A methodology to correlate simulated airwake data and unsteady helicopter load measurements to shipboard helicopter flight test data

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ABSTRACT: The National Research Council Canada (NRC) has developed a ship-helicopter analysis methodology for correlating simulation data gathered in a wind tunnel with flight trial data gathered by CH124 Sea King pilots conducting landings on the flight deck of the Canadian Patrol Frigate (CPF). Simulation data are composed of mean and unsteady wind speed data in the airwake of a ship model and unsteady aerodynamic loading acting on helicopter fuselage and rotor models mounted over the flight deck of the CPF model. Flight trial data gathered in 1993 characterized the difficulty of conducting landings using the pilot rating scale (PRS), which was subsequently used to develop the operating limits of the Sea King landing on the CPF flight deck. Relationships correlating the streamwise airwake turbulence and unsteady helicopter rotor thrust from the wind tunnel simulation to PRS from flight trials have been successfully identified. This correlation analysis allows simulation data to be used to evaluate new ship designs and to estimate the resulting operational limits for the Sea King operating from a different ship once appropriate simulation data have been acquired.

KEY WORDS: Airwake, Helicopter, Unsteady Aerodynamic Loading, Particle Image Velocimetry

1 INTRODUCTION

Over the past decade, the National Research Council Canada (NRC) and Defence Research and Development Canada-Atlantic (DRDC-A) have been supporting shipboard helicopter operations of the Royal Canadian Navy (RCN) and Royal Canadian Air Force (RCAF) with simulation technology. The Ship Helicopter Operational Limits Analysis and Simulation (SHOLAS) Asses-sment Methodology (SAM) is the name for the group of aerodynamic simulation tools and models that are used to analyze shipboard helicopter operations.

The RCAF conducts helicopter operations with the CH124 Sea King helicopter from the flight deck of the Canadian Patrol Frigate (CPF). Photographs of a Sea King conducting an approach and landing on the flight deck of the CPF are shown in Figure 1. An automatic landing system is installed on the CPF and is used to land helicopters. The CPF has a hangar and a flight deck and is capable of operating the Sea King helicopter. The CPF is a surface combatant ship that can operate independently or in support of other ships as required. The CPF is capable of amphibious operations and can operate in a wide range of environments. The CPF is equipped with a hangar and a flight deck and can operate the Sea King helicopter. The CPF is a surface combatant ship that can operate independently or in support of other ships as required. The CPF is capable of amphibious operations and can operate in a wide range of environments. The CPF is equipped with a hangar and a flight deck and can operate the Sea King helicopter.

An airwake refers to the characteristics of the flow in the area downstream of the superstructure of the ship over the flight deck. This highly unsteady aerodynamic environment is characterized by flow separation, multiple shear layers, and elevated levels of turbulence. A sketch of the mean flow structures over the flight deck of a simplified frigate geometry in headwinds is shown in Figure 2a [1]. The flow field is characterized by flow separation and shear layers emanating from the top and sides of the hangar in addition to a large recirculation zone. Rahdes and Healey also sketched topologies for a relative wind direction of 50°, as shown in Figure 2b [1]. At large enough relative wind directions, separation occurs from the hangar top, the hangar sides, and the flight deck edges, and in some cases three distinct recirculation regions exist. The flow features represented in Figure 2 are based on a time-averaged flow pattern. In real time, separation bubbles can flap and the associated shear layer and reattachment point will move in space over the flight deck. Figure 2b illustrates two extreme separation bubble positions that were observed for a 50° wind direction. Unsteady flow features can also originate upstream of the hangar face, off the front and side edges of the superstructure, from the exhaust stack or mast, and from objects on the hangar. The unsteady aerodynamic environment in the airwake will affect the pilot handling over the flight deck and will influence the operational limits for safe take off and landing maneuvers.

