Extending UAV Operating Envelopes

Dr. Stephen R. Borneman, Aerospace Engineer

Michael LaRosa, MSc, Mechanical Engineer

James McCallum, Director of Engineering

Curtiss-Wright Flow Control - INDAL Technologies, Mississauga, Ontario, Canada

Abstract

Unmanned Air Vehicle (UAV) operations from ships in adverse weather conditions from high hover to touch down through on deck handling requires a detailed understanding of ship and, more importantly, the ship/UAV coupled dynamics. Classical static and quasi-static analysis can be adequate for high level reviews. However, designing UAV/Ship systems based solely on these can be very misleading. For example, onset of sliding or tipping can be generated at very low roll angles when coupled with critical acceleration levels. Consequently, to understand the true dynamics of the UAV/ship interface, a time dependant non-linear analysis is necessary. A dynamic interface analysis (DIA) approach to UAV handling, including securing, aligning and traversing, using non-linear dynamics can extend the UAV's operational capabilities beyond those estimated from a static analysis.

Keywords

UAV, stability, non-linear, dynamic, Dynamic Interface Analysis (DIA) and operating envelopes

Introduction

Unmanned Aerial Vehicles (UAVs) have demonstrated strategic advantages in facilitating real-time intelligence gathering over many years. Various types of UAVs exist, including fixed wing and rotorcraft, however, aircraft capable of vertical take-off and landing are considered in this paper. Moreover, UAVs are smaller, lighter, less conspicuous, and for well-selected missions, equally or more capable than their piloted alternative. In hostile environments, their use avoids exposing flight crews to unnecessary risk. Typically UAVs are launched from land based areas, however increasingly UAVs are being used on ships. However, for UAVs to fulfill embarked mission requirements they must be capable of operating in sea conditions equally or more severe than those in which piloted aircraft routinely operate (typically greater than sea state 4 for small ships). INDAL Technologies, a business of Curtiss-Wright Flow Control Company, is a developer of maritime aircraft recovery, securing, and handling equipment that has extensive experience in analyzing the embarked operation of marine helicopters and UAVs. In 2000, INDAL Technologies conducted a collaborative project with Bombardier Inc. regarding the interface requirements for UAV (CL-327 'Guardian') embarked operations aboard two vessels, namely the 'Oliver Hazard Perry' (FFG 7) and the U.S. Coast Guard 'Famous Cutter' (WMEC) [1]. The results of this study found that the design objective of the CL-327 being operational from small ships in severe sea conditions imposes a demanding requirement for both air vehicle controls during launch and recovery and on-deck securing due to the potential severity of flight deck conditions resulting from induced ship motion. The study concluded with the importance of on-deck securing, including vertical restraint, in all but the most benign sea conditions. However, when adequate securing is present no restrictions on operation exist. Further, for the case where vertical restraint is not used, operational envelopes were defined based on sea state, ship heading, apparent wind direction, and apparent wind speed.

The main purpose of UAVs are to mitigate risk to human life by allowing unmanned aircraft to be used in environments that would otherwise exhibit significant danger to pilots. This also holds true for UAV remote operators and deck crew. The greatest risk to safety occurs during securing and handling operations. On deck handling of UAVs by automated securing systems provides a safer environment for crew members where securing equipment can be operated from a remote location during high sea states. INDAL Technologies, has extensive experience in the field of aircraft securing and handling systems aboard naval vessels. From large helicopters (>15 tonnes) to small UAVs (<0.5 tonne)), INDAL has conducted cutting edge numerical and experimental investigations in the realm of non linear dynamics.

A detailed understanding of this UAV/ship interface and the corresponding dynamic loads can be achieved by conducting a time domain analysis. Incremental time steps in the kinematics allows for capturing significant nonlinearities that if missed could adversely impact the validity of the solution. Other methods such as, static, quasi-static or frequency domain approaches exist, however can grossly under estimate aircraft responses, such as slipping, tipping and/or force magnitudes. The accuracy of a ship/UAV interface mathematical model depends greatly on how the ship motion is developed. In the last century extensive development of linear based ship motion theories have been formulated and presented. A number of authors have considered equating ship motion in the frequency domain [2, 3]. In the field of marine hydrodynamics predicting the non-linear behaviour of free-surface boundary conditions, wind gust, waves and the body geometry can be cumbersome. To fully understand the capabilities of landing a UAV on a ship and the generated coupled motions, non-linear dynamic modelling is necessary to capture the interface dynamics of a particular ship aircraft combination. This can be accomplished using a time domain approach where, random ship motion can be generated for any specified ship in a known sea state and then used as a baseline for design and dynamic loading to an aircraft.

To accurately define these operational envelopes, an appropriate mathematical model needs to be used to capture the aircraft's dynamics on the flight deck. This paper investigates the differences between a fully non-linear dynamic UAV/ship interface as compared to results attained from static and quasi static dynamic approximations. In addition, it is the incentive of this paper to show how accurate knowledge of the non linear dynamics at different sea states impacts operational safety of an aircraft and the deck crew. Moreover, anticipating the dynamics of a UAV and the on-deck load interactions with the ship can curb the direction of autonomous coding of the on-board aircraft computer.

