Development and Application of the SAFEDI Tool for Virtual Dynamic Interface Ship Airwake Analysis

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Dynamic interface refers to shipboard aircraft launch and recovery operations including the testing required to determine flight envelope limits as a function of wind speed and direction. Ship-based flight operations must contend with challenges unique to the maritime environment such as ship motion and airwake turbulence created by the ship's superstructure. Ship airwake affects aircraft performance and handling qualities characteristics which in turn impact pilot workload. Ship airwake characteristics vary from ship to ship and also from one relative wind angle to the next for the same ship. The ability to assess ship airwake severity in a simulation environment allows airwake related design considerations, such as ship geometric layout and aircraft flight control design, to be addressed during the design process. NAVAIR has developed a desktop airwake analysis tool to model the handling characteristics of an aircraft when subjected to time accurate ship airwake velocities created with Computational Fluid Dynamics (CFD). The tool has been applied to multiple ship configurations to assess airwake impact on both rotary wing and fixed wing aircraft. This work describes the real-time aircraft flight dynamics models and CFD airwake models that make up the airwake evaluation tool, summarizes verification and validation efforts, and describes the comparative process used to evaluate ship airwake severity for an example ship configuration.

I. Introduction

Operating aircraft from sea-based platforms is a challenging endeavor due to multiple factors [Fig. 1]. The major challenges are associated with ship motion, restricted landing area, and airflow turbulence, all of which affect the piloting task by increasing pilot workload. Ship motion requires the pilot to compensate for pitch, roll, yaw and heave motions of the landing area, as well as ship forward speed. The restricted landing area necessitates precise maneuvering to avoid nearby structures. Workload induced by ship motion and restricted landing area is exacerbated by freestream airflow conditions since the

Figure 1. H-60 over a destroyer flight deck.

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aerodynamic characteristics of the aircraft directly impact its handling qualities which in turn affect pilot workload. In fact, wind conditions are so important at the dynamic interface that flight envelopes are created to define the limits of safe operations as a function of wind speed and direction.

For US Navy applications, flight testing is executed to create envelopes that are unique to a particular aircraft and ship combination [Fig. 2]. This process is often referred to as Dynamic Interface (DI) testing. DI flight tests, in addition to being expensive and time consuming, cannot be executed until vehicles (aircraft and ship) are available for testing. This can be an issue for existing ships and aircraft and is obviously a problem for vehicles in the design stage. Flight modeling and simulation (M&S) offers the possibility of simulating the DI environment when live articles are not available.

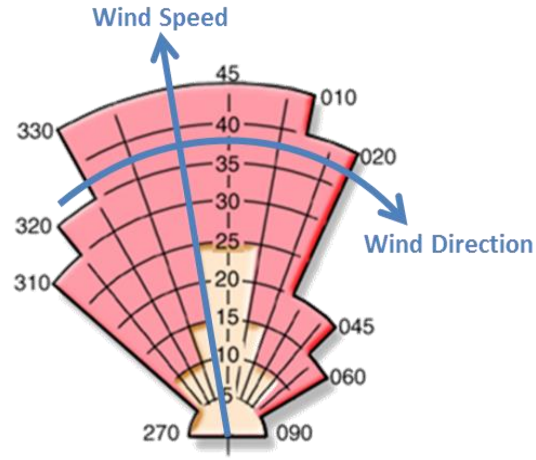


Figure 2. Example flight envelope.

One of the first concerted efforts to use flight simulation for shipboard launch and recovery simulation was executed by the Joint Shipboard Helicopter Integration Process (JSHIP) in the 2000 timeframe. The goal of JSHIP was to enable interoperability of shipboard operations for US Navy, Army and Air Force helicopters [Ref. 1-4]. A man-in-the-loop flight simulation was developed at the NASA Ames Vertical Motion Simulator (VMS), which replicated the dynamic interface environment for an LHA class ship and UH-60A Black Hawk helicopter. When the program was initiated, only atmospheric-based stochastic turbulence models were available to represent the ship's airwake. Recognizing the importance of the effect of ship aerodynamics on pilot workload, efforts were undertaken by NAVAIR to develop temporally and spatially correlated airwake models representative of LHA class ships. Models were created using computational fluid dynamics (CFD) for a simplified LHA configuration [Fig. 3, top]. Databases consisting of airwake time histories were generated for discrete wind angles every 15 degrees around the azimuth and integrated into the VMS simulation [Ref. 5]. Results from the JSHIP program demonstrated that high-fidelity, ship-specific airwake models were required for realistic DI simulations.

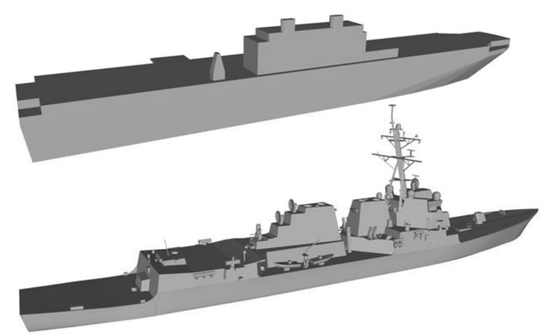


Figure 3. CFD surface geometry fidelity for legacy LHA (top) vs. current DDG (bottom).

In the same time frame, a number of US Navy air-capable ship design programs were also underway. Historically, while naval architects designed to many aviation-related requirements (e.g. landing area and hangar size, deck lighting and markings, replenishment stations, etc.), the effect of ship topside configuration on aircraft launch and recovery performance was generally not part of the design process. The primary reason for this was simply that the capability to predict airwake and its impact on aircraft did not exist. Wind tunnel tests were occasionally executed to understand gross airwake characteristics and collect wind velocity data along the aircraft approach path and in the landing area [Ref. 6]. Results were used to identify the extent of regions where "high" turbulence (e.g. area behind an island) or "large" velocity gradients (e.g. a shear layer behind a hangar) could be expected and to highlight areas of concern. However, determining whether "high" turbulence or "large" velocity gradients will have an adverse effect on aircraft operations is not possible without considering the aircraft characteristics. This is true whether the airwake data originates from wind tunnel testing or from CFD analysis. As such, an airwake analysis tool must consist of two fundamental pieces: airwake flowfield models and aircraft flight dynamics models. The JSHIP program demonstrated the feasibility of integrating CFD ship airwake models with a high fidelity aircraft flight dynamics model to create a realistic DI simulation. Recognizing the opportunity to build upon the JSHIP experience, a research and development program was launched to create an airwake evaluation tool for ship and aircraft design applications. The Ship Airwake Analysis For Enhanced Dynamic Interface (SAFEDI) program, sponsored by the Office of Naval Research, focused on improving CFD airwake modeling fidelity, verification and validation (V&V) of CFD airwake predictions, and creation of a desktop simulation tool (the SAFEDI Tool) for flight simulation-based airwake analysis.

This paper describes the real-time aircraft flight dynamics models and CFD airwake models that make up the SAFEDI Tool, summarizes V&V efforts to date, and describes the comparative process used to evaluate ship airwake severity for an example ship configuration.

II. Computation Fluid Dynamics Ship Airwake Model Development

Computational fluid dynamics provides the capability to create physics-based airwake models that preserve temporal and spatial correlation of unsteady velocities throughout the flowfield. This is a unique capability not possible through empirical data collection (i.e. subscale wind tunnel or full scale at-sea testing). Prior to the availability of CFD time domain airwake models, frequency domain models were typically used to represent ship airwake turbulence. In some cases, the effects of ship topside configuration were neglected altogether (typically due to lack of data) and atmospheric models were used [Ref. 7]. More sophisticated models use wind tunnel data for mean flow velocities specific to ship configuration and wind-over-deck (WOD) angle. Measured turbulence intensities are used to create randomly varying velocity fluctuations around the measured mean velocities. In some cases, the fluctuation spectral content is based on atmospheric models (Dryden or von Karman) instead of being purely random [Ref. 7]. The spatial applicability of these models is usually constrained to ideal flight paths (i.e. the extent of the underlying wind tunnel data). Time accurate CFD-based airwake models represent a leap in the state of the art over frequency domain airwake models. Flowfield features that manifest as turbulence (eddies, shear layers, etc.) are an inherent part of the data and therefore the turbulence is physically coherent instead of reconstructed using a reduced order frequency domain model. Additionally, since data exists throughout the computational domain, aircraft encounter realistic airwake profiles even when away from an ideal approach path.

The NAVAIR CFD process for ship airwake predictions has matured over the years since the JSHIP program and significant efforts have been made to validate the results. Increases in computer processor speed and available compute nodes for parallel processing have allowed increased fidelity in surface geometry definition and overall grid density. As with any CFD application, V&V is required to establish confidence in the results. The current numerical approach along with relevant V&V efforts are discussed below.

A. Numerical Approach

Ship topside surface models are built up from three dimensional computer aided design (CAD) models provided by a ship builder or responsible Navy entity. Watertight surface models are created using NASA Langley's Gridtool software. Detail included in the ship surface definition has increased significantly since the initial JSHIP efforts and includes elements 1 foot in size and sometimes smaller if deemed important from an aerodynamic perspective [Fig. 3]. Unstructured volume grids are created using the NASA VGRID software [Ref. 8-9]. The computational domain is constructed with boundaries a minimum of 3 ship lengths away from the ship in the lateral and longitudinal directions. The domain boundary height is typically 1000 feet above the lower boundary which represents the sea surface. Viscous boundary conditions are applied to ship surfaces. The sea surface is modeled as either viscous for cases where an atmospheric boundary layer is modeled or inviscid for cases modeling all ship speed. Fifteen to twenty viscous layers are generated from the viscous surfaces. The first grid spacing off the wall is set to 0.005 feet. For a 25 knot freestream wind, this results in an average y+ of ~1. VGRID creates volume grids containing only tetrahedral elements. The grid utility Blacksmith [Ref. 10] is used to combine tetrahedra in the viscous layers into prismatic cells. After combining viscous layers, current grid densities are typically on the order of 20 million cells with no more than half the cells in the viscous layers.