The ship-helicopter operating limit (SHOL) envelope of a helicopter characterizes the difficulty associated with completing safe launch and recovery maneuvers from the flight deck and specifies relative wind speed and direction boundaries within which
safe flight operations are possible. Figure 3 shows the development of the factors that influence the operational limits related to aerodynamic effects of a helicopter operating from the flight deck of a ship. In addition to aerodynamic effects, operational limits may also be influenced by sea spray, visual cues, exhaust gases, or flight control systems. Following the model in Figure 3, a particular ship geometry creates an airwake flow field which can be influenced by the atmospheric boundary layer as well as the motion of the ship. The relationship between ship geometry and an airwake is marked as 1 in Figure 3 and is typically simulated either numerically or experimentally. Current techniques generally assume a stationary ship, however preliminary studies have shown that ship motion is an important aerodynamic factor for operational limits in high sea states. The downwash from a helicopter introduced into the airwake modifies the flow field and the resulting flow field acts on the helicopter rotor and fuselage with unsteady loading. This relationship, marked as 2, is more complex. The relationship between helicopter unsteady loading and operational limits for a particular helicopter control system is represented by 3 in Figure 3. Based on this model, which is applicable for the range of wind directions over which aerodynamic effects dominate for operational limits, the root cause of flying difficulty is the presence of the superstructure of the ship. A key component of SAM is the characterization of the relationship between measurable simulated aerodynamic quantities (airwake and unsteady helicopter loads) and ratings for flying characteristics assigned by a pilot during flight trials.

The NRC has developed an approach that can be used to characterize the anticipated level of pilot workload by applying two experimental techniques. These methods were applied using a wind tunnel model of the Canadian Patrol Frigate. The first approach involves using particle image velocimetry (PIV) to measure mean and turbulent quantities in the airwake. These airwake-only measurements are conducted without a helicopter model over the flight deck. The second novel experimental technique measures unsteady helicopter rotor and fuselage aerodynamic loads in response to the airwake of a ship using scaled models. Helicopter fuselage and rotor models generate a representative flow field over the flight deck. The fuselage and rotor models thus serve to...
integrate the fluctuating loading over their surfaces and, taken together, can be considered as an airwake probe that can be used to determine root-mean-square (rms) magnitudes of fluctuating aerodynamic loads.

![Diagram](image)

Figure 3: Simulation components for the ship-helicopter interface due to aerodynamic effects.

The identification of a relationship between the simulation quantities measurable by SAM and helicopter operational limits determined from sea trials would allow for an estimation of anticipated pilot workload when operating behind a new ship design or when pairing a new helicopter to an existing ship. The goal of this work was to identify and characterize the relationships between each of these quantities (airwake-only and unsteady aerodynamic loading) and pilot ratings assigned during flight trials, which are a measure of the workload associated with a particular manoeuvre. Additionally, the relationships between airwake-only measurements and unsteady aerodynamic loading were investigated.

## 2 EXPERIMENTAL SETUP AND PROCEDURES

### 2.1 3 m × 6 m Wind Tunnel

The experiments conducted in support of this project were completed in the NRC 3 m × 6 m Wind Tunnel, shown in Figure 4. The test section of this open-circuit wind tunnel is 3.1 m wide, 6.1 m high and 12.2 m long. The height and length of the test section were reduced in this study to 5.4 m and 6.4 m, respectively, as the lower insert was installed. The lower insert is used as a false floor in which to house the turntable. The turntable has a diameter of 2.9 m and was operated with angles from -45 to +45 degrees during this test. The experiments were conducted using the electric drive for the wind tunnel fan, which can generate nominal speeds of up to 50 m/s in the test section with inserts.

![Image](image)

Figure 4: The NRC 3 m × 6 m Wind Tunnel.

