Contributions to the Understanding of Ship Airwakes Using Advanced Flow Diagnostic Techniques

Dhuree Seth

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CONTRIBUTIONS TO THE UNDERSTANDING OF SHIP AIRWAKES USING
ADVANCED FLOW DIAGNOSTIC TECHNIQUES

By

Dhuree Seth

A Dissertation Submitted to the Faculty of Embry-Riddle Aeronautical University
In Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Aerospace Engineering

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CONTRIBUTIONS TO THE UNDERSTANDING OF SHIP AIRWAKES USING ADVANCED FLOW DIAGNOSTIC TECHNIQUES

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This Dissertation was prepared under the direction of the candidate's committee chairman, Dr. J. Gordon Leishman, Department of Aerospace Engineering, and has been approved by the members of the dissertation committee. It was submitted to the Office of Senior Vice President for Academic Affairs and Provost, and was accepted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Aerospace Engineering.

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Dedicated to my family, my advisor, and to all the extraordinary professors…….
ACKNOWLEDGEMENTS

I would like to thank my parents, sister, and my extended family (Becky and Margaret) for their continued support, patience, and unconditional love that they have bestowed upon me over the years. I consider myself extremely fortunate to be a daughter and sister of such great people. Growing up, I looked up to my Mom and Dad for motivation, kindness, support, and love, and they were a constant source of my motivation. This success and any other of mine belong to them.

I would like to thank my advisor and my mentor Dr. J. Gordon Leishman for taking me under his wings and teaching me valuable lessons inside and outside the classroom. His life and the quality of work has always been an inspiration to me every single day. He is the one person whom I have always looked up to in every aspect of my life. Not just because he is my advisor but because he is a perfect example of how disciplined and dedicated he is to his work. He has a very unique way of looking at a problem and analyzing results that amaze me every time. I have always adored his work ethic and in every way, and he set the bar high for me to shoot for.

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The objective of this research was to better characterize the complex, three dimensional, unsteady aerodynamic flows produced by the superstructure of a ship, which is referred to as an airwake. This problem is relevant and important because the turbulent airwake significantly and adversely affects the ability for rotorcraft to operate safely from the decks of Navy ships. To this end, a series of wind tunnel measurements were performed on the SFS2 simplified frigate shape, which has a flight deck at its stern. The measurements were performed with and without a simulated atmospheric boundary layer (ABL), which included the aerodynamic scaling of its thickness, velocity profile, and turbulence. The ABL was simulated using Cowdrey grid method, which comprises sets of horizontal rods placed in the wind tunnel upstream of the test section. Two wind tunnels were used, in part to cover a wind range of Reynolds numbers based on ship length in the range of 0.6–6.2 million. The first was a 1:235 scale SFS2 ship model in the Boundary Layer Wind Tunnel (BLWT), and the other was a 1:90 scale SFS2 in the Low-Speed Wind Tunnel (LSWT). The measurements were performed using a combination of hot-wire anemometry and particle image velocimetry measurements, especially time-resolved particle image velocimetry (TR-PIV) in the LSWT in various streamwise and crosswise planes. The TR-PIV experiments were also supported by surface oil flow visualization, which was used to help interpret the off-surface flow measurements. The airwake was seen to comprise large regions of unsteady flow separation, dominant vortical flows, and significant wall-normal flows, especially over the region of flight deck regions, which was caused, in part, by the shedding of the vortices and turbulence from
the upstream funnel and superstructure of the ship. The turbulence intensities were found
to be particularly high over the flight deck. The results also suggested the existence of
asymmetric, intermittent flow in the near-wall regions of the deck, and bistable
movements were observed in the recirculation region behind the hangar and behind the
stern of the ship. The measurements also showed the development of shear layers at the
corners of the flight deck on both the port and starboard sides, and sets of counterrotating
vortices at the edges of the flight deck. These results were found to be affected by the
presence of the ABL, but were not strongly affected by the Reynolds number. An energy
spectrum analysis was also performed, showing dominant frequencies in the regions
where the shear layer was developed behind the funnel and above the flight deck. Proper
Orthogonal Decomposition and Spectral Proper-Orthogonal Decomposition was used to
extract the dominant energy modes from the TR-PIV measurements to better quantify the
complex unsteady flow structures exhibited in the airwake. The application of Spectral
Proper Orthogonal Decomposition revealed that the physically relevant coherent
structures in the airwake were low frequency modes near the flight deck and at large
scale of the order of the length of the deck. Although the concentration of the energetic
modes in the airwake were at low frequencies, the overall energy content was still
broadband. At lower frequencies, large-scale structures were observed in both the
streamwise and wall normal directions in the near-wall regions of the flight deck, which
help to explain the production of the intense zones of unsteady upwash/downwash over
the flight deck that are known to affect rotorcraft that operate in the airwake.
# Acknowledgements