Unsteady (time accurate) solutions of the Reynolds Averaged Navier-Stokes (URANS) equations are used to generate time accurate ship airwake velocity databases. The flow solver Cobalt [Ref. 11] was used for all results shown in this work. Cobalt is an implicit, cell-centered, finite volume, modified Riemann solution method. Second-order spatial accuracy is achieved via upwind-biased reconstruction based on least-squares gradients. Stability of the second-order method is ensured by a Cobalt in-house developed, multi-dimensional, total variation diminishing TVD limiter. Second-order temporal accuracy and Newton sub-iterations provide accuracy with relatively large time-steps in time-dependent flows.

Turbulence is modeled using a monotone implicit large eddy simulation (MILES) approach [Ref. 12]. The MILES approach directly models grid scale eddies; however, unlike a large eddy simulation (LES) approach, sub-grid scale turbulence is neglected. Application of standard RANS turbulence models tends to damp out grid scale eddies predicted by the time accurate solver erroneously eliminating most of the unsteadiness in the flowfield [Ref.13].

Flow solutions are initialized using the inflow boundary conditions. Transients resulting from the impulsive start are allowed to wash out of the computational domain over 240 seconds with a time step of 0.04 seconds (6000 iterations). For a 30 knot freestream wind and a ship with length of 1000 feet, this results in 12 air exchanges over the ship. The time step is then dropped to 0.01 seconds to improve temporal accuracy. Flowfield data are saved every 10 steps (0.1 Hz) over at least 60 seconds of real-time (6000 iterations). This process is repeated for each discrete WOD angle of interest. On the DoD high performance computer (HPC) “Spirit”, an SGI ICE X, each WOD condition requires 12,000 hours of CPU time on 512 processors and 24 hours of wall clock time for a 20 million cell grid. For flight simulation applications, solutions are typically generated for every 15 degrees of wind azimuth (i.e. 24 datasets). For a 20 million cell grid, ~60 GB of archival storage is required for the 600 sets of flowfield solution files from each WOD case.

Modified Riemann invariant inflow/outflow boundary conditions are applied to all domain boundaries with the exception of the “sea surface” boundary. The sea surface boundary is set as an inviscid wall boundary condition for cases with no natural wind and all ship speed, and as a viscous wall for cases modeling all atmospheric winds and no ship speed. In reality, WOD is produced by a combination of ship speed and natural winds. For flight simulation purposes, it is assumed that the two extremes (all ship speed and all natural wind) cover the spectrum of airwake characteristics that may be encountered as the proportion of ship speed to natural wind changes. For winds down the bow and ±10 degrees either side of centerline, CFD solutions are created for both all ship speed and all atmospheric wind cases. For WOD azimuths beyond ±10 degrees, it is assumed all WOD is due to atmospheric winds and therefore all cases due solely to ship speed are neglected. However, as discussed in the CFD V&V section below, there are situations when the combination of ship forward speed and wind speed are important and should be modeled.

For cases with atmospheric winds, a fully developed, steady atmospheric boundary layer is applied as part of the inflow boundary condition. The profile shape is generated using the power law function: $U = U_0(Z/Z_0)^\alpha$ where U_0 is the flow velocity outside of the boundary layer and Z_0 is the height for U_0. Typical values for a marine boundary layer are used to generate the profile shape: U_0 = 1000 feet, and α = 0.13 [Ref. 14].

B. CFD Verification and Validation

As with any CFD analysis, verification and validation (V&V) are key to gauging the accuracy of the results and building confidence in their application. The NAVAIR approach for ship airwake V&V consists of a combination of numerical studies (e.g. grid density, turbulence model, Mach scaling, geometric fidelity, etc.) and comparisons against experimental data. Ideally both sub-scale wind tunnel data and full-scale at-sea data are collected for V&V purposes. Both sub-scale and full-scale data are desired because of advantages and limitations in both approaches. Wind tunnel testing offers the advantage of controlled conditions where the freestream conditions can be quantified. However, wind tunnel tests cannot typically match full scale Reynolds numbers since, for even larger test sections (i.e. 8 ft x 10 ft), model scales are on the order of 1:100 and maximum flow speeds must be constrained to avoid compressibility effects. Reynolds number effects on flow separation points are minimized by the many sharp edges that exist on a ship (in contrast to aerodynamic shapes like airfoils); however, not all geometric features can be considered “sharp edged” and Re effects on wake characteristics are not fully understood. At-sea testing provides data at full-scale conditions; however, it is currently not possible to fully quantify freestream conditions or collect data more than ~30 feet away from the ship surfaces. An approximation of the freestream wind conditions is based on the ship’s mast-mounted anemometer, which is situated in flow distorted by the ship itself. Further complicating matters, atmospheric and navigational considerations limit the ship’s ability to hold constant WOD conditions.

Table 1. Summary of V&V against subscale and full scale experimental data.

Method	Ship	Reference
Wind Tunnel	LHA	AIAA Paper 2000-4126 AIAA-paper 2002-1022 AIAA Paper 2004-4832 AIAA Paper 2004-4841
Wind Tunnel	CVN-78	Unpublished (2005)
Wind Tunnel	DD 963	AHS Paper 2007
Wind Tunnel	CVN-73/76	AIAA Paper 2005-6298
Wind Tunnel	DDG-95	AIAA-Paper 2005-4958
Wind Tunnel	DDG-95	AIAA Paper 2007-4484
Wind Tunnel	Land-based hangar	AIAA-Paper 2011-3351
Wind Tunnel	JHSV	Unpublished (2012)
Full Scale	LHA	AIAA paper 2002-1022 AIAA Paper 2003-3657
Full Scale	LHD	Unpublished (2002)
Full Scale	CVN-76	Unpublished (2005)
Full Scale	DDG-95	NAVAIR Technical Report (2015)
Full Scale	JHSV	Unpublished (2012)

Since different ship types have different dominant bluff body features, V&V studies have been executed for multiple US Navy ship classes. A summary of experimental V&V studies executed to date is provided in Table 1. Numerical V&V studies executed to date include: grid quality, turbulence modeling, time step sensitivity, time accuracy, Reynolds number scaling, geometric fidelity, ship speed, CFD domain size and flow solver comparisons. Results from many of these studies are available in References 15-25. Results from a few previously unpublished numerical and experimental V&V studies are highlighted below including: grid density, time step and ship speed studies.

1. Grid density study

A grid density study was completed in 2002 using the simple LHA configuration [Fig. 3, top]. Time accurate solutions were generated for a grid with "standard" grid density, which at that time was 4 million cells and ~5 foot spacing on the ship surface, and a "double density" grid with 8 million cells and ~2.5 foot spacing. Time averaged data and frequency content results were examined and compared against full scale ultrasonic anemometer data from a location on the forward part of the ship. As a rule of thumb, airwake frequencies between 0.2 Hz and 2.0 Hz are considered important for helicopter pilot workload [Ref. 26]. Power spectral density analysis of the CFD results clearly shows that the higher density grid retains higher frequency content much better than the lower density grid in general, and especially in the 0.2 Hz to 2.0 Hz range [Fig. 4]. This study set the minimum grid density standards for all subsequent ship airwake grid generation.

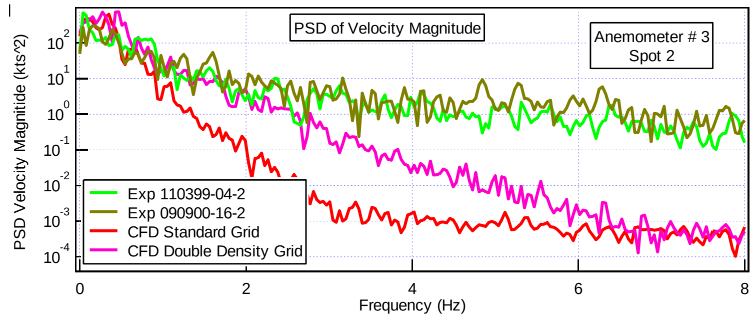


Figure 4. Power spectral density vs. frequency: experimental data and two CFD grid densities.

2. Time step study

A time step study was executed in 2002 also using the simplified LHA geometry. Solutions were computed for a base time step of 0.0025 seconds and time steps 1/2, 1/4, and 1/8 of the base time step. Again, time-averaged and frequency content results were examined. Power spectral density analysis indicated that the time step did not have a significant effect on the frequency content of the predicted flow [Fig. 5]. For subsequent calculations, the larger time step was applied to minimize CPU usage and wall clock time. Note that at that time, the ship airwake calculations were scaled by Mach number for numerical stability reasons. The Mach scaling increased the freestream flow speed by a factor of 4 and the freestream pressure was scaled by a factor of 1/4. In this way, the correct full scale Re was retained. This was necessary because the 2002 version of Cobalt did not have a preconditioning scheme. Since that time, a preconditioner was added to Cobalt and ship airwake calculations are computed without Mach scaling. The decrease in freestream flow speed allowed a proportional increase in time step by a factor of 4 resulting in the 0.01 second time step used currently.