### 2.2 Atmospheric Boundary Layer Simulation

It has been previously demonstrated that the shear and turbulence present in the atmospheric boundary layer (ABL) are important aspects of ship airwake simulation [2]. For this investigation, three triangular spires were placed at the entrance to the test section to produce a representative turbulent atmospheric boundary layer. The spires measured 3.05 m tall and 0.29 m at the base and produced a representative boundary layer that can be approximated by

\[
\frac{V}{V_{ref}} = \left( \frac{z}{z_{ref}} \right)^{0.25}
\]

(1)
where $V$ is the wind speed at a distance $z$ above the floor of the test section or the surface of the water. The flow profile was characterized using a four-hole, fast-response, Cobra probe which allows three components of wind speed as well as static pressure to be resolved. The probe has pressure transducers built into the stem which, combined with the short length of tubing between the probe tip and the transducers, allows for correction of the frequency response of the system with a resolution up to 1.5 kHz, above which the on-board electronics filter the output signals. For this test, the reference height ($z_{ref}$) is taken as the height of the mast anemometer on the CPF model. The resulting boundary layer profile had a power law exponent ($\alpha$) of 0.05 and a turbulence intensity of 10% at a ship anemometer reference height located 49 cm above the test section floor.

### 2.3 Scaling the Experiment

For ship-helicopter studies, the parameters addressing kinematic and dynamic similitude, respectively, are reduced frequency ($k$) and Reynolds number ($Re$). Reduced frequency — or advance ratio — matching ensures that the imposed time variations between full-scale conditions and the simulation are similar; as a result, reduced frequency matching relates the frequency scale ($\lambda_f$), geometrical scale ($\lambda_D$), and the velocity scale ($\lambda_V$) as follows:

$$
\frac{k_m}{k_o} = \left( \frac{f_m}{f_o} \right) \left( \frac{D_m}{D_o} \right) \left( \frac{V_o}{V_m} \right) = \frac{\lambda_f \cdot \lambda_D}{\lambda_V} = 1
$$

(2)

where subscripts $o$ and $m$ refer to full-scale and model-scale quantities, respectively, for the frequency ($f$), geometrical ($D$), and velocity ($V$) ratio quantities. For the present study, the geometrical scale, $\lambda_D = D_m/D_o$, was fixed at 1/50 [3].

Based on the application of actuator disc theory, the velocity scale can be shown to be related to model-scale rotor thrust as follows:

$$
\lambda_V = \frac{V_m}{V_o} = \sqrt{\frac{T_m}{W_o \cdot \lambda_D \cdot \lambda_f}}
$$

(3)

where $T_m$ represents measured model-rotor thrust, $W_o$ is the weight of a full-scale helicopter, and $\lambda_D$ is the density scale (assumed to be unity throughout this investigation). The frequency scale can be obtained with $\lambda_D$ and $\lambda_V$ after rearranging Equation (2) as

$$
\lambda_f = \frac{\lambda_V}{\lambda_D}
$$

(4)

Similitude was achieved by satisfying Equations (2) to (4) and unsteady loading and wind speeds were subsequently interpreted at full scale. The force ($\lambda_F$) and moment ($\lambda_M$) scales are expressed, respectively, as

$$
\lambda_F = (\lambda_D \cdot \lambda_V)^2
$$

(5)

$$
\lambda_M = \lambda_D \cdot \lambda_F
$$

(6)

The scale factors for force spectral densities ($S_F$) and moment spectral densities ($S_M$) are

$$
\lambda_{S_F} = \frac{\lambda_f}{\lambda_F}
$$

(7)

$$
\lambda_{S_M} = \frac{\lambda_f}{\lambda_M}
$$

(8)

Thus, the measurement of the thrust developed by the model rotor is critical for establishing the velocity, frequency, force and moment, and spectral-density scales for the experiment. For the geometrical scale and relative wind speeds being considered for this investigation, the lowest beam-based Reynolds number exceeded 11,000, the minimum recommended for the modelling of ships in a wind tunnel [4].

### 2.4 Description of the Ship Model

A schematic of the 1/50-scale model of the CPF is illustrated in Figure 5. The ship coordinate system indicated in Figure 5 is aligned with the longitudinal ship axis. The origin of the coordinate system aligns with the centreline of the flight deck and with the intersection of the flight deck and the face of the hangar.