We acknowledge the support of the National Science Foundation under Grant Nos. 07122419 and 0841440.

# Abstract

This dissertation presents a comprehensive study of the ship airwake. The research was conducted in the Atmospheric Boundary Layer (ABL) and in a low-speed wind tunnel facility. The objectives were to investigate the flow characteristics and to develop methodologies for validating numerical simulations.

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- Table 1: Detailed comparison of flow parameters.
- Table 2: Summary of experimental conditions.
- Table 3: Performance metrics for different scenarios.

# Symbols

- $Re$: Reynolds number
- $Tu$: Turbulence intensity
- $U_{*}$: Wind speed at the wall

# Abbreviations

- BL: Boundary Layer
- ABL: Atmospheric Boundary Layer
- PIV: Particle Image Velocimetry
- LSWT: Low-Speed Wind Tunnel

# 1. Introduction

- Motivation
- Objectives
- Technical Background and Literature Review

## 1.1. Motivation for this Research

The study aims to understand the flow characteristics around a simple frigate shape.

## 1.2. Objectives of the Present Research

The objectives are to:
- Develop a comprehensive understanding of the ship airwake.
- Validate numerical simulations against experimental data.

## 1.3. Technical Background and Literature Review

1.3.1. Ship Airwake
1.3.2. Detailed Literature on Wind Tunnel Studies of Airwakes

## 1.4. Conclusions on Prior Experimental Research

The results from previous studies are summarized and compared with the current research.

## 1.5. Atmospheric Boundary Layer (ABL)

The ABL is simulated using specific conditions.

## 1.6. Unanswered Questions About the Ship Airwake

The current research addresses gaps in the understanding of ship airwakes.

## 1.7. Outline of this Dissertation

- Chapter 2: Experimental Setup
- Chapter 3: Results and Discussion
- Chapter 4: Conclusion

# 2. Experimental Setup

- Simple Frigate Shape (SFS2)
- ABL Simulation
- Boundary Layer Wind Tunnel Facility
- Low-Speed Wind Tunnel Facility

## 2.1. Simple Frigate Shape (SFS2)

The SFS2 shape is used for preliminary tests.

## 2.2. ABL Simulation

- Simulation setup and parameters.

## 2.3. Boundary Layer Wind Tunnel Facility

- Cowdrey Grids in the BLWT
- HWA Measurements in the BLWT
- PIV Setup in the BLWT
- Seeding in the BLWT
- Test Conditions in the BLWT

## 2.4. Low-Speed Wind Tunnel Facility

- Cowdrey Grids in the LSWT
- Measurement of the Simulated ABL
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### SYMBOLS