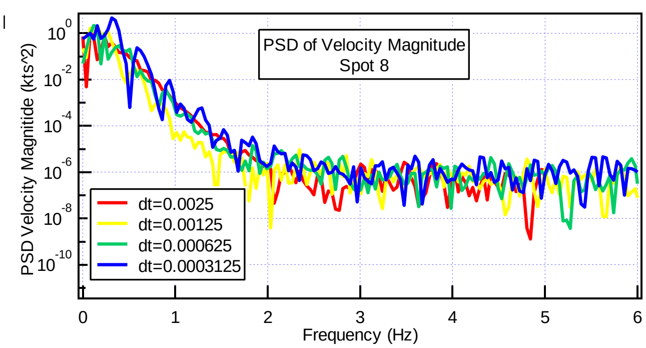


Figure 5. Effect of time step on predicted airwake frequency content.

3. Modeling ship speed

As mentioned in the Numerical Approach section, ship airwake databases for flight simulation analysis are typically generated assuming the WOD is created solely by ship speed or solely by atmospheric winds. However, when comparing CFD results against full scale at-sea data, there are situations where modeling the combination of ship speed and atmospheric winds is important. In reality, relative WOD is composed of a component due to ship speed and a component due to the ambient wind. The contribution of WOD from ship speed is independent of height above the sea surface. However, the ambient wind varies with height due to the effect of the atmospheric boundary layer. At the sea surface, the ambient wind speed is zero and increases to the freestream speed above the sea surface along a profile approximated by a power law [Fig. 6]. Thus, the sum of the wind due to ship speed and the ambient wind creates a wind vector that changes with height both in speed and direction [Ref. 27]. Fig. 7 illustrates the resulting spiral profile for an example case where the ambient wind is perpendicular to the direction of ship speed. Consequently, the WOD speed and direction measured at the ship mast anemometer (SMA) is not the same as the

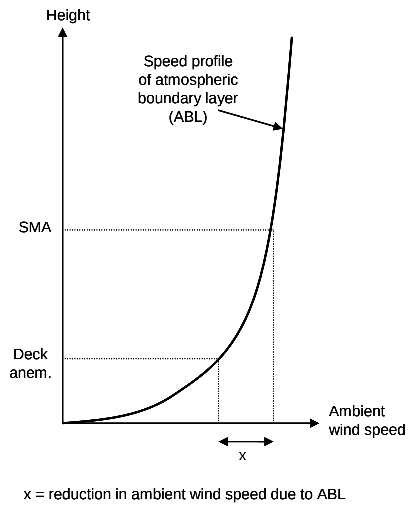


Figure 6. Atmospheric boundary layer profile.

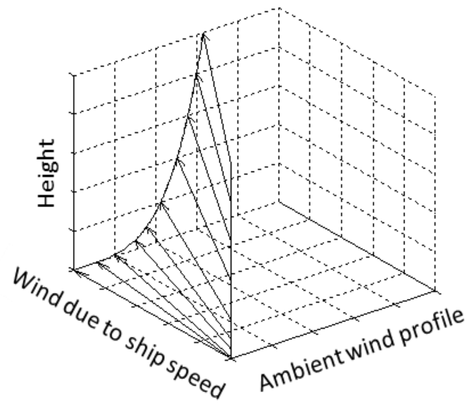


Figure 7. Spiral profile of relative wind.

WOD speed and direction at the deck. The difference between them is a function of the contribution to the WOD of the wind due to ship speed and the ambient wind.

The importance of modeling the spiral effect was brought to light by a 2013 V&V study conducted for a US Navy destroyer class (DDG) ship. Full scale ultrasonic anemometer data were collected on the DDG flight deck for a wide range of WOD azimuths. Comparisons of the at-sea and CFD data showed large differences in the local flow direction over the deck for 090 winds (beam winds). A top view of a DDG flight deck outline is shown in Fig. 8 along with experimental and CFD planar velocity vector data. The ultrasonic anemometer positions are shown as circles. Time averaged velocity vectors are shown for at-sea (blue) and CFD (red) results. The WOD is 10 knots from 090 and the full-scale ship is moving through the water at 10.3 knots. In these conditions, the difference between the WOD azimuth at ship mast anemometer height (measured as 090) and the estimated WOD azimuth at deck anemometer height is 11 degrees. For the CFD prediction, however, the ship is effectively stationary in the water and the WOD azimuth of 090 at SMA height is the same as the WOD azimuth at deck anemometer height. To better simulate at-sea conditions, a CFD prediction was computed using a spiral inflow profile with a 10.3 knot wind speed at the sea surface. The results are plotted in Fig. 9.

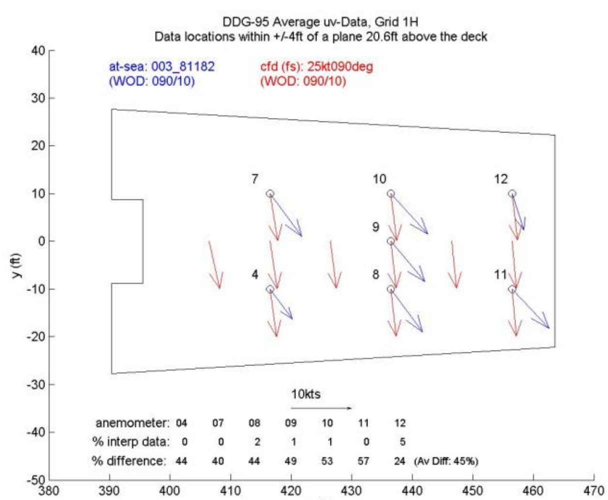


Figure 8. Mean velocities, uniform CFD inflow, WOD 090.

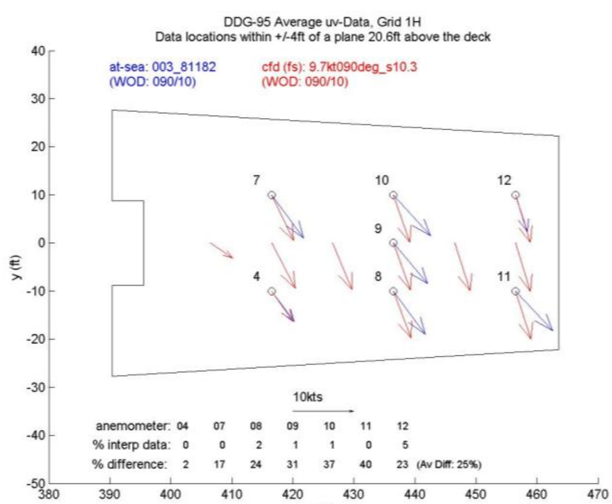


Figure 9. Mean velocities, spiral CFD inflow, WOD 090.

The CFD results are considerably improved when modeling the spiral inflow effect, with the difference between the experimental and CFD results reducing from 45% to 25%. For this study, percent difference is the magnitude of the vector difference between the computational and experimental data expressed as a percentage of the WOD speed at the SMA.

In summary, significant emphasis is placed on verifying the CFD ship airwake results. The numerical approach is continually improved as additional data and computer resources become available.

III. Aircraft Simulation Model V&V Considerations

For airwake evaluation analysis, the integrity of the aircraft flight dynamics model is equally as important as the accuracy of the airwake models. Typically, V&V processes are executed to establish the accuracy and fidelity of an aircraft simulation model relative to "truth data" for the modeled air vehicle [Ref. 28]. Verification of the simulation insures that the software implementation is correct (no "bugs" exist). Once verification of the coding is complete, validation of a simulation determines how closely the model resembles the actual air vehicle.

Validation fidelity testing may include comparisons against both wind tunnel and flight test data. Aircraft simulations developed by NAVAIR's Manned Flight Simulator (MFS) follow a basic workflow outlined in Fig. 10. Within this framework, verification, validation and accreditation processes vary depending on the intended application of the simulation.

Aircraft flight dynamics models used for the airwake analysis described by this work have typically originated through other Navy requirements such as pilot/operator training. For example, work is underway to integrate a Fire Scout (MQ-8B) simulation into the inventory of aircraft available for airwake evaluation analysis. The Fire Scout Unmanned Aerial Vehicle UAV simulation, developed for operator training, underwent a detailed V&V process managed by Naval Air Warfare Center Training Systems Division (NAWCTSD). The V&V process utilized both NAWCTSD guidelines [Ref. 30] and FAA criteria [Ref. 31] to establish the fidelity of the simulation.

Employing high fidelity aircraft simulation models from the MFS inventory provides increased confidence in the aircraft simulation-based airwake analysis process.

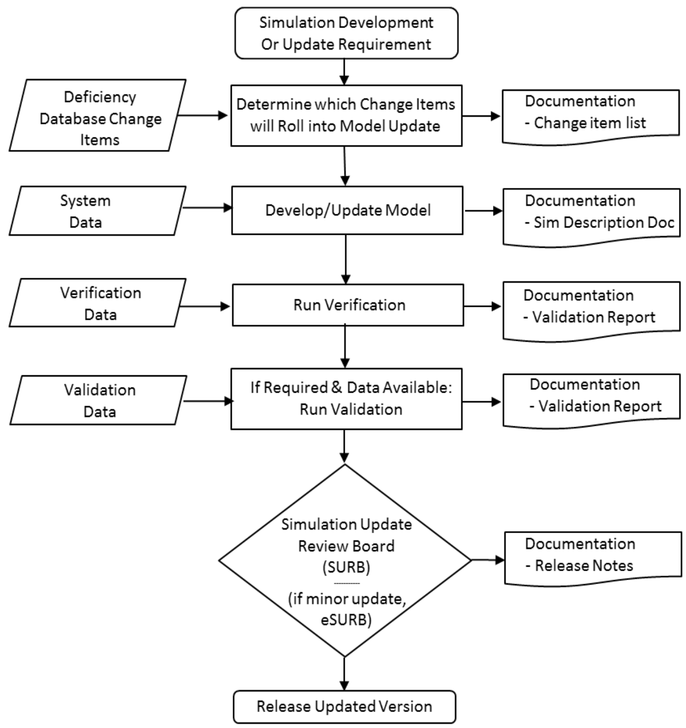


Figure 10. Simulation development/update workflow [Ref. 29].