The ship coordinate system corresponds to the wind tunnel coordinate system when the ship model is at 0° relative wind angle, except that its origin is at the middle of the hangar laterally, and at the forward-most point on the flight deck longitudinally. The ship coordinate system moves with the ship when the relative wind direction is changed using the wind tunnel turntable. The wind direction convention is illustrated in Figure 6. Relative wind directions approaching the port side of the ship are negative and are denoted as Red winds, whereas wind directions approaching the starboard side of the ship are positive and are denoted as Green winds.
2.5 **Description of the Helicopter Model**

The 1/50-scale of model of the Sea King helicopter shown in Figure 7 was used in the unsteady aerodynamic loading measurement campaign and is comprised of fuselage and rotor models. The decoupled fuselage and rotor models measure the aerodynamic forces and moments imposed on the model using separate instrumentation.

The fuselage model was fabricated from a lightweight, high density, structural plastic foam. Some details of the fuselage, such as the tail rotor and various antenna, were omitted. The fuselage model has a representative attitude characterized by a pitch angle of 5° and a roll angle of 3° and is mounted on a dynamic balance that measures aerodynamic forces and moments. The longitudinal axis of the fuselage was always aligned with that of the CPF, which is typical for a landing manoeuvre.

The five-bladed rotor model was a representation of a Sea King main rotor. The rotor was designed to be stiff, since full articulation at this model scale is not practical. The rotor is capable of spinning up to 11,000 rpm to generate correctly scaled thrust, advance ratio, and downwash. Although the diameter of the rotor has been scaled geometrically, the rotor blade airfoil (NACA 0012), the chord, and the twist distribution were adjusted so that the rotor produces a representative downwash and correctly-scaled thrust. The blades were fabricated from aerospace-grade titanium and the rotor hub was oversized to reduce the stresses in the roots of the blades. The capability to set the collective angle was included via an adjustable blade pitch which can only be changed when the rotor is not spinning. The clearance between the bottom surface of the rotor hub and the fuselage was approximately 5 mm (Figure 7); as a consequence, the rotor plane was placed higher above the fuselage than allowed by proper geometric scaling. This discrepancy was not expected to have a significant impact on the aerodynamic loading acting on the fuselage or the thrust produced by the rotor. Unlike the fuselage, the rotor model was not pitched or rolled.

The helicopter was positioned such that the rotor plane was located at three distinct positions:

- **Port-edge high hover**, positioned laterally from the landing spot (Figure 8a);
- **High hover**, centred over the landing spot (Figure 8b); and
- **Low hover**, centred over the landing spot (Figure 8c).

These three positions reflect the transitory nature of a landing manoeuvre, during which a helicopter moves across the deck, to the high hover position, to the low hover position, and then to touchdown. In the airwake-only measurements conducted in the absence of a helicopter, data were interpolated onto discs that corresponded to the three helicopter rotor planes.
2.6 Airwake-only Measurements

The flow field measurements in the airwake-only study were performed using particle image velocimetry. This technique allows resolution of instantaneous velocity vectors in a single plane of the flow and is useful for understanding and characterizing complex flows like a ship’s airwake.

The overall test section setup for airwake-only measurements is shown in Figure 9. The laser and camera positions restrict the possible relative wind directions to the range from 0° to 30° port (or 0° to 30° starboard with the alternate camera location). This is the range of wind directions through which the ship airwake has the largest effect on the SHOL envelope. Prior to each run with the CPF model, the turntable, upon which the ship, camera and laser modules were mounted, was rotated to set the incident wind angle. To capture the flow for both positive and negative wind directions, it was necessary to relocate manually the camera module from one side of the ship to the other. This kept the cameras downstream of the ship model for all turntable yaw angles.

2.6.1 Data Acquisition and Reduction

A pair of 120 mJ Nd:YAG lasers were used for this study. A 20° cylindrical lens coupled with a laser beam collimator were used to produce and focus the light sheet in the measurement region. Due to the large size of the test section and the limitation of the power rating of the lasers, it was necessary to mount the laser/lens module in the airflow, above and behind the ship model to generate a light sheet of acceptable intensity at the flight deck. The laser cooling units were placed downstream of the laser stand. Two charge-coupled device cameras oriented obliquely to the laser light sheet and to each other allow the resolution of three components of velocity in the measurement plane, using a technique known as stereoscopic PIV. The two cameras had a resolution of 1600 x 1200 pixels and a sensitivity of 14 bits.