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<tr>
<td>$A$</td>
<td>Eigenvectors</td>
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<tr>
<td>$A_1,A_2$</td>
<td>Cross-section area ($m^2$)</td>
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<td>$a_i$</td>
<td>Expansion coefficient</td>
</tr>
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<td>$C$</td>
<td>Calibration constants</td>
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<td>$\tilde{C}$</td>
<td>Auto covariance matrix</td>
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<td>$d$</td>
<td>Rod diameter (in)</td>
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<td>$d_p$</td>
<td>Particle diameter ($\mu m$)</td>
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<tr>
<td>$DL$</td>
<td>Flight deck length (m)</td>
</tr>
<tr>
<td>$E$</td>
<td>Output voltage (V)</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>$f_{fs}$</td>
<td>Full-scale</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>Maximum frequency (Hz)</td>
</tr>
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<td>$f_{N/2}$</td>
<td>Nyquist frequency (Hz)</td>
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<tr>
<td>$f_s$</td>
<td>Sampling frequency (Hz)</td>
</tr>
<tr>
<td>$FSH$</td>
<td>Full-scale ship height (m)</td>
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<tr>
<td>$h$</td>
<td>Height of the rods above the floor (in)</td>
</tr>
<tr>
<td>$HH$</td>
<td>Hangar height (in)</td>
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<td>$j$</td>
<td>Mode index</td>
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<td>$k$</td>
<td>Turbulent kinetic energy ($m^2 s^{-2}$)</td>
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<td>$K$</td>
<td>Local pressure drop coefficient of the Cowdrey grid</td>
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<td>$K_1$</td>
<td>Overall pressure drop coefficient of the Cowdrey grid</td>
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\( l \) Spacing between the centerline axes of the Cowdrey rods (in)

\( L \) Characteristic length (m)

\( m \) Mode number

\( \text{ms} \) Model-scale

\( \dot{m} \) Mass flow rate (kg s\(^{-1}\))

\( M \) Total number of image snapshots

\( n \) Index of the power law profile

\( N \) Number of data points

\( N_b \) Total number of blocks

\( N_f \) Number of snapshots in each block

\( N_o \) Number of snapshots in which each block is overlapped

\( p \) Static pressure (Pa)

\( R \) Correlation coefficients

\( Re \) Reynolds number, \( Re = \rho U_\infty SL/\mu \)

\( SH \) Scaled ship height (m)

\( SL \) Scaled ship length (m)

\( S_{fk} \) Cross-spectral density tensor

\( St \) Strouhal number

\( Stk \) Stokes number

\( t \) Time (s)

\( u \) Flow velocity in the streamwise direction, \( u = \bar{u} + u' \) (m s\(^{-1}\))

\( \bar{u} \) Time-averaged velocity in the streamwise direction (m s\(^{-1}\))

\( u' \) Velocity field in low-rank (m s\(^{-1}\))
\( u' \) Fluctuations in the streamwise \( x \) direction (m s\(^{-1}\))

\( u'_{\text{rms}} \) Turbulence in the streamwise \( x \) direction (m s\(^{-1}\))

\( U \) Flow velocity in the mid-deck region (m s\(^{-1}\))

\( U_{\infty} \) Free-stream flow velocity (m s\(^{-1}\))

\( U_\delta \) Mean velocity at a representative boundary layer thickness (m)

\( v \) Flow velocity in the spanwise direction, \( v = \overline{v} + v' \) (m s\(^{-1}\))

\( \overline{v} \) Time-averaged velocity in the spanwise \( y \) direction (m s\(^{-1}\))

\( v' \) Fluctuations in the spanwise \( y \) direction (m s\(^{-1}\))

\( v'_{\text{rms}} \) Turbulence in the spanwise \( y \) direction (m s\(^{-1}\))

\( w \) Flow velocity in the wall-normal direction, \( w = \overline{w} + w' \) (m s\(^{-1}\))

\( w_j \) Scalar weights

\( \overline{w} \) Time-averaged velocity in the wall-normal \( z \) direction (m s\(^{-1}\))

\( w' \) Fluctuations in the wall-normal \( z \) direction (m s\(^{-1}\))

\( w'_{\text{rms}} \) Turbulence in the wall-normal \( z \) direction (m s\(^{-1}\))

\( W(x) \) Hermitian matrix

\( x \) Streamwise direction

\( x_r \) Streamwise reference location (m)

\( y \) Spanwise direction

\( z \) Wall-normal direction

\( z_0 \) Roughness length scale (m)

\( z_g \) Height above ground/sea level (m)

\( z_r \) Wall-normal reference location (m)

\( \delta \) Boundary layer thickness (m)
\( \delta_{SH} \)  Boundary layer thickness of the scaled ship (m)