In addition to evaluating the aircraft/ship dynamics of a UAV on touchdown without restraint, an evaluation of the forces and loads generated from a restrained aircraft provides insight into design and optimization of these supporting fixtures. Two basic steps for UAV operation aboard a naval surface vessel are generally required. First, UAV/ship dynamic interface analysis is conducted on touchdown, and second, the securing and traversing of the UAV is analyzed. On a number of modern helicopters, a probe attached to the belly of an aircraft is secured to the ship deck via a grid or capturing device. Given, UAVs are considerably lighter than full size helicopters, and the corresponding inertial impact on the dynamics of the aircraft is considerably less, the design of the securing interface can be much smaller reducing impact on the range of operation.

Static Approach

The first step to investigate the on-deck behaviour of a UAV under static conditions (simulating the conditions of a listed ship) is to define the location of the center of gravity of the aircraft relative to the deck and supporting contact points (refer to Figure 1). The contact points of the UAV with the ship deck are shown in Figure 2a and Figure 2b, additionally, the F_g represents the force of gravity of the UAV with location defined by x_1 and y_1. F_{xa}, F_{ya}, F_{xb} and F_{yb} represent the reaction forces at the two front aircraft supporting legs in the vertical and lateral directions of the ship coordinate system. A static evaluation of the UAV stability is performed based on the dimensions illustrated in Figure 2(a) and Figure 2(b) where, x_1 and y_1 is 0.56 m and 0.628 m, respectively. The distance *d* from the center of gravity to the dashed line (line of tipping) is 0.454 m. Friction forces at point of contact '*c*' are neglected for the sliding stability of the aircraft.

A wind drag force in the lateral direction is applied at the centre of pressure of the lateral side of the UAV's fuselage defined by,

$$F_{Wind,Drag} = \frac{1}{2}\rho V^2 C_D A \qquad (1)$$

Where, ρ is the mass density of air, V, is the apparent wind velocity C_D is the coefficient of drag and *A*, is the lateral projected area of the aircraft. Table 1 summarizes the parameters used for this analysis.

Table 1: UAV parameter values for static analysis

Parameters	Value
Wind Speed, V	19 knots
Mass of UAV	200 kg
μ_f	0.6
C_D	1.0
A	1.5 m^2
ρ	1.225 kg/m^3
y_1	0.628
x_1	0.560

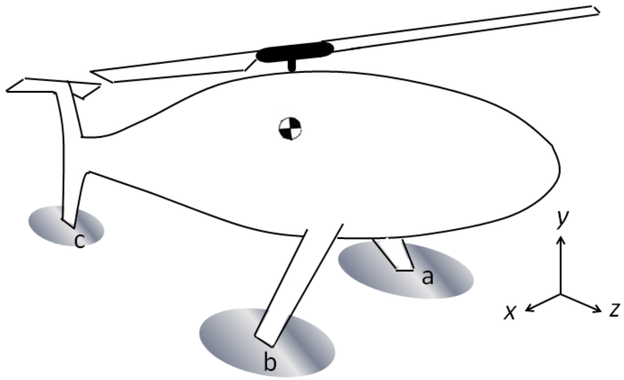
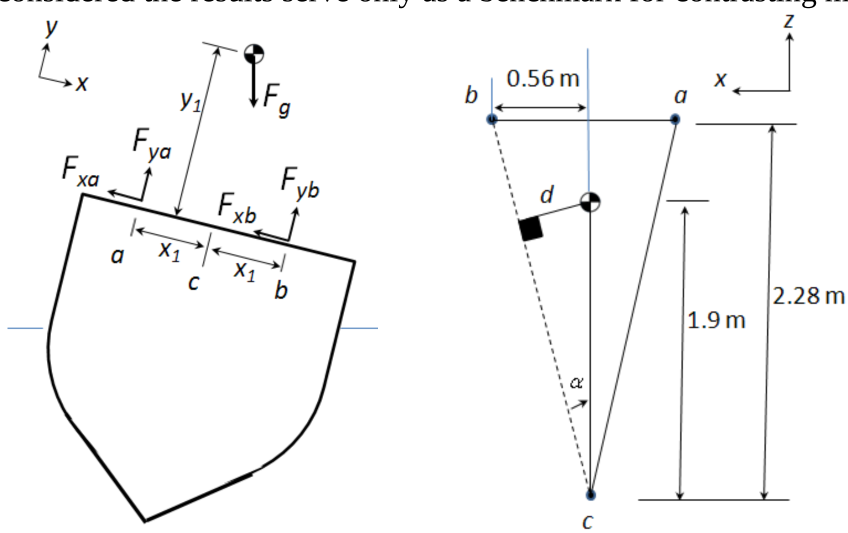


Figure 1: 3D View of a UAV

From Figure 3, the stability of the aircraft is presented for both sliding and tipping. The vertical axis of this figure is normalized to show a value of 1 for maximum stability and a value of zero or less for exceeding the onset of sliding or tipping. The UAV is shown to slide at a critical ship roll value of greater than 29 degrees. For static equilibrium of forces and moments to be satisfied, a ship roll angle cannot exceed 35 degrees; otherwise the aircraft becomes unstable and tips over. Moreover, the maximum roll angle of most ships never exceeds 20 degrees in sea state 6. Consequently, the UAV considered in this analysis based on static balance of equations remains stable up to minimum sea state 6 [4]. However, since dynamic accelerations as result of inertial roll are not considered the results serve only as a benchmark for contrasting methods.