The images were first preprocessed by masking out areas located outside of the laser light sheet, and then by applying a sliding filter to remove large-scale light intensity fluctuations, for example, due to reflections. A multi-pass stereo cross-correlation calculation with decreasing window size and adaptive window shifting was then performed. The interrogation window size was 128 × 128 pixels for the first three passes and decreased to 64 × 64 pixels for the final three passes, with an overlap of 50% for all passes. A round Gaussian weighting function was applied to the interrogation windows for all passes. In between passes, a median filter was used to remove spurious vectors, groups with less than 5 vectors were also removed, empty spaces were filled by interpolation and a smoothing algorithm was applied. A final high-accuracy pass was conducted with Lanczos reconstruction mode and no interpolation or smoothing was applied to the final calculated velocity field.

For each incident wind direction, PIV data were collected for 15 x-z (streamwise-vertical) planes in the ship coordinate system. The actuators on which the camera and laser modules were mounted were programmed to traverse laterally so that all 15 planes could be surveyed sequentially at each wind direction. For each measurement plane on the CPF flight deck, a set of 700 image pairs was acquired at a rate of approximately 11 Hz. A time delay of $\Delta t = 20 \mu s$ between each image pair was found to produce the most reliable velocity vectors throughout the measurement plane. The data were postprocessed to obtain 700 instantaneous three-component velocity fields for each plane and for each incident wind direction. The approximate camera window position for each x-z plane is presented in Figure 10a. The data from the 15 planes collected at each relative wind direction were subsequently...
interpolated onto discs representing the rotor plane in the high hover, low hover, and port-edge hover positions. A schematic of the interpolated rotor plane position in high hover is shown in Figure 10b.

The similitude considerations for this PIV experiment were much simpler than rotor loading or ship motion experiments. In this case, the only parameter that must be selected is the wind speed. Tests were conducted at a nominal reference wind speed \( V_{ref} \) of 17 m/s. The flow field was measured for relative wind directions between Red 30 and Green 30; the CPF is asymmetric, so both positive and negative directions were of interest. Angular increments of 5° were used, leading measured flow fields at 13 distinct wind directions. At the start of the CPF test campaign, the PIV system was calibrated with the cameras mounted on the starboard side, and data for all ship model configurations was collected for seven wind directions varying from 0° to -30° (Red) in steps of 5°. The cameras were then moved to the port side, recalibrated, and the remainder of the data were collected for the corresponding Green wind directions (0° to +30° in steps of 5°).

2.7 Unsteady Aerodynamic Loading

The NRC ship-helicopter methodology is capable of quantifying unsteady helicopter rotor loads and fuselage loads in response to the airwake of a ship. The experimental setup of the unsteady aerodynamic loading apparatus is shown in Figure 11. The three ABL spires and the wind tunnel fan blades are visible in the background. The unsteady loading apparatus can be seen aft of the flight deck of the ship. The rotor is positioned using a support structure and is driven with a DC motor mounted above the rotor. The helicopter fuselage balance was mounted to the flight deck of the ship.

2.7.1 Data Acquisition and Reduction

The instrumentation suite for unsteady loading measurements comprised two dynamic balances which measured the aerodynamic loading acting on the Sea King model, an encoder to monitor rotor speed, two orthogonally-aligned accelerometers to
monitor the vibration of the rotor support system, and thermocouples to sense the surface temperature of the drive motor and the rotor balance.

The position of the balances within the fuselage and rotor stack assemblies is indicated in Figure 12. A commercial off-the-shelf balance was used to measure the aerodynamic loading acting on the rotor model. The balance geometry possesses an annular opening that passes from the ground-side to the live-side of the balance. The annulus allows a rotor shaft spinning at high rotational speed to pass through the balance and deliver mechanical power to the rotor. A specialized mechanism allows a reliable measurement of unsteady thrust in spite of this driving shaft. Although all six load components of the balance were acquired, only the thrust was of primary interest; the mean thrust, in particular, was essential to develop the scaling factors, as highlighted earlier. The drag and side forces, and pitching, yawing and rolling moments acting on the fuselage model were sensed by a five-component moment balance that has been adapted for ship-helicopter testing.