IV. Aircraft Simulation Based Airwake Analysis

A. CASTLE® Simulation Environment and the SAFEDI Tool

The SAFEDI Tool comprises a number of simulation components developed by NAVAIR as described below.

1. CASTLE

The CASTLE® (Controls Analysis and Simulation Test Loop Environment) simulation environment is a modular software architecture developed and used by NAVAIR Flight Vehicle Modeling and Simulation Branch for desktop engineering and pilot-in-the-loop simulation. It was developed to effectively and efficiently support an airframe simulation throughout its entire life cycle. CASTLE® consists of two executables communicating via TCP sockets. The first executable is the airframe which consists of two parts: a set of generic libraries and a set of airframe-specific libraries. The second executable is the Graphical User Interface (GUI), which provides the user a means of controlling the simulation.

CASTLE® provides a generic simulation executive and standard environment models such as equations of motion, atmosphere, wind, gusts, and turbulence for the airframe executable. CASTLE® also provides model development tools, such as simulation variable dictionary and recording functions, as well as general function table lookups using linear interpolation. Development of a flight dynamics simulation requires specification of aircraft-unique models for aerodynamic loads, engine/transmission, weight/balance, control laws, and sensor models.

The CASTLE® GUI allows easy operation and control of an airframe simulation and has the added advantage of providing a consistent look and feel across all simulations. It gives the experienced operator a powerful set of tools, but also allows the less-experienced operator to run an airframe simulation effectively. The CASTLE® GUI process also provides a macro language which supports the development of graphical user interfaces which can be used to setup and run CASTLE® simulations. This language was developed by the CASTLE® team and modeled after Visual Basic for Applications. Complex V&V macros and simulation configuration macros have been developed for several aircraft simulations.

2. Example Helicopter (ExHel) Aircraft Model

The generic helicopter simulation, designated the "Example Helicopter (ExHel)", is typically used for helicopter-based airwake analysis. The simulation has characteristics similar to an UH-60 with a gross weight of 19,000 lbs. ExHel was derived by NAVAIR solely from public source information and based primarily on Howlett [Ref. 32]. This report is often referred to as the "GENHEL Math Model" and describes the main and tail rotor parameters, fuselage and empennage aerodynamics, flight control system, and basic mass properties. The engine model is derived from Ballin [Ref. 33]. A set of generic, re-usable base classes forms the foundation for both the blade element model rotor system and the landing gear kinematics. These are contained in the NAVAIR Flight Vehicles Modeling and Simulation (FVMS) models library. The main rotor is implemented as a blade element model using the data from the math model report, and the tail rotor can be selected as either a Bailey disc model or a blade element model. Landing gear characteristics are based on drawings and generalized oleo characteristics. Provisions are also made to connect the simulation to a piloted cockpit environment.

3. ExHel Pilot Model

Desktop based (i.e. offline) analysis requires an autopilot/controller to fly approaches through the ship airwake databases. Airwake analysis using the F-18 airframe simulation employs the Automatic Carrier Landing System (ACLS) software developed for fleet use. The Fire Scout also has an automatic approach and landing system. For the “Example Helicopter”, an in-house pilot model was developed to enable offline simulations. The general strategy for designing the pilot model was to develop a set of inner loops to control aircraft attitude, altitude, and turn coordination. A set of outer loops were built on top of the inner loops to control airspeed, ground speed, and position, and the approach task was broken down into a sequence of specific tasks in the form of commands and mode switches to these loops.

The inner loops were designed by first finding second order equivalent systems for each axis to simplify the full non-linear model. Each control axis also included a 10 rad/s second order low-pass filter to simulate neuromuscular system of a pilot. Together these formed the plant model to control. The innermost loops are pitch rate, roll rate, and climb rate. The directional axis uses heading rate or yaw rate depending on airspeed. In addition, the longitudinal axis includes a turn compensation path and the directional path includes a sideslip feedback at higher speeds. Airspeed-dependent proportional and integral gains provide a 2.0 rad/s open-loop bandwidth and 60° phase margin. A linear fit or constant set of gains is used depending on the variability of the gains with airspeed

Outside of these innermost loops are pitch attitude, roll attitude, and altitude loops. The pitch and roll attitude loops use only proportional gains. The altitude loop also includes an integral gain to allow zero error during descents. Data from piloted simulation was used to determine that the pilot has a 1.8 rad/s bandwidth in the pitch axis. Similarly, 2.8 rad/s was used for the roll axis and 2.0 rad/s for the vertical axis. The integral gain in the vertical axis was chosen by trial and error.

A set of outer loops were developed to allow the pilot model to control a variety of parameters. The longitudinal outer loop includes options to control longitudinal position, longitudinal ground speed, or airspeed. The lateral outer loop includes options for lateral position, lateral ground speed, or heading. These include several mode flags allowing a task model to indicate the desired control strategy. The outer loops feed into the pitch attitude and roll attitude inputs of the inner loops.

The approach task model sets the appropriate command modes for the outer loops and provides the needed commands to fly the approach. The sequence of command modes used and the transition points are listed in Table 2.

Table 2. Approach task sequence.

Phase	Mode	Transition to Next Phase
1	Airspeed Command Mode	Ground speed command close to desired ground speed
2	Ground Speed Command Mode (hi-speed) Cross-track error controlled by heading	Airspeed less than 35 knots
3	Ground speed Command Mode (low-speed) Cross-track error by lateral ground speed Current heading captured and held	Ground speed command from deceleration model equal to command from position mode.
4	Position Command Mode Heading held	Inside 20 feet of spot
5	Position Command Mode, Pedal Turn Heading aligned with ship heading	Position in tolerance Hover time exceeded Deck motion "quite"
6	Position Command Mode Heading aligned with ship heading H-dot Command Mode to descend to deck	

4. The SAFEDI Tool GUI

The SAFEDI Tool macro provides a GUI to simplify running ship approaches for airwake evaluation in the CASTLE® environment. The SAFEDI Tool running with the ExHel simulation is shown in Fig. 11. The SAFEDI Tool was developed with the CASTLE® macro language so the tool can be used with multiple simulations and small changes can be made easily. The SAFEDI Tool currently supports the F/A-18, Fire Scout and ExHel simulations as well as a number of classes of ships, including FFG, DDG, LHA, LHD and CVN.

The SAFEDI Tool can be configured to initialize the simulation at a user-defined "start time" in the airwake data or at randomized times for multiple runs. This facilitates testing of the whole range of possible conditions the aircraft could experience as it approaches the ship.

For each ship supported by the simulation, the tool allows the user to select one or more landing spots for each selected airwake azimuth. The airwake module uses flowfield data for a particular interval of time (typically about a minute) to determine the airwake parameters in the vicinity of the simulation. When the end of the file is reached, linear interpolation is used to smooth the transition back to the start time. The simulation is run with each selected airwake to each of the selected landing spots at each of the airwake start times that are selected. If the "Enable Synchronization" checkbox is selected, the simulation will be configured to run in a real-time mode so that the aircraft's performance in the airwake can be visualized while the simulation runs.

The SAFEDI Tool reads the airwake speed and direction from the airwake data files. The airwake speed can be overridden by a value or several values specified on the SAFEDI Tool GUI. The ship speed is also specified on the GUI. The macro automatically configures the CASTLE® wind model to be consistent with the airwake speed and direction and the ship speed selected. The ship speed is used along with the input freestream wind speed to determine the WOD, and the CFD airwake data is scaled to match the resulting WOD conditions.

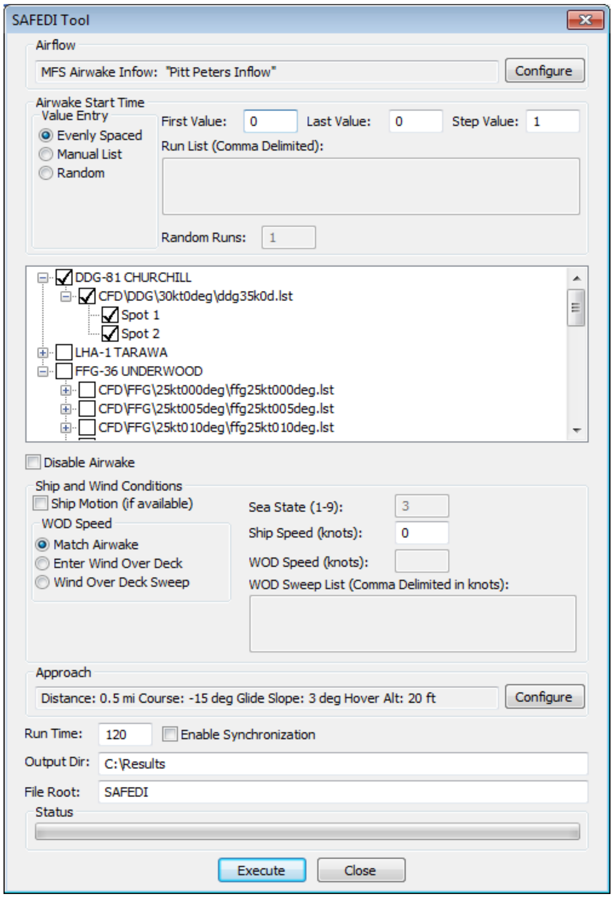


Figure 11. SAFEDI Tool GUI.