(a) (b)

Figure 2: (a) UAV forces on rolled ship, (b) Elevation view of the UAV on-deck contact points (not to scale).

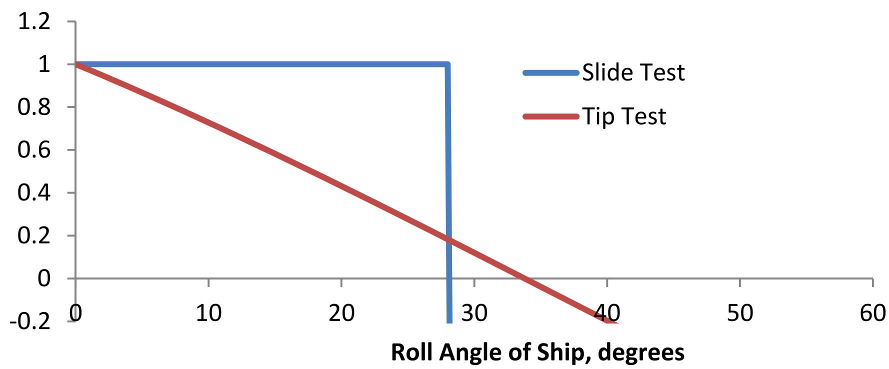


Figure 3: Stability of a UAV based on static analysis

Quasi-Static Approach

Quasi-static methods are commonly used in engineering and physics to simplify the complex dynamic system to a static system, by retaining the accelerations and forcing them to be in equilibrium for a specific point in time. The following approach involves mathematically solving the system illustrated in Figure 4, statically, with applied accelerations for different increments of ship roll angle θ. For each angle increment the stability of the UAV is tested for specifically sliding and tipping. The UAV is considered stable if the friction forces at ship/UAV contact points '*a*' or '*b*' are greater than the forces required to maintain static equilibrium in the aircrafts lateral direction. The UAV model is identical to the one used in the static approach with addition of ship acceleration terms as per MIL-T-81259B(AS) [5].

The UAV is considered to be stable and not tip over, if the moments about point '*a*' are in static equilibrium. For this to hold true, reaction force F_{yb} (see Figure 4) must be positive or zero. When the reaction force at '*b*' is negative, a pull down force is required at '*b*' to balance the moments on the aircraft. However, an unrestrained UAV is not capable of providing such a force therefore the UAV is considered to be unstable and aircraft rolling motion occurs due to the unbalanced forces. MIL-T-81259B(AS) forces lateral and vertical components are denoted by $0.25F_g$, and $0.85F_g$, respectively.

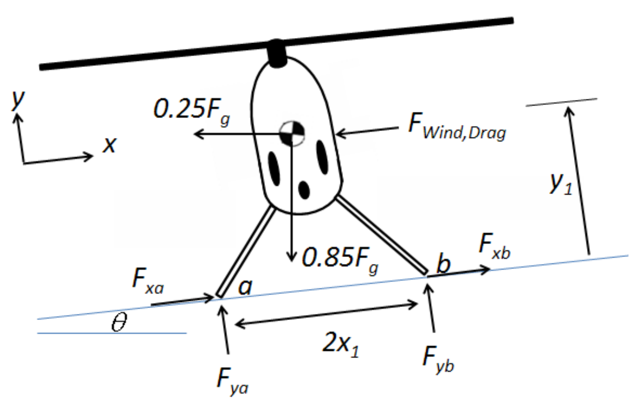


Figure 4: Quasi-static model of an unrestrained UAV

From Figure 5, the stability of the aircraft is presented for both sliding and tipping. As in the static scenario, the vertical axis of this figure is normalized to show a value of 1 for maximum stability and a value of zero or less for exceeding the onset of sliding or tipping. The UAV is shown to slide at a critical ship roll value of greater than 14 degrees. The stability value for sliding remains unchanged to this critical roll angle which indicates both contact points ‘a’ and ‘b’ begin to slide at the same ship listed angle.
As expected, the UAV tips over at a much lower angle (approximately 22 degrees) than the angle presented in the previous static case.

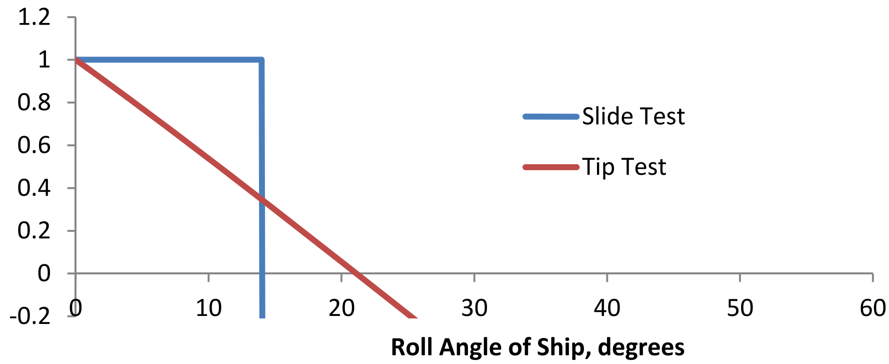


Figure 5: Stability of a UAV based on quasi-static analysis

<u>Time domain Approach</u>

The aircraft/ship Dynamic Interface Analysis (DIA) is a specific application of a more general two body problem. The general two body problem consists of two rigid bodies each having spatial motion coupled by force generators and acted upon by applied forces. The simulation may be considered to predict the three-dimensional motion of a landed UAV aircraft in response to a platform whose motion is a defined as a function of time.