Data from both dynamic balances, the accelerometers, and the thermocouples were acquired at a sampling rate of 625 Hz with a low-pass filter cutoff frequency of 242.5 Hz. The shaft encoder data (representing the rotor speed) were obtained via an ethernet data socket at a sampling rate of 10 Hz. All channels were sampled for a duration of 60 seconds for each sample point.

The time-histories of each load component of a dynamic balance were developed by converting the tared voltage output signals to engineering units with the calibration matrix of the balances. These model-scale time-histories were digitally filtered with a low-pass Butterworth filter of order three with a cutoff frequency of 200 Hz. Based on these filtered time-histories, model-scale frequency spectra with a frequency resolution of 0.5 Hz were developed with a 1,250-point fast Fourier transform, a window size of 1,250 samples, and a window overlap of fifty-percent.

The fuselage force and moment data and the rotor thrust data were postprocessed to remove the effects of mechanical resonance. Mechanical resonance for the fuselage force and moment data tended to be centred on peaks that fell outside the frequency range of interest at model scale, but the build up to a peak could lead to an overestimation of rms loading. Mechanical resonance was not present or only present below the frequency range of interest in the rotor thrust data.
removed from the fuselage force and moment data by filtering the model-scale spectrum with a one-degree of freedom (1-DOF) transfer function.

The mechanical resonance appearing in the rotor thrust data was not be filtered in this way because the resonant peaks fell within the frequency of range of interest — filtering with a similar 1-DOF transfer function could have attenuated the unsteady rotor thrust signal in the upper end of the frequency range of interest. Instead, mechanical resonance was effectively filtered from the rotor thrust by fitting a least-squares cubic spline to the full-scale spectral data, excluding the narrow frequency band of a resonant peak. An example of a least-squares cubic spline fitted to a rotor thrust spectrum can be seen in Figure 12(b). For consistency, least-squares cubic splines were fitted to the full-scale fuselage force and moment spectra. The least-squares cubic splines were subsequently integrated over the range of full-scale frequencies from 0.2 to 2.0 Hz, which is the frequency interval over which a helicopter pilot reacts to disturbances produced by airwake turbulence or other excitations [5]. The square root of the integrated quantity was computed to obtain the full-scale rms loading of the rotor thrust and the fuselage forces and moments for each test point.

Contour plots were developed for the rotor and fuselage force and moment components using the full-scale rms loading determined from the power spectral densities at each data point. The results were interpolated onto a fine mesh using a Kriging interpolation scheme to generate contour plots such as the plot shown in Figure 12(c). The dots in the contour plots indicate the full scale relative wind speeds and relative wind directions where data points were recorded. The unsteady aerodynamic loading based on these contours was used in the subsequent correlations with flight trial data.

Unsteady aerodynamic data were acquired at the high hover, low hover, and port-edge high hover helicopter positions. At each hover position, data were collected over a survey envelope consisting of 19 wind directions and nine wind speeds. Each sample point in a survey was collected at a target relative wind speed and wind direction. The surveys were conducted with a target velocity scale of 0.6:1. Frequency scaling of approximately 30:1 resulted in a target model-scale rotor speed of 8000 rpm.

3 RESULTS

3.1 Airwake-only

Figure 13 shows the mean and fluctuating streamwise component of velocity in the airwake in the high hover rotor disc for three relative wind directions. The relative wind direction in each case is indicated with an arrow inset in the plots. Figure 13a demonstrates that a greater localized velocity deficit is present in the high hover plane at +20°, whereas the velocity deficit occurs over a larger area in Red winds. The separation bubble over the flight deck may therefore be larger in Red winds due to the asymmetric hangar design. For a wind direction of -20°, the areas of high turbulence intensity (I_u) occur mainly inside the time-averaged location of the separation bubble, while the entire rotor disc is submerged in higher turbulence for Green winds (Figure 13b). The mean and unsteady data within the high hover, low hover, and port-edge high hover rotor planes were averaged at each test condition and were used in the development of correlations with flight test data.