The approach profile can be configured through a dialog that varies based on the simulation selected. For the F/A-18, no dialog is available since all of the approaches use the ACLS to guide the aircraft to the ship. For the

ExHel simulation, various parameters for the pilot model can be configured such as the hover altitude and whether or not to perform a pedal turn over the landing spot to align the aircraft with the ship. For the Fire Scout, the amount of time the aircraft spends in hover before it begins the approach is selectable.

The SAFEDI Tool runs the simulation multiple times when executed based on the number of airwakes, landing spots and airwake start times selected. Data from the runs are collected using the built-in CASTLE® data storage functionality and saved to the directory specified in the tool. A summary of test conditions and filenames is also written out to the same directory.

B. Airwake Integration

The SAFEDI airwake real-time model requires a structured grid with some specific caveats in order to efficiently perform the search for multiple points per simulation step. Once this structured grid is defined by the user, a tool is used to extract the velocity at each grid point from the unstructured output of the CFD flow solver. Both the grid and velocity files are stored in the industry-standard PLOT3D ASCII format. These two files are then consolidated into a binary (unformatted) file for use by the real-time model using the CFD_to_MFS conversion tool described in Reference 35.

1. SAFEDI Airwake Extraction Grid Description

Real-time aircraft simulations require environmental velocity component input in order to calculate the forces and moments on the aircraft. In practical terms, this means that CFD ship airwake data must be queried to retrieve u, v, and w velocity components at one or more locations in the flowfield for each simulation time step. Performing searches over millions of unstructured CFD grid points in the required time is not practical or even necessary. To facilitate fast searches and reduce data storage requirements, airwake data from a subset of the CFD domain volume are interpolated onto a structured volume grid confined to the region of interest. The volume shape and grid density is tailored to specific aircraft requirements and can be different shapes and densities for different applications (e.g. helicopter and fixed wing simulations). The interpolation grids are generally referred to as airwake extraction grids.

The structured extraction grids are constructed based on a number of restrictions required to accommodate the real-time lookup algorithms:

- The X axis is the primary axis
- The grid coordinate system must be right-handed and orthogonal
- Each Y-Z plane must be parallel to one another, and perpendicular to the X axis (e.g. orthogonal)
- Each set of Y breakpoints must have the same number of points, but need not be the same values
- Each set of Z breakpoints must have the same number of points, but need not be the same values
- All breakpoint sets (X, Y, and Z) must be monotonically increasing or decreasing
- The time slices must be evenly spaced
- The X, Y, and Z grid points can be unevenly spaced
- The origin is always at (X,Y,Z) = (0,0,0) and not necessarily the first point in the grid (i,j,k) = (1,1,1)

An example of a multi-shaped airwake extraction grid aligned to the aircraft carrier angled deck is shown in Fig. 12. An asymmetric grid with X pointing out the port side of the ship and aligned parallel to ship keel is shown in Fig. 13.

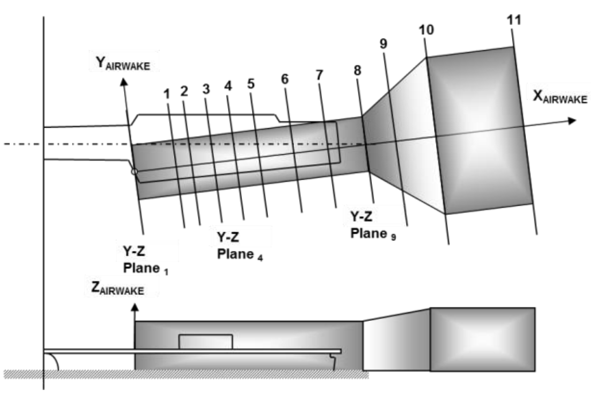


Figure 12. Example of a multi-shaped airwake grid aligned to the aircraft carrier angled deck.

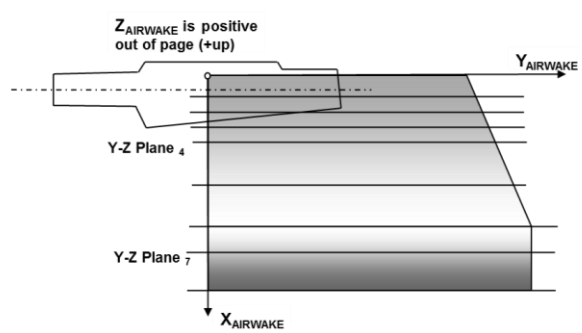
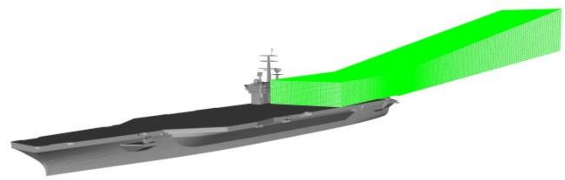


Figure 13. Example of an asymmetric grid with X pointing out the port side of the ship and aligned parallel to ship body axis.



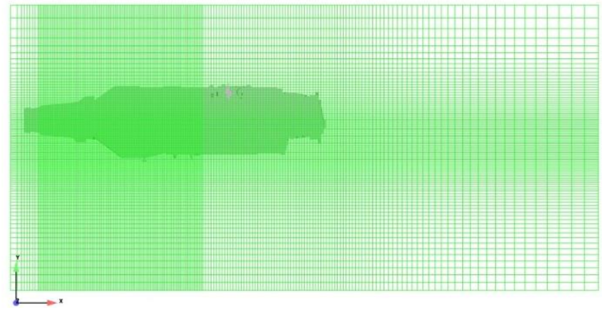


Figure 14. Airwake extraction grid for fixed wing carrier landing simulations.

Figure 15. Airwake extraction grid for helicopter carrier landing simulations.

Two airwake extraction grid examples used for different simulation applications are shown in Figures 14 and 15. Grid density over "areas of interest" (typically the flight deck) is generally set between 2.5 to 5 feet and allowed to increase away from the area of interest. The grid spacing is chosen based on a number of factors including the size of the blade elements for rotorcraft simulations, the speed of the aircraft through the grid for fixed wing simulations, speed of the search algorithm, spatial flow gradients, and the density of the supporting CFD unstructured grid. The complete CFD flowfield solution files are archived so that new extraction grids can be applied as needs arise.

Airwake extraction grids and interpolated data are stored in PLOT3D format [Ref. 34]. As described in a following section, additional post-processing is required to prepare the data for integration into the SAFEDI Tool.

2. Coordinate Systems

There are several coordinate systems used in the airwake process. These consist of the reference, airwake position (airwake extraction grid), airwake velocity, ship body, and aircraft body systems. The user defines the relative placement and orientation of the ship body and two airwake systems relative to the reference system (see The CasAirwakeViewer section below).

The reference coordinate system [Fig. 16] is used to provide a common point on the ship from which all other coordinate systems can be defined. This can be likened to the fuselage station, buttline station, and waterline station reference system used to define aircraft component locations. Good practice is to choose some recognizable physical feature on the ship for the reference coordinate system origin, such as the front edge of the deck at centerline (large deck) or the first frame at the waterline (small deck). The reference coordinate system is X positive aft, Y positive starboard, Z positive up, and coordinate transformations are defined from the reference to the coordinate system of interest (all other coordinates systems are measured in the reference system).

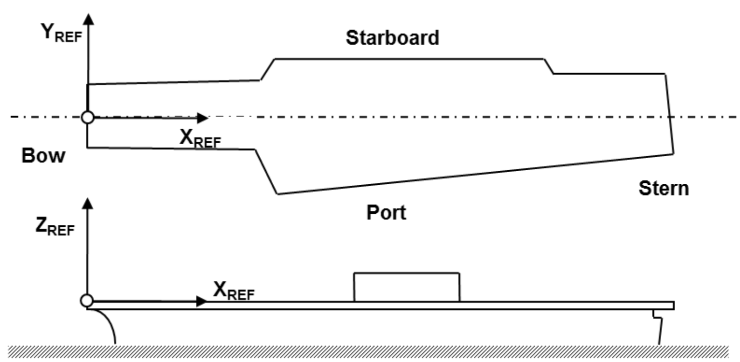


Figure 16. Reference coordinate system.

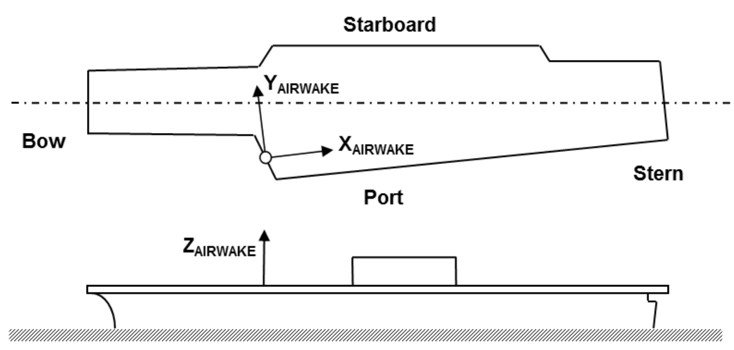


Figure 17. Airwake position coordinate system.

The airwake extraction grid (position) coordinate system origin can be located anywhere desired, with any orientation. Having the orientation generally aligned to the reference system may make it easier to correlate back to the original data however. The origin does not need to lie on the ship, nor be located at a corner in the grid. The lookup algorithm can handle negative numbers for X, Y or Z. Fig. 17 depicts a typical origin location and coordinate system orientation of the airwake extraction grid on an angled-deck aircraft carrier.