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.

INDAL has developed, extensively validated, and applied the *Dynaface*® aircraft/ship dynamic interface simulation software package [6, 7] to expand the understanding of the dynamic interface of aircrafts and UAVs fitted with either wheeled or skid-type landing gears. *Dynaface*® consists of a special-purpose 16-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. 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.

Assuming the UAV has negligible influence on the inertia of the ship, the six degree of freedom generalized governing equation of motion of the ship can be solved based on random excitation. The Response Amplitude Operator (RAO) ship motion generation approach is commonly used to generate ‘realistic’ ship motion through a complete range of ship headings, speeds, and sea states theoretically developed. Established methods and corresponding computer programs are available for calculating RAO’s based on a description of the ship and the operating environment [8, 9]. The RAOs are the amplitudes, frequencies, and phases of sinusoidal solution components which, when multiplied by the seaway wave spectrum and summed, generate ‘realistic’ ship motion. For each of the ship configuration coordinates, the motion is calculated from the ship motion spectrum by summing the contributions of a finite number of solution components.

$$q_i(t) = \sum A_{ij} \sin\left(\omega_{ij} t + \theta_{ij} + \theta_{RND\,j}\right) \tag{2}$$

Where N is the number of solution components contributing to the motion, A_{ij} is the amplitude of the solution component j contributing to motion configuration coordinate i, ω_{ij} is the frequency of solution component j, θ_{ij}, is the phase angle of solution component j, and $\theta_{RND\,j}$ is a random phase angle uniformly distributed on domain $[0, 2\pi]$ associated with solution component j. Ship velocities and accelerations are the first and second time derivatives of equation (2), respectively.

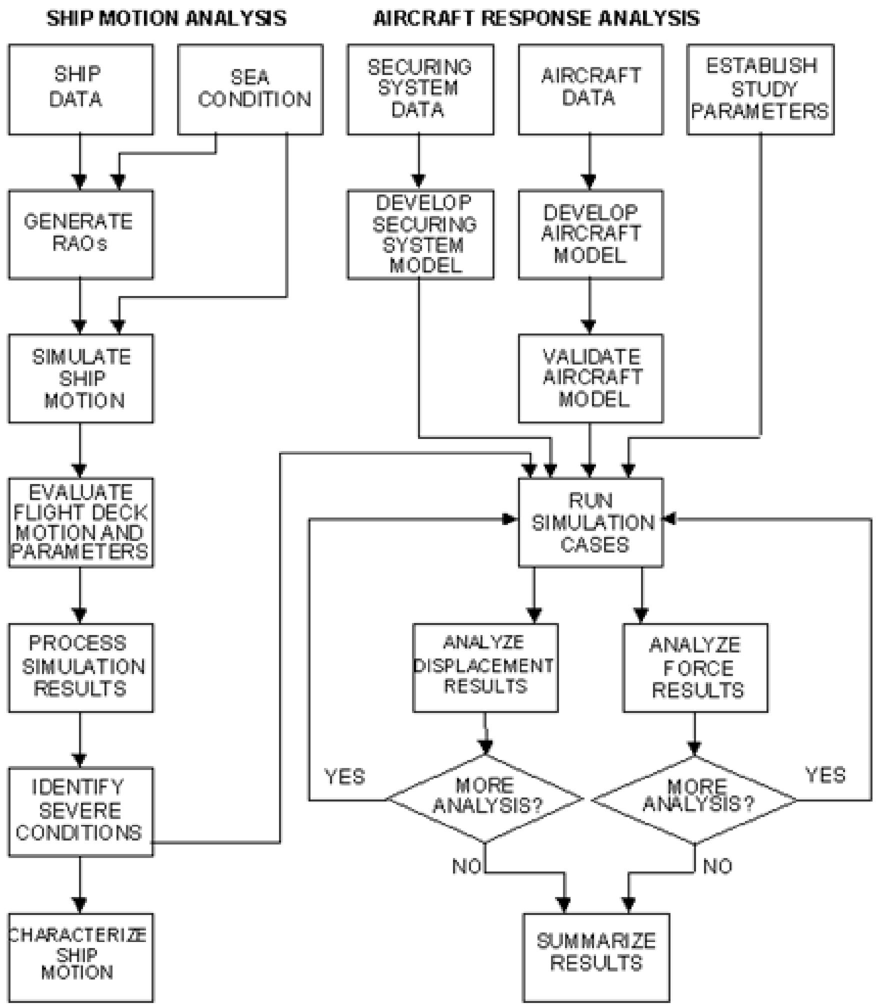


Figure 6: UAV/Ship time domain analysis procedure

The following equation governs the fundamental force balance on the aircraft,

$$[M_{UAV}]\ddot{q}_n = f_n \tag{3}$$

Where, $[M_{UAV}]$ is the inertial matrix of the aircraft and q_n is the generalized coordinate representing surge, sway, heave, roll, pitch and yaw.