![Normalized streamwise mean velocity at Red 20, headwinds, and Green 20](image)

(a) Normalized streamwise mean velocity at Red 20, headwinds, and Green 20

![Normalized streamwise turbulence intensity at Red 20, headwinds, and Green 20](image)

(b) Normalized streamwise turbulence intensity at Red 20, headwinds, and Green 20

Figure 13: Normalized mean and unsteady velocity components interpolated to the high hover rotor disc (x-y) plane for three relative wind directions. The coordinates are expressed at full scale in the ship reference frame.
3.2 Unsteady Aerodynamic Loading

The unsteady aerodynamic loading methodology measures aerodynamic forces and moments integrated over the fuselage model as well as rotor thrust integrated over the rotor disc. The unsteady loads are reported at full scale values based on the scaling methodology described above and have been normalized by the weight of the Sea King helicopter \( W_0 \). The normalized unsteady rotor thrust \( \tilde{F}_{\text{rotor}} / W_0 \) has been identified as the most promising indicator of helicopter flying quality and therefore only the results obtained for the rotor will be shown here.

The contour plot developed for the unsteady rotor thrust in high hover is shown in Figure 14a. The test points included in Figure 14a indicate a small amount of variation in the full scale wind speed over a particular yaw sweep due to the use of mean rotor thrust at model scale in the scaling methodology. The outer regions of the contour plots have also been masked as these conditions fell outside of the target survey envelope and data were not available for interpolation. Note that the wind direction labels in the contour plots indicate positive values for Green (from starboard) wind directions and negative values for Red (from port) wind directions. \( \tilde{F}_{\text{rotor}} / W_0 \) ranges from 2% to 8% of the helicopter weight over the survey envelope and exhibits an asymmetry which becomes more pronounced at higher wind speeds. Unsteady rotor thrust in high hover was observed to be higher in Green winds than in Red winds.

![Figure 14a: Unsteady rotor thrust contour plots for the Sea King helicopter over the flight deck of the CPF model.](image)

The low hover results for the unsteady rotor thrust measured over the CPF flight deck are highlighted in Figure 14b. The magnitudes of the \( \tilde{F}_{\text{rotor}} / W_0 \) contours at low wind speeds in low hover are generally greater than those observed at low wind speeds in the high hover position. Additionally, the contours are asymmetric at low wind speeds and result in increased unsteady rotor thrust at wind directions that range from -15° to -35°.

![Figure 14b: Unsteady rotor thrust contour plots for the Sea King helicopter over the flight deck of the CPF model.](image)

The unsteady loading contours at the port-edge high hover position are shown in Figure 14c. The unsteady rotor thrust contours are asymmetric and the wind directions resulting in the highest unsteady loading have been shifted compared to the high hover case due to the relative position of the helicopter over the flight deck and the change in projected area of the hangar in Green winds.

The interpolated unsteady rotor thrust values corresponding to wind direction and wind speed conditions encountered during flight tests were used in the subsequent development of correlations with flight trial data.
3.3 Correlations With Flight Trial Data

Flight trials conducted in 1993 characterized the difficulty of landing a Sea King on the flight deck of the CPF over a wide range of expected relative wind speeds and directions. The level of flying difficulty was quantified using a pilot rating scale (PRS) that encompasses all aspects of a manoeuvre and is assigned to each set of conditions. The PRS values for a landing range from 1 to 6 and increase with increasing level of difficulty associated with a landing. Operating limits for the Sea King paired with the CPF were developed based on the PRS system. The current work has identified correlations between unsteady helicopter loading and airwake-only data measured in a wind tunnel with pilot workload ratings. Data from the airwake and unsteady loading data sets were interpolated to the same wind direction and wind speeds reported in the flight trials for use in the development of these correlations.