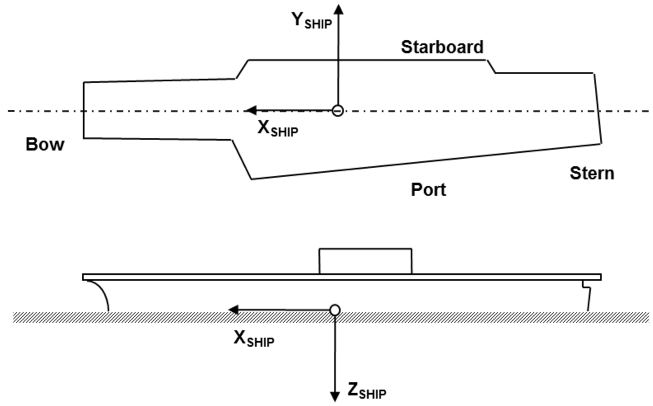


Figure 18. Ship body-axis coordinate system.

The airwake velocity coordinate system has no origin; it is used only for alignment purposes. It is decoupled from the airwake position grid orientation to allow the velocity to retain the original alignment from the CFD output grid if desired. The user may also elect to align the velocity grid with the position grid (or some arbitrary orientation), in which case the CFD_to_MFS conversion tool will perform the necessary transformation from the original CFD grid to the specified velocity grid. However, this may result in loss of correlation between the original data and the visual reference system.

Both the ship and aircraft body axis coordinate systems have their origins at the body center of gravity (CG). The orientation is such that the X axis is positive forward, Y is positive starboard (right) and Z is positive down to follow the sign conventions used in CASTLE® [Fig. 18].

3. SAFEDI File Format

Each SAFEDI airwake data file contains three basic components: a “header” describing the airwake conditions, a definition of the airwake grid points, and the airwake velocity data for the specified time block. This file is stored as binary unformatted data both for storage space reasons and to allow access to specific locations in the file when retrieving the velocity data. The intent is that each SAFEDI file is defined such that it will completely represent an airwake condition when loaded into the SAFEDI tool. The user has the ability to override information in the file header section, such as the coordinate system origin and orientation for the airwake and ship axis systems. This is done via an airwake “description” file. This file is an input to the CFD_to_MFS tool to initially define the header information, but it can be modified later to avoid reprocessing the data file simply to adjust the airwake grid origin, for instance.

The CFD_to_MFS conversion tool stores the velocities as the full flowfield values in original dimensional units as opposed to normalized by freestream wind speed, or as perturbations from freestream. This is done so that the lookup velocities can be easily correlated to the original (pre-conversion) CFD outputs.

C. The CasAirwakeViewer: Aligning the Airwake Grid

A critical part of integrating the airwake into a simulation is to ensure spatial alignment between the airwake extraction grid, ship and aircraft. Determining the relationship between these systems and verifying that they are correct has been a challenge. To help with this, an in-house application was developed to allow visualization of the various coordinate systems together with the visual representation of the ship, the sea surface plane, the airwake extraction grid, and the geometry used to produce the CFD solution. The application is called the CasAirwakeViewer [Fig. 19].

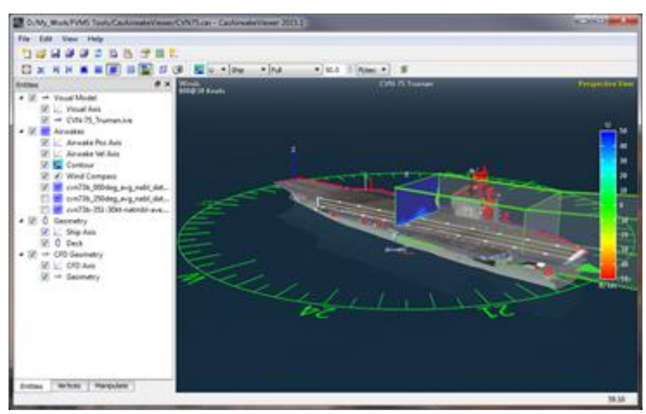


Figure 19. CasAirwakeViewer GUI.

For piloted simulation, the ship visual model location with respect to the water and its center of motion must also be aligned. The simulation setup is further complicated if the coordinate system used to generate the original CFD airwake data is different from the coordinate system used to produce the airwake extraction grid. For example, the original CFD coordinate system used for an aircraft carrier case may be aligned to the ship's keel. However, the airwake extraction grid coordinates may be aligned to the angled deck allowing more optimal use of the grid.

Ultimately the goal is to select a position on the aircraft in body axes and compute its location within the airwake. This requires a sequence of axis transformations from body axes to inertial axes to ship axes to airwake axes. CasAirwakeViewer allows the user to manipulate the various coordinate systems to see what is required to ensure correlation between the geometries. Once everything is aligned, the manipulated values can be saved to the various input files required by the simulation.

To further assist in this task, CasAirwakeViewer allows airwake contours to be displayed. These 2-D contour plots can be used to gain confidence that the airwake features align with the visually represented ship. The interior grid points can also be displayed to better understand the density of the grid.

An additional component of the ship modeling in CASTLE® is the ship geometry used by the flight dynamics model. This describes the locations of the landing surfaces and landing spots, which may be different than those in the ship visual model. CasAirwakeViewer includes the ability to show these geometries and ensure that they align properly with the visual representation of the ship.

D. Real-time Implementation of the Airwake

The SAFEDI Tool queries the airwake model and returns linear velocity perturbations at specified points, which represent the change in the freestream air mass caused by flow over the ship structure. These perturbations are summed into the overall "velocity with respect to the wind," or "total" components which are in turn used to determine the velocity, angle of attack, and angle of sideslip for the aerodynamic surface calculations.

1. Determining Lookup Points

For a fixed wing aircraft, typically only the location of the aircraft CG is used as the lookup point. The returned perturbation is then summed into the overall velocity vector and a global angle of attack and sideslip change is the result. In the case where multiple aerodynamic surfaces are available with local velocity calculations, then each reference point can be used which will also tend to capture the effect of flow gradients on aircraft rotations. For the single point case, this effect is lost.

The rotary wing case presents a better opportunity to take advantage of the airwake data, especially if a blade element model is used for the rotor(s). Typically the lookup points will consist of fuselage and empennage points, as well as points along the rotor blades. Since the rotor speed is quite high, a simple prediction algorithm is used to estimate where the blade will be in the next time step, so the returned airwake perturbations will be more representative.

The rotor model can also request points in a variety of ways:

- Hub only (simple disk or Bailey model)
- Hub and each blade tip
- User specified number of evenly-spaced points along the blade
- Each aerodynamic segment along the blade

For the latter three methods, the perturbations at each aerodynamic segment are computed. In the case of the hub/tip and evenly-spaced methods, this is done by linear interpolation across the blade using the available perturbations from the lookup and the requested points along the blade. By definition the last method will return the perturbations at each segment and no further processing is required. Once the perturbation at each segment is found, the local velocity, angle of attack, and angle of sideslip are determined and used for the calculation of lift and drag forces in the normal fashion for each rotor. The same approach is used for each of the aerodynamic surfaces for the helicopter.

2. Determining Perturbations

The real-time lookup tool allows the user to load multiple airwake data sets as defined in a list file. These data files can be blocks of time for one WOD condition, as well as multiple WOD conditions. Each WOD condition is called a "model" for convenience, so one "model" may contain multiple files to fully specify a long time span, and there may be multiple "models" in the overall airwake lookup package. It should be noted that current NAVAIR practice is to only simulate WOD azimuths for which there is a model. Interpolation between WOD azimuths is not recommended as the properties of the flowfield can change significantly with only a few degrees of change in azimuth. Velocity scaling of the models, however, is considered reasonable as described below.

Next the model is called to extract the perturbation at the specified point. Since the data per model is stored by time slice at a lower frequency than the simulation update rate, the two slices required for interpolation need to be identified. Once the airwake start time offset is applied, the time is scaled by the ratio of the current WOD condition to the WOD used in the CFD calculations. The two slices are then extracted from the file(s) or from memory if all the files were loaded at once. The X, Y, and Z positions are found, a 3-D interpolation is performed for each of the two slices, and the velocities at the interpolated positions are interpolated across time to yield a velocity component for the requested time and lookup point.

The velocity coming out of the search is in the same format as the original CFD data file. For the SAFEDI Tool this is the full flowfield and not normalized. It is aligned to the coordinate system defined for the airwake velocity when the data file was created. This velocity includes turbulence, so it would be inappropriate to superimpose another set of freestream turbulence onto the airwake perturbations; care must be taken to disable the CASTLE® turbulence model when implementing the SAFEDI airwake.