Time Domain Dynamic Analysis of an Unsecured UAV

The dynamic analysis of a generic UAV resting on the deck of a naval vessel in moderately high sea state conditions (i.e. Sea state 4) is performed in this section. The UAV geometry is identical to the models used for the static and quasi-static approaches. From experimental and analytical results of reference 1, it is anticipated that the aircraft slides or tips in sea state 4, therefore it is assumed the aircraft will require some form of extra support to ensure it remains stable. A typical vertical takeoff/landing UAV is illustrated in Figure 7, with a representation of the typical forces acting on the aircraft. The loads are identical to the previous loads used for the static and quasi-static approaches for aerodynamic drag and gravity, however, ship motion accelerations are of similar magnitude but applied in a different way. Stability of the aircraft is evaluated based on its ability to remain in contact with the deck without sliding during a specific domain of time. The friction between the contact points of the aircraft and the deck is assumed $\mu_f = 0.6$. This is representative of wet and oily flight deck conditions as typically used by various Navies.

Aerodynamic forces generated, such as, wind drag on the fuselage, and lift and drag on the rotor are considered. Wind is assumed to be directed normal the ship at a speed of 19 knots and can be coming from either the port or starboard side. Also, various cases involved different on-deck alignments. Realistic random ship motion is created based sea-state 4 conditions with ship speeds of 8, 12, 18 and 22 knots using RAOs. The total number of solved cases based on various ship speeds, ship headings, rotor conditions, on-deck alignment, etc. is approximately 5000.
The on-deck behaviour of a helicopter must account for the dynamic interface conditions between the helicopter and the ship to meet the fundamental requirement for security. Additionally, the security of the helicopter impacts the safety of the crew during on-deck helicopter operations. For this reason, a quantitative definition of helicopter security 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.

Ship limits in terms of ship angular displacements (mainly roll and pitch) are typically used by several Navies to indicate operating limits. For each case simulated, a test for stability is performed where the aircraft is checked against threshold slip and tip values. Values that exceed this threshold are displayed in red, and the corresponding case that produced this roll and pitch instability for a specific ship speed, heading and aerodynamic loading criteria is flagged and deemed unsafe. The results are summarized in Figure 8. Typically two regions are formed based on primary and secondary (alternate) limits. The primary limit is governed by maximum safe roll values with corresponding safe pitch value, whereas, the secondary (alternate) region is governed by a boundary value based on max pitch and corresponding roll.

In Figure 9, ship speeds and corresponding wave directions are flagged as safe and unsafe. Unsafe conditions were predicted to occur for all ship speeds over wave directions from ±45-120 degrees. To increase the maximum roll and pitch values before the aircraft goes unstable, and thus widen the operational range based on wave direction, the aircraft requires some form of external securing.