\( \Delta \rho \)  Overall pressure drop along any streamline (Pa)

\( \Delta U \)  Uncertainty in the measurements of flow velocity (m s\(^{-1}\))

\( \Delta t \)  Image straddling time (\( \mu s \))

\( \Delta x \)  Spatial separation in the streamwise direction (m)

\( \varepsilon_{\Delta M} \)  Magnification factor

\( \varepsilon_{\Delta t} \)  Pulse separation factor

\( \varepsilon_{\Delta x} \)  Pixel displacement factor

\( \kappa \)  Von Kármán constant

\( \lambda \)  Eigenvalues

\( \mu \)  Dynamic viscosity of air (kg m\(^{-1}\) s\(^{-1}\))

\( \phi \)  Basis function

\( \rho \)  Density of air (kg m\(^{-3}\))

\( \sigma \)  Standard deviation

\( \psi \)  Basis function in terms of \((x, f')\)

\( \tau \)  Relaxation time of the particle (s)
## ABBREVIATIONS

<table>
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<tr>
<th>Abbreviation</th>
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<tr>
<td>ABL</td>
<td>Atmospheric Boundary Layer</td>
</tr>
<tr>
<td>AOML HRD</td>
<td>Atlantic Oceanographic and Meteorological Laboratories Hurricane Research Division</td>
</tr>
<tr>
<td>CSD</td>
<td>Cross-Spectral Densities</td>
</tr>
<tr>
<td>DI</td>
<td>Dynamic Interface</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>HWA</td>
<td>Hot-Wire Anemometry</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
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<tr>
<td>LSWT</td>
<td>Low-Speed Wind Tunnel</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>Neodymium-doped Yttrium Aluminum Garnet</td>
</tr>
<tr>
<td>Nd:YLF</td>
<td>Neodymium-doped Yttrium Lithium Fluoride</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>POD</td>
<td>Proper Orthogonal Decomposition</td>
</tr>
<tr>
<td>SHOL</td>
<td>Ship Helicopter Operational Limits</td>
</tr>
<tr>
<td>SFS2</td>
<td>Simple Frigate Shape 2</td>
</tr>
<tr>
<td>SPOD</td>
<td>Spectral Proper Orthogonal Decomposition</td>
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<tr>
<td>TiO$_2$</td>
<td>Titanium Dioxide</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbulent Kinetic Energy</td>
</tr>
<tr>
<td>Tomo-PIV</td>
<td>Tomographic Particle Tracking Velocimetry</td>
</tr>
<tr>
<td>TR-PIV</td>
<td>Time-Resolved Particle Image Velocimetry</td>
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The motivation behind the present research is discussed in this first chapter of the dissertation, along with a chronological review of relevant prior research that has been reported in the published literature. The primary objective of this research was to perform a series of wind tunnel experiments to better understand the details of the complex, unsteady, turbulent aerodynamic flows produced by the unstreamlined superstructure of a Navy ship, i.e., a phenomenon known as the *airwake*. Ship airwake measurements were made on a generic, scaled Navy frigate in a low-speed wind tunnel, primarily by using time-resolved particle image velocimetry techniques, which had the ability to measure the time-history of the evolving flows.

Aerodynamically, a ship is basically a large bluff body. As it sails over the ocean, then it creates an airwake over its superstructure that comprises of numerous interacting flow topologies that contain regions of flow separation and turbulence of various scales and energy. This airwake problem is important because its associated turbulence affects the ability to safely deploy and land various types of aircraft from the stern of a ship, particularly helicopters and other rotorcraft, as well as unmanned flight vehicles. The issues associated with operating an aircraft from a ship is generally called the Dynamic Interface (DI) problem (Carico et al., 1985).