The unsteady rotor thrust has been identified as the most suitable unsteady aerodynamic loading metric for comparison with flight trial data. Data were acquired in the wind tunnel in the high hover, low hover, and port-edge high hover positions. A composite hover metric consisting of the maximum unsteady rotor thrust value from the three hover positions was selected for comparison with PRS at a particular wind speed and direction. This composite metric partly accounts for the transitory nature of a landing manoeuvre. The PRS data are based on flights conducted at low sea states and correspond to cases with limited amounts of ship motion, as the present experiment was conducted with a static ship. Normalized unsteady rotor thrust is compared to PRS over the range of equivalent wind speeds and wind directions evaluated during flight trials in Figure 15a. Figure 15a identifies a relationship between the level of flying difficulty, characterized by PRS, and the unsteady rotor thrust.

Analysis of the airwake-only data identified a similar relationship between the streamwise component of turbulence ($\sigma_u$) at key locations in the airwake and PRS. The hover position resulting in the best correlation was also considered, including the high hover, low hover, and port-edge high hover positions. The composite hover position that captures the maximum of the three discrete hover positions was also considered. The high hover position dominated the composite metric and was therefore deemed to provide a suitable correlation between PRS and airwake. The correlation between the streamwise component of turbulence and PRS is shown in Figure 15b and highlights that increasing levels of turbulence results in a higher expected level of flying difficulty. The scatter observed in Figures 15a and 15b is due to the existence of other factors beyond airwake characteristics that contribute to a pilot rating. The relationships that were developed indicate the level of change in the metrics that could be expected to cause a change in the pilot rating, assuming the other conditions are similar. Additional work to separate and identify these other effects is ongoing.

The relationships identified between simulation quantities and pilot ratings can be used as an indicator and predictor of helicopter limits. These relationships can be used to convert contour plots of unsteady rotor thrust (or airwake-only data) into equivalent PRS contours. The predicted operating limits can then be identified based on a PRS rating selected to correspond to safe flight operations.

3.4 Comparing Airwake Quantities and Unsteady Aerodynamic Loading

The current understanding of airwake quantities and unsteady aerodynamic loading analysis for helicopter operations highlights the notion that simulations involving a rotor are more robust that simulations of airwake only. The model shown earlier in Figure 3 assumes that a direct relationship exists between airwake and the resulting unsteady aerodynamic loading and that helicopter aerodynamic loads are more closely related to operational limits than airwake features. This is because the presence of the rotor causes changes in the flow field itself that cannot be explicitly predicted. In a comparative sense, however, changes in airwake characteristics should correspond to a change in operating limits through the relationships shown in Figure 3. Indeed, the ability to use airwake characteristics to refine or evaluate the merits of different ship designs for helicopter operations has the benefit of being much more cost-effective than analysis methods that include the effect of the rotor.

Figure 15: Unsteady rotor thrust and streamwise turbulence correlations with PRS from flight trials (low sea states).
The current analysis process has allowed a first look at the relationship between airwake-only and unsteady aerodynamic loading quantities. Figure 16 shows the relationship between the unsteady rotor thrust and both the streamwise and vertical turbulent velocities. Clearly a relationship exists between the quantities, and this finding supports the use of airwake-only evaluations in a ship design evaluation process. Currently, unsteady loads analysis is deemed more robust than airwake-only analysis, particularly for SHOL envelope prediction, however, further investigation of the factors at play will improve the understanding of this relationship.

4 CONCLUSIONS

The NRC has developed a novel experimental technique that can be used to measure simulated helicopter rotor loads and fuselage loads in response to the airwake of a ship. The unsteady rotor thrust was correlated to pilot ratings that indicate the level of flying difficulty while landing on the flight deck of a Canadian Patrol Frigate. A relationship was also identified between airwake-only measurements of the streamwise component of turbulence obtained with PIV and pilot ratings. These relationships allow the estimation of SHOL envelopes for new ship designs and new ship-helicopter pairings. Although unsteady load measurements involving a rotor are considered to be more closely-related to operational limits, these results have demonstrated that airwake-only data may also be used to characterize anticipated pilot workload when landing on the flight deck of a ship.

REFERENCES