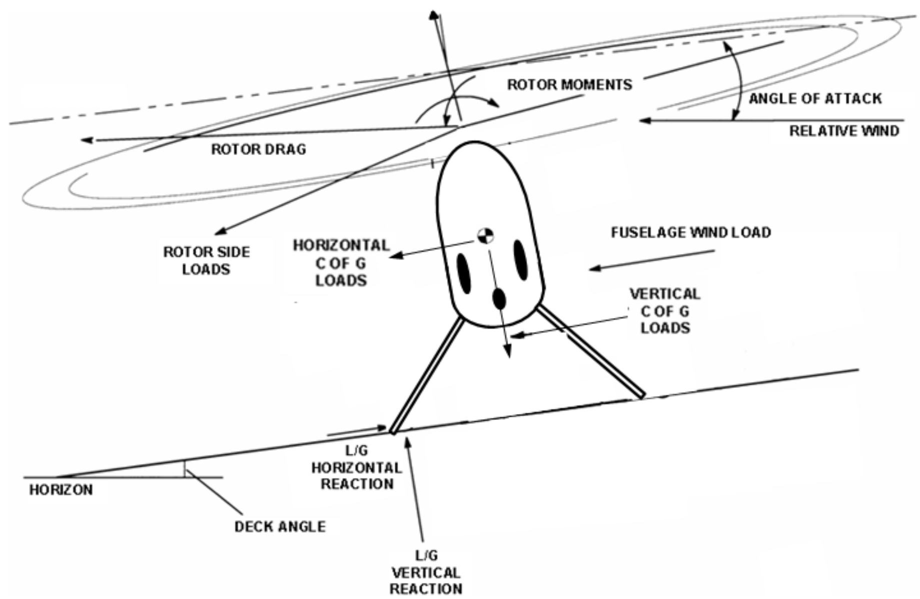


Figure 7: Load diagram of an unrestrained UAV on-deck

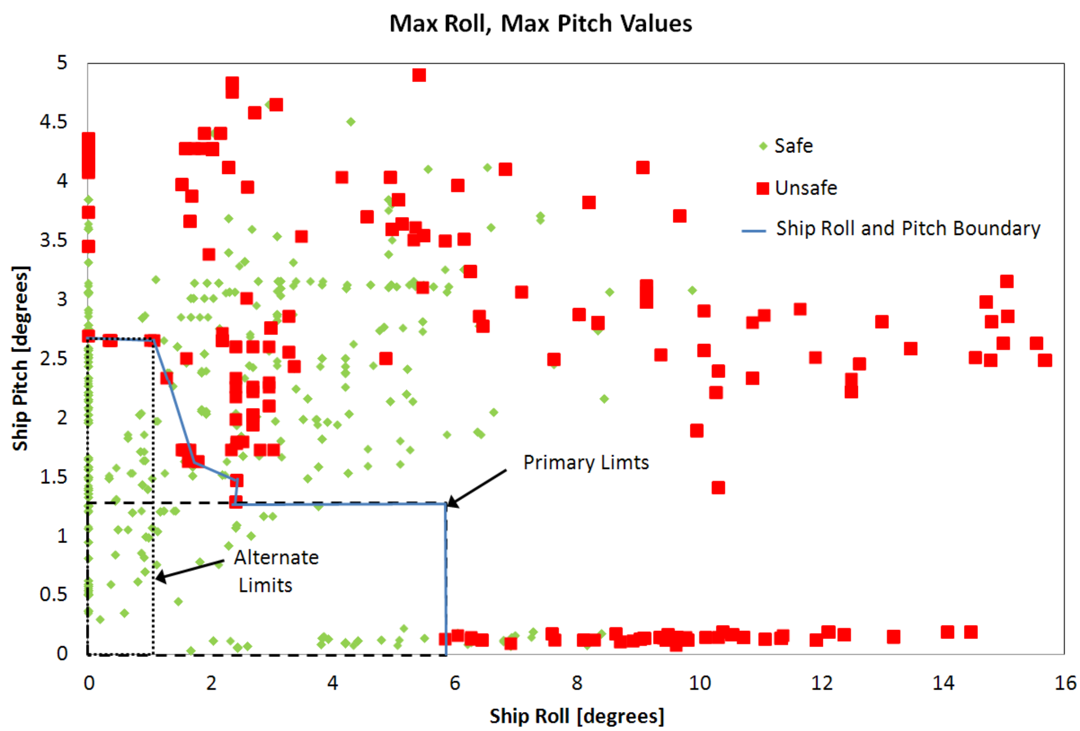


Figure 8: Maximum roll and maximum pitch values for an unrestrained UAV.

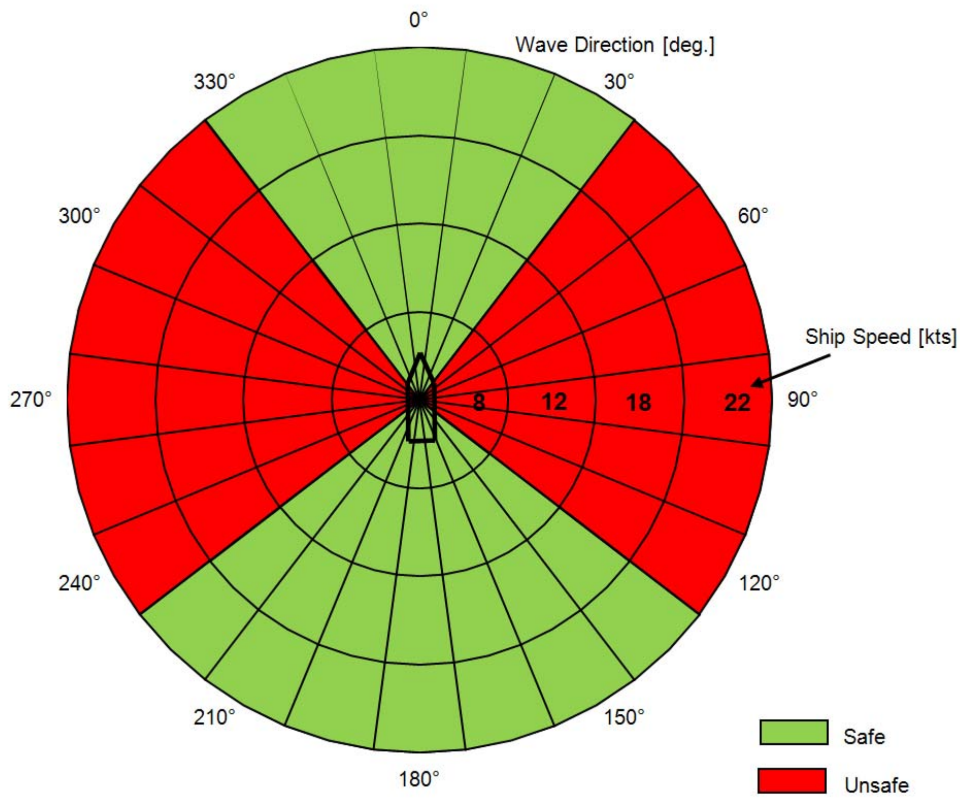


Figure 9: Safe and unsafe wave directions and corresponding ship speeds for an unrestrained UAV.