Once the "raw" airwake velocity is determined, it must be scaled to the desired WOD speed and turned into a perturbation that can be used by the airframe. The wind speed applied to the aircraft simulation ($\vec{V}_{a/c}$) consists of the input freestream wind speed ($\vec{V}_{fs}$) and perturbations due to airwake ($\overrightarrow{\Delta V}_{airwake}$) [Eq. 1]. The input ship speed ($\vec{V}_{ss}$) plus the input freestream wind speed are used to calculate the simulation WOD speed and angle [Eq. 2]. Interpolation between WOD angles is highly discouraged since airwake characteristics do not change linearly with changing wind angles. Therefore, the resulting WOD angle must align with a WOD angle from the original CFD datasets. The CFD airwake velocity components at each lookup point ($\vec{V}_{CFD}$) are scaled based on the simulation WOD speed, and the perturbation velocities ($\overrightarrow{\Delta V}_{airwake}$) are calculated using Equation 3.

$$\vec{V}_{a/c} = \vec{V}_{fs} + \overrightarrow{\Delta V}_{airwake} \tag{1}$$

$$\vec{V}_{WOD_{simulation}} = \vec{V}_{fs} + \vec{V}_{ss} \tag{2}$$

$$\overrightarrow{\Delta V}_{airwake} = \left(\vec{V}_{CFD} * \frac{|\vec{V}_{WOD_{simulation}}|}{|\vec{V}_{WOD_{CFD}}|} \right) - \vec{V}_{WOD_{simulation}} \tag{3}$$

When the original airwake speed is scaled, the frequency of the airwake data is also scaled. This is implemented by scaling the airwake lookup time variable so that data is queried at the airwake time history location ($Time_{lookup}$) that corresponds to the aircraft simulation time ($Time_{simulation}$) (Eq. 4). This process is repeated for each requested lookup point.

$$Time_{lookup} = Time_{simulation} * \frac{|\vec{V}_{WOD_{simulation}}|}{|\vec{V}_{WOD_{CFD}}|} \tag{4}$$

The set of scaled velocities are then transformed back to the aircraft body axis through the various coordinate systems. For the fixed wing case, the single airwake perturbation is further transformed in the locally-level (inertial) frame and summed with the inertial velocity, wind velocity, gust disturbance and turbulence (as noted previously, turbulence should be disabled for simulations with CFD ship airwake). The airframe simulation code supplies the connection between the airwake output and the inputs to the CASTLE® total wind calculations.

For the rotary wing case, or a fixed wing that has individual aerodynamic surfaces, the perturbations are transformed to align with each surface reference coordinate system. Again the airframe code provides the connections to distribute the appropriate points to the appropriate surfaces. Typically each surface will perform its own transformation from aircraft body axis to local axis. The perturbations at the rotor blade segments are ultimately transformed to align with the blade chord at each segment, including the blade azimuth, lag, and flap angles as well as the local segment twist. Note that the NAVAIR FVMS Branch Rotor Model defines the requested lookup points and interpolates to get the perturbations at each blade segment.

3. Special Effects

A few "special effects" options are available to the user, including:

- Time offset (user or random)
- Fading at grid edges

An airwake start time offset can be specified by the user, or implemented as a random number. Both methods are disabled by default, with the user-specified time having precedence. This allows the airwake to be non-repeatable for successive runs if desired. If the time offset is larger than the last time available, the time stamp will "wrap" around as described below in the "Limitations" section.

Another issue encountered is a potentially large transition in velocity when the aircraft first enters the airwake grid. When the aircraft is outside the grid, the perturbations are set to zero. A fading factor is applied to interpolate from zero to the velocity at the edge of the grid, using the length defined by the average airwake extraction grid spacing for each axis. For an airwake extraction grid that extends far away from the ship, it would be expected that the velocity at the edges is very close to freestream (no perturbations other than free-air turbulence). Provisions are made to enable or disable the fader, as well as define a weighting factor, but these are not exposed to the user at this time. By default the fader is enabled.

E. Limitations

To maintain the volume of CFD data within reasonable limits and to enable implementation of the airwake dataset in real-time simulation, the simulation capability is restricted by the limitations described below.

1. Airwake Superposition

It is important to note that the airwake velocity data is applied as a superposition of the airwake perturbations onto the freestream (see Eq. 1). The resulting velocity vector is passed to the airframe model to calculate aircraft forces and moments which in turn are used to determine the aircraft motion. Perturbations to the airflow due to the aircraft (i.e. rotor downwash, wing circulation, etc.) have no effect on the airwake. In reality, the external airflow environment is modified by the presence of the aircraft to greater or lesser degrees depending on the aircraft type, size, etc. The superposition approach is necessary to maintain real-time execution speeds. For the majority of a flight path, this approach is acceptable. For some cases, however - in particular for helicopters hovering near a ship deck - the wake produced by the aircraft can have a significant effect on the surrounding environment including the airwake from the ship. In these regions, confidence in the superposition approach is diminished and results should be used with caution.

2. Ship Motion and the Airwake Grid

Typically, CFD ship airwake data is created in the absence of ship motion. However, ship motion is important from a pilot/controller workload perspective and is therefore modeled as part of the airwake analysis simulations. At this time, airwake extraction grids are fixed to the ship body in both translation and rotation, such that the extraction grid moves with the ship without modifying the airwake velocity data itself. Alternatively, the airwake extraction grid could be fixed in the original neutral position and the ship allowed to roll/pitch/yaw/heave independently. Neither approach is strictly correct physically; however the former approach was chosen to support cases where ship motion is included in the CFD simulations.

For cases where ship motion effects on airwake are a primary concern, CFD airwake data are generated with a prescribed ship motion. The airwake extraction grid is fixed to the ship as described above, and ship motion for the aircraft simulation is synchronized to the ship motion used to generate the airwake data. In this way coherence between ship motion and ship airwake is maintained.

3. Airwake Looping

The CFD airwake time histories are created for a finite period of time. For fixed wing simulations in which the aircraft is moving rapidly through the flowfield, this generally does not present a limitation. However, helicopter approaches tend to last for longer periods of time. To prevent the airwake from stopping at the last available time step in the file, a wrap function is implemented. This is done in a simple fashion by dividing the adjusted time stamp by the available time range (including offset) until the remainder falls within the available time range. Currently this is an abrupt transition, using the last time slice and first time slice and interpolating in between if necessary. Attempts to fade or filter the velocity across this wrap-around were found to be problematic.

Limitations on airwake time history length are mainly due to limitations in available computer time needed to run the solutions. As more powerful computers become available, this limitation is diminishing.

V. Airwake Analysis Approach and Example

For a new ship design, the goal of the airwake analysis is to determine whether the new ship will have better or, more importantly, worse airwake characteristics compared to a similar existing ship. Regions of concern are identified for possible redesign or to provide caution areas for flight testing. Flight simulation analysis is used to evaluate the impact of airwake on an aircraft type. For aircraft carrier analysis, the airwake impact on a fixed-wing jet aircraft model may be evaluated. However, a helicopter simulation model is used most often since helicopters operate from all US Navy air-capable ships.

The SAFEDI Tool is used to perform approach and landing simulations through CFD-generated airwake time histories created as described earlier. A number of factors preclude making absolute conclusions regarding a particular aircraft's performance characteristics using the SAFEDI Tool simulation including: 1) use of pilot models for manned aircraft, 2) lack of "whole simulation" validation data, and 3) known physical modeling deficiencies (e.g. near flight deck interactional aerodynamics neglected using the airwake superposition method). Using the "relative" ship comparison method, simulation results are used to establish "deltas" in airwake effect relative to known airwake effects established through flight testing.

CFD airwake databases are created for the new ship design and for the "baseline" ship at the WOD azimuths of concern. Depending on the intended air operations, WOD databases may be created for only a few directions or for a full 360 degrees of wind azimuth at specific increments. For the latter situation, CFD models are typically created with wind direction increments of 15 degrees. For helicopter analysis, typical approach and landing scenarios are executed to each landing spot on the ship of interest.

A. Example Airwake Analysis

SAFEDI Tool airwake evaluation analysis is often executed for new ship designs or existing ships with altered flight deck configuration to aid in flight test planning and risk reduction. For this example case, the new or altered ship is referred to as Ship 1 and the baseline ship with existing flight envelopes as Ship 2. CFD analysis was used to generate ship airwake databases for both ships and to identify general flow characteristics.

1. CFD Analysis

Airwake datasets for seven WOD azimuths were computed: 000, 030, 045, 060, 090, 180 and 330 degrees. Six WOD speeds were considered: 15, 20, 25, 30, 35, and 45 knots. All cases, with the exception of 000, were run using a steady atmospheric boundary layer profile applied as an inflow boundary condition. A power law profile with the exponent set to 0.13 was used to generate a profile that produced the desired WOD speed at the ship mast anemometer height. The low speed (15 knot) bow wind case was run with a uniform inflow profile to simulate winds generated solely from ship speed. The CFD volume grids consisting of approximately 30 million cells were generated as described previously. Smaller features such as flags and day shapes on the mast, air handlers, and hand railings were deemed insignificant and removed from the model to ease grid generation. Special attention was paid to ensure adequate grid density in the near field wake region to resolve turbulence scales of interest. Grid spacing on the flight deck was approximately 2 feet.

2. Flight Simulation Analysis

ExHel rotary wing simulations were executed using CFD airwake datasets generated for each ship. Approach and hover simulations were executed for two landing spots 1 and 2 on each ship. The ExHel pilot model was used to fly the helicopter through the airwake to the selected landing spots at each WOD azimuth. Three approaches were conducted per azimuth/spot combination, each using a different start time in the airwake time history (0, 20 and 40 seconds).

The pilot model flew the aircraft along a 3 degree glide slope to a 10 foot wheel height hover over the selected spot. A pedal turn over the deck aligned the aircraft with the ship and the hover was maintained for at least 30 seconds. Descent to the deck and landing were not modeled in this study. Approaches were conducted from a point 0.5 miles aft and 45 degrees to port or starboard of the ship depending on the landing spot.

For analysis, the data were extracted during post-processing into three periods: approach to ship, transition over deck and hover over spot. The approach period began when the aircraft first experienced airwake perturbations and ended when the aircraft CG was 100 feet laterally from the ship centerline. The transition period began at the end of the approach period and ended when the aircraft achieved a hover for 4 seconds within a 2 foot radius of the landing spot. The hover period began when the transition period ended and lasted 30 seconds.