The ship airwake may also be affected by other factors, including but not limited, to the characteristics of the upstream atmospheric boundary layer as the wind blows over the ocean, the wind direction relative to the bow of the ship, as well as the dynamic pitch, roll and heave motion of the ship. Other factors that contribute to the DI problem and limit the
safe operation of aircraft can be specified in terms of piloting workload, allowable limits of the ship motion, landing spot obstructions, and visibility conditions (Carico et al., 1985), although these latter issues are outside scope of the present work. The piloting challenges of landing an aircraft on a ship can, however, be directly correlated to the turbulence levels of the airwake (Healey, 1987), the better understanding of which is a primary focus in the present research. To a pilot encountering the airwake, the associated turbulence can result in sudden roll or pitch motions for which quick and decisive corrective control inputs must be applied to avoid flight excursions to a level that may cause a mishap. The issues of the the DI are particularly acute during the landing phase in the presence of high winds and/or rough seas.

Prior research studies yet have not accurately measured ship airwake phenomena with sufficiently high spatial and temporal fidelity. This issue is, at least partially, because of previous limitations in suitable measurements techniques, i.e., those that can measure in a temporal manner the unsteady flows over relatively large spatial fields. For the present research, a campaign of wind tunnel flow measurements of high spatial and temporal fidelity using new state of the art instrumentation were performed on a scaled but a representative Navy ship model in a simulated atmospheric boundary layer (ABL) flow. Flow measurements on a generic Navy frigate SFS2 model were made in two wind tunnels at Embry-Riddle Aeronautical University (ERAU), including the simulation in the wind tunnels of the characteristics of the upstream ABL. The measurements were made, primarily, by using two-dimensional time-resolved particle image velocimetry (TR-PIV) and three-dimensional stereo TR-PIV techniques. The PIV measurements were
complemented by more limited measurements that were made using hot-wire anemometry.

The measurements presented in this dissertation were made over several separate wind tunnel entries over period three years and, as will be described, the results are considered to give much new insight into the characteristics of ship airwakes. Specifically, the research helps in understanding as to why the airwake comprises of dominant and energetic turbulent eddies of certain scales, and it also reveals why the airwake often has an intermittent nature, i.e., a flow that rarely reaches a true steady-state and often comes in bursts. Furthermore, the work suggests that an airwake might also have an inherent asymmetry and bistable nature, even when the bow of the ship is pointed directly into the wind. The study also suggests that the unsteady and turbulent nature of the ship airwake contains primary energy bearing flow scales that are inhomogeneous in nature.

The outcomes from the work, in part, set down benchmarks for future verification and validation of computational models. The results could be further used as a basis for the development of flight dynamics models for handling qualities assessments in flight simulators, although this is a longer term goal and is not part of the present effort. Nevertheless, the techniques used in the present research to analyze the measurements expose a new understanding of the airwake and give good directions toward that end.

1.1 Motivation for this Research

As previously mentioned, the flow over the unstreamlined and rather bluff shape of the deck of a Navy ship can create a complex and turbulent airwake environment that extends well downstream of the ship (Zan, 2005; Polsky, 2010). This airwake and
subsequent unsteady aerodynamic environment can adversely affect the launch and recovery of all types of aircraft, including rotorcraft and unmanned air vehicles. The superstructure of a Navy ship such as a frigate consists of many individual unstreamlined parts on the superstructure, which in aggregate create a massively separated, three-dimensional, unsteady, turbulent downstream flow, as shown schematically in Fig. 1.1. This wake is the essence then of what is generally referred to as the ship’s airwake.

![Figure 1.1](image)

**Figure 1.1.** The airwake produced by a Navy frigate can produce a highly three-dimensional, unsteady flow that may limit the ability for helicopters and other rotorcraft to operate safely from the deck.

Notice that the airwake affects mostly the rear deck of the ship, which is from where flight operations are conducted. Landing a helicopter here is known to be a challenging piloting task that carries considerable risk and poses a serious safety of flight issue (Hofman and Fang, 1984). In particular, airwake issues have led to serious handling qualities (HQs) and safety-of-flight concerns during helicopter and other rotorcraft operations from ships, even under good weather conditions. The airwake and its effects
are difficult to predict a priori, so to mitigate the possibility of mishaps then the DI must be explored for each and every ship and helicopter/rotorcraft type combination to develop specific launch and recovery limit envelopes (Brownell et al