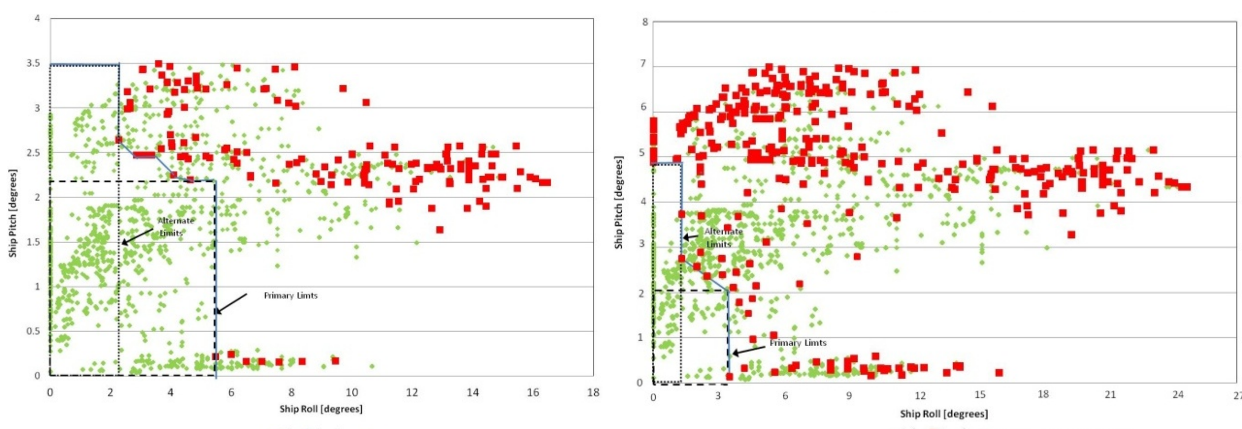

Figure 16: Ship roll and pitch limits in a) sea state 5 and b) sea state 6 when using a constant tension securing device

In the case of the probe-based system operating limits in terms roll and pitch can be said to be 24° roll and 7° pitch as these values represent the maximum expected ship motion predicted for sea state 6 (actual operating limits can be higher). For the constant-tension system limits of 5° roll and 2° pitch in sea state 5 and 3° roll and 2° pitch in sea state 6 were predicted. As operating limits generally do not include sea states, as identification of a sea state is subjective without proper instrumentation, the limits that potentially would be the values derived from the sea state 6 analyses and applied to lower sea states. This would reduce the operating capabilities of the aircraft when in fact increased operations are possible in lower sea states.

As can be seen in Figure 16, a number of cases satisfy the securing definition (green points) but are outside of the boundary envelope (blue line). This is a strong indication that the underlying helicopter dynamics are primarily driven by ship linear and angular accelerations rather than angular displacements alone. The prediction of the roll and pitch limits would not be possible using a static or quasi-static based analysis.

DYNAFACE® CAPABILITIES

Dynaface® was developed as a versatile analysis tool. Since it's initial development, significant experience has been gained with its use. Below are some of the additional analyses that can be performed.

Analysis of Aircraft Handlers

The simulation model provides capability to simulate a wide variety of existing and proposed aircraft handling devices that may operate independently or in combination with a securing system. Some aircraft handling systems, such the one shown in Figure 17, are not track based and rely on deck friction to prevent unwanted sliding. Analysis of the on-deck stability of such systems becomes essential for which *Dynaface®* is well suited.

Figure 17: Aircraft handling using MANTIS

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. Extended periods of time-domain data can be generated by *Dynaface®* to ensure statistically representative loading and this data can be subsequently post-processed using rainflow counting methodologies of load cycles leading to fatigue spectra as shown in Figure 18.

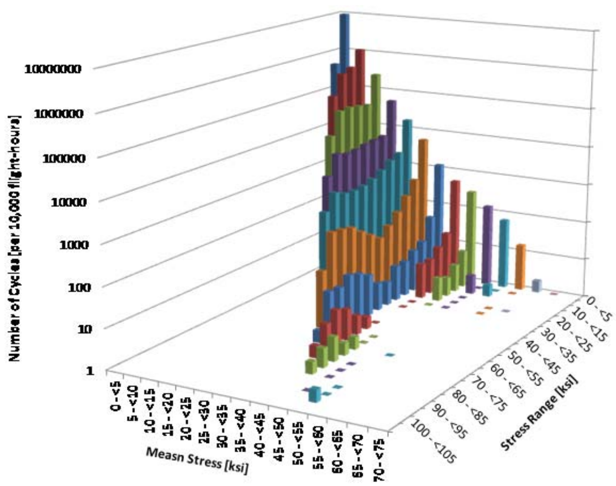

Figure 18: Sample rainflow cycle counting results of probe stress (per 10,000 flight-hours)

Clearance Analysis

Static and quasi-static analyses are insufficient to address clearance issues between helicopter-mounted and ship-mounted equipment 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. *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. 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 (refer to Figure 19).

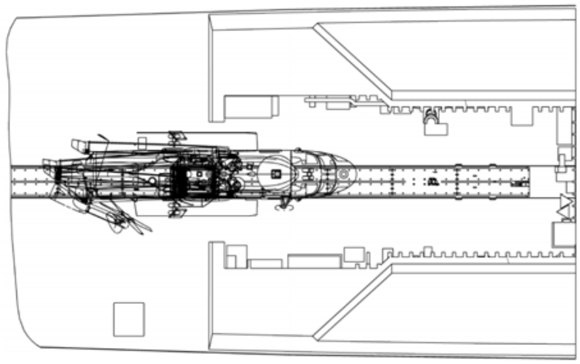

Figure 19: Helicopter positioned at hangar door opening for clearance analysis

Parameter Optimization

A wide variety of sensitivity and optimization analyses are 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.

Incident Investigation

While emphasis is most often placed on analysis to prevent potential accidents involving shipboard aircraft, accidents do occasionally occur (refer to Figure 20) and the resulting consequences can be severe including the damage/loss of helicopter, injury/loss of personnel, 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.

Figure 20: Aircraft rolled over on a moving platform

CONCLUSION

INDAL is continually applying proven expertise in the field of aircraft securing and handling systems and of aircraft/ship dynamic interface analysis to further explore factors affecting aircraft securing requirements thus providing optimized solutions to aircraft securing and handling systems. The primary objectives are to:

- maximise availability of aircraft for takeoff and landing to the full operating envelopes of the helicopter and ship; and

- ensure maximum safety of personnel and equipment.

This paper has presented several solutions to recovery and handling of aircrafts in an “all-in-one” fully integrated solution package that supersedes limitations of other systems. In addition, an overview of the computer simulation modeling fundamentals and capabilities was provided.

Study results indicate that constant tension active systems are unable to secure intermediate and large helicopters without using excessively high tensions that potentially exceed those acceptable for landing gear design limits. The results also indicate that passive devices provide the necessary securing and handling capabilities of intermediate and heavy helicopters over a wider range of the ship operating envelope.

Only through the use of nonlinear transient dynamic analysis cast in the form of a computer simulation can the full potential of both the helicopter and ASHS can be realized thus providing “profound value” to the end users.

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