3. Airwake Evaluation Metrics

Metrics representing the severity of the airwake during the approach and transition periods were computed based on standard deviation of aircraft attitude, autopilot control activity and airwake perturbation velocities at the rotor hub (Eqns. 5-8). For the hover period, an additional metric was computed based on standard deviation of aircraft position relative to the landing spot. Since the standard deviation is a measure of the unsteadiness in the data, these metrics provide an indication of the level of airwake-induced workload that the pilot might expect. The metrics are calculated as follows:

$$\text{Position} = \sqrt{\overline{\sigma_x}^2 + \overline{\sigma_y}^2 + \overline{\sigma_z}^2} \tag{5}$$

where $\overline{\sigma_x}$, $\overline{\sigma_y}$ and $\overline{\sigma_z}$ are standard deviations of aircraft x, y and z position relative to the landing spot, averaged across the 3 airwake start times (hover period only). Units are feet.

$$\text{Attitude} = \sqrt{\overline{\sigma_\theta}^2 + \overline{\sigma_\phi}^2 + \overline{\sigma_\psi}^2} \tag{6}$$

where $\overline{\sigma_\theta}$, $\overline{\sigma_\phi}$ and $\overline{\sigma_\psi}$ are standard deviations of aircraft pitch, roll and yaw attitudes, averaged across the 3 airwake start times. Units are degrees.

$$\text{Activity} = \sqrt{\overline{\sigma_{lat}}^2 + \overline{\sigma_{long}}^2 + \overline{\sigma_{coll}}^2 + \overline{\sigma_{ped}}^2} \tag{7}$$

where $\overline{\sigma_{lat}}$, $\overline{\sigma_{long}}$, $\overline{\sigma_{coll}}$ and $\overline{\sigma_{ped}}$ are standard deviations of lateral, longitudinal, collective and pedal activity, averaged across the 3 airwake start times. Units are percent of control throw.

$$\text{Airwake} = \sqrt{\overline{\sigma_u}^2 + \overline{\sigma_v}^2 + \overline{\sigma_w}^2} \tag{8}$$

where $\overline{\sigma_u}$, $\overline{\sigma_v}$ and $\overline{\sigma_w}$ are standard deviations of longitudinal, lateral and vertical airwake velocity perturbations experienced by the aircraft at the rotor hub in ship axes, averaged across the 3 airwake start times. Units are feet per second.

Control activity, airwake velocities, and aircraft state data for each of the three periods were analyzed and compared for each ship to assess the severity of the Ship 1 airwake relative to the Ship 2 airwake [Figs. 20-22]. A few instances were identified where Ship 1 metric values were somewhat higher than those for Ship 2; however, in all instances, the metric values were lower than the highest Ship 2 values for all scenarios examined. For this example case, the flight simulation results indicated that airwake effects on helicopter recoveries to the Ship 1 would be similar to those for the Ship 2 for the wind conditions tested.

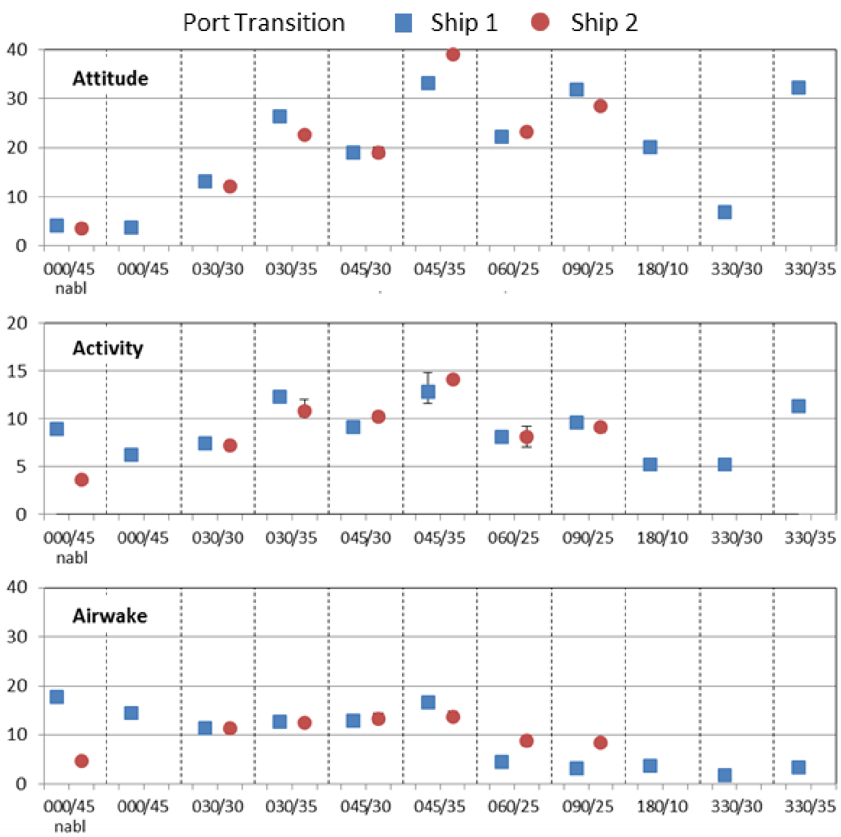


Figure 20. Metrics for transition to port side landing spots.

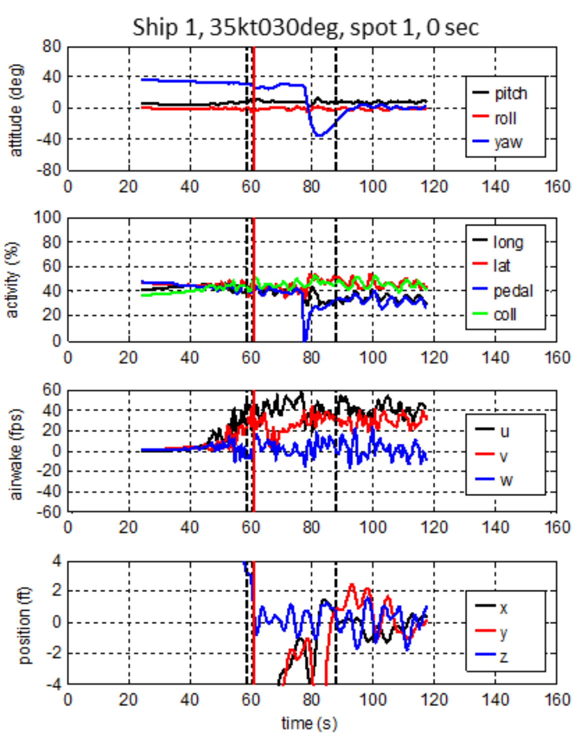


Figure 21. Ship 1, 030 deg at 35 kt, port recovery to Spot 1.

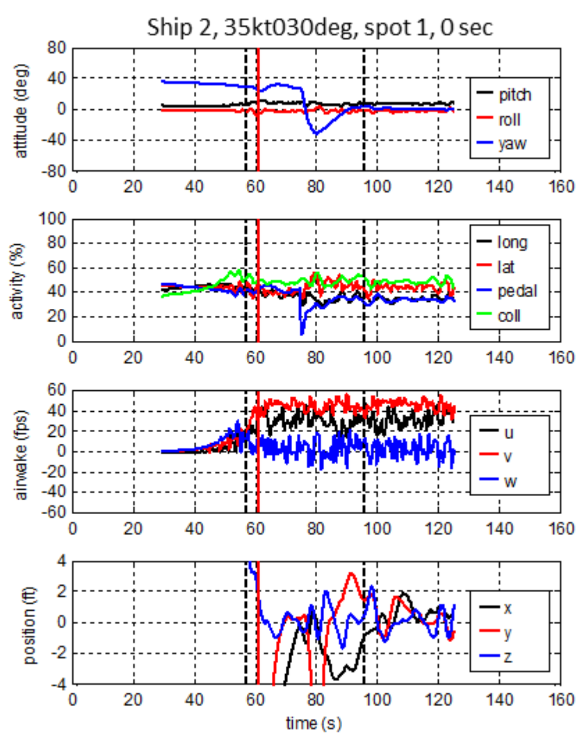


Figure 22. Ship 2, 030 deg at 35 kt, port recovery to Spot 1.

VI. Conclusions

An aircraft simulation based ship airwake evaluation process has been developed and applied to multiple ship classes. The analysis process is facilitated through development and application of the SAFEDI Tool which provides a graphical user interface tailored for dynamic interface simulations. Confidence in computational fluid dynamics (CFD) generated ship airwake models have been established through comparisons with sub-scale wind tunnel data and full-scale ultrasonic anemometer data from multiple ship classes. The SAFEDI Tool airwake analysis approach enables comparative analysis of aircraft flight characteristics in an airwake environment for the purposes of ship design evaluation, flight test planning and risk reduction, and other applications.

Current research efforts focus on developing both CFD and real-time applicable methods to account for interactional aerodynamics as part of the airwake analysis process. While the one-way airwake coupling approach is sufficient for many applications, there are known deficiencies when an aircraft is in close proximity to a structure. Fully coupled CFD analysis is being pursued [Ref. 36] to model interactional aerodynamics with the long term intention of developing reduced order models for real-time applications.

The ultimate goal is to increase the fidelity of airwake analysis techniques to enable quantitative assessments of aircraft performance as opposed to the current comparative analysis approach. V&V are key to establishing a quantitative analysis capability. The design and execution of experiments for virtual dynamic interface V&V is a challenging and expensive endeavor that has not yet been fully scoped or funded.

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