Secured UAV Dynamic Analysis

The UAV model presented in Figure 10 is identical to the model illustrated in Figure 7 with the same aerodynamic loads, geometry and applied ship motion; however, an additional probe restraint is implemented to improve the aircraft's on-deck performance. UAV restrained to the deck via a probe will significantly extend the operable range.

Assuming the probe is structurally capable of withstanding stresses caused by restraining loads, the UAV is capable of operating in all of sea state 4. In Figure 11, the ship roll and pitch boundaries are the fundamental boundaries of sea state 4. Naturally, sliding or tipping of the aircraft is not possible in this scenario since it's constrained in both directions with the application of the probe. Therefore, the aircraft could be suitable for much higher sea states not limited by stability rather limited by strength of the probe or load capacity of the UAV landing gear. However, stress of the UAV is beyond the scope of this paper and the dynamics of an aircraft restrained to the deck in sea state 4 is only used to compare and show the impact on stability.

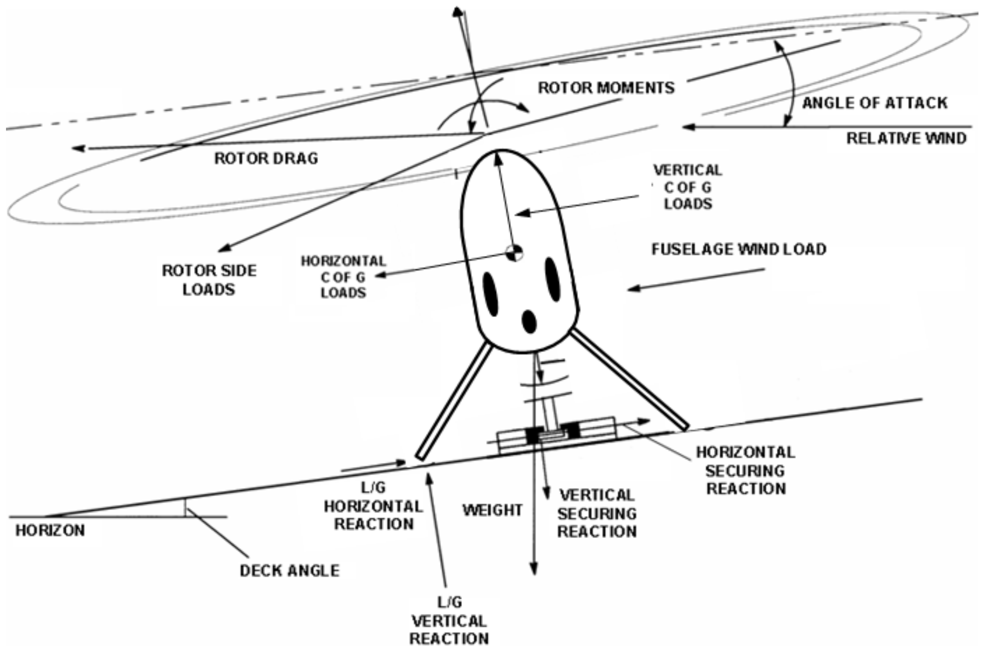


Figure 10: Load diagram of a restrained UAV on-deck

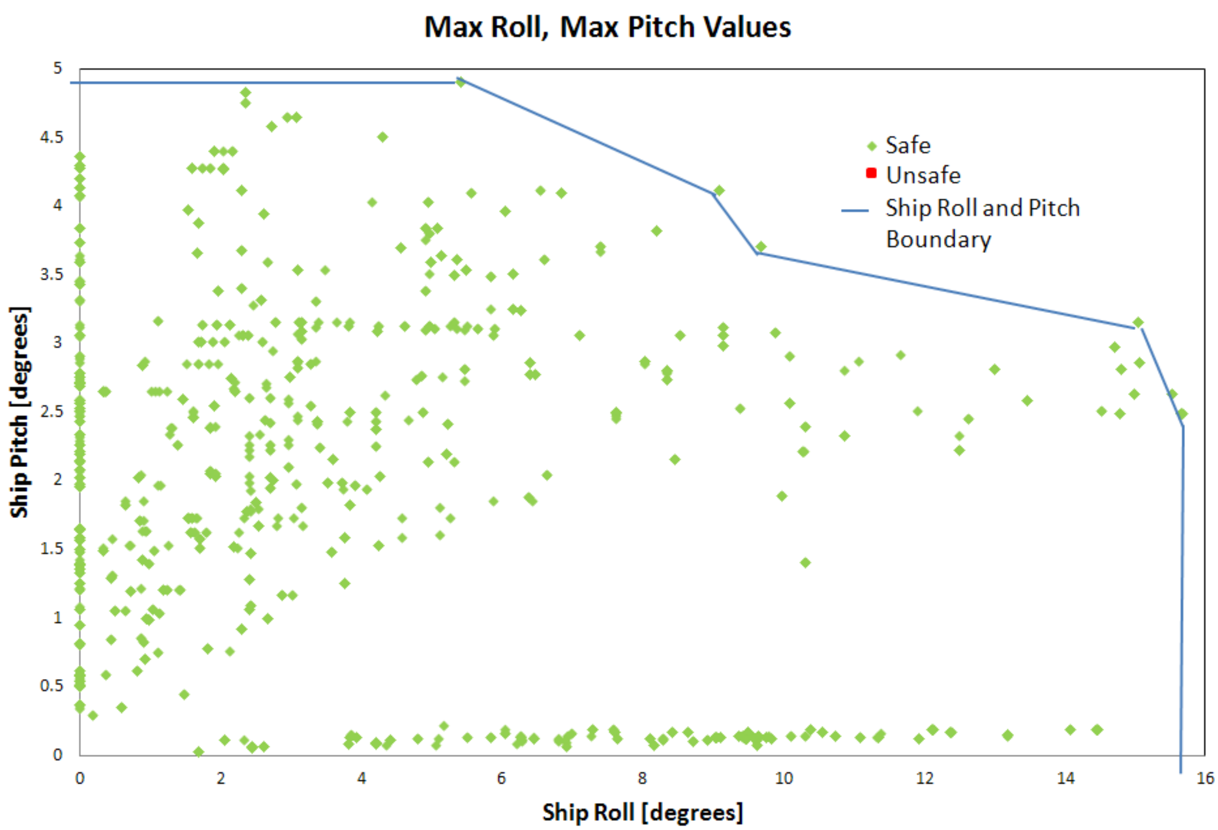


Figure 11: Maximum roll and maximum pitch values for a restrained UAV.

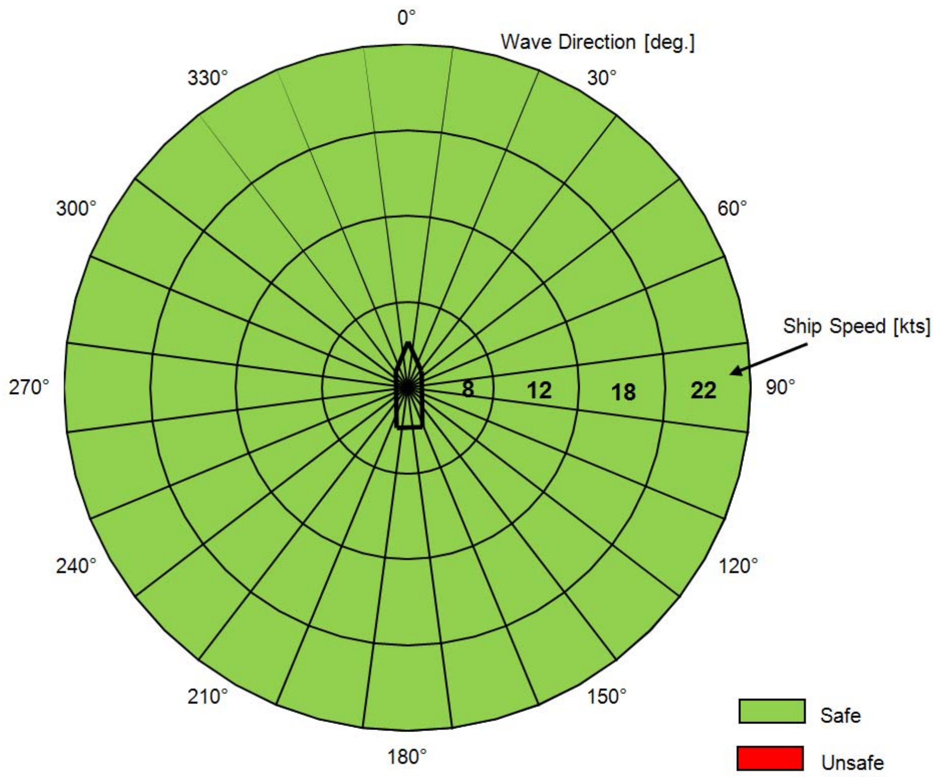


Figure 12: Safe and unsafe wave directions and corresponding ship speeds for a restrained UAV.

Conclusion

Computational techniques have matured considerably over the past century with the aid of computers. For this reason, the introduction of highly non-linear numerical methods for solving ship/UAV interface dynamics has been shown in this paper to not only be feasible, but also necessary given the divergence of static and quasi-static solutions as compared to the non-linear time domain technique. The solution calculated using a quasi-static based approach predicted on-deck aircraft stability nearly 2.5 times higher than the non-linear time domain approach. Although, a quasi static analysis is a useful mathematical approach for preliminary assessment of the dynamics of UAVs aboard ships, for accurate evaluation of the on-deck stability of a UAV, unrestrained or restrained, a naval ship, a more detailed analysis of the dynamics of these systems should be considered, specifically a non-linear time domain analysis. The dynamic interface analysis simulation presented in this investigation provides the capability for UAV design optimization and extension to greater envelops of operation by providing accurate knowledge of an aircrafts non-linear dynamics.

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Info

curtisswrightds.com

Email

ds@curtisswright.com

CURTISSWRIGHTDS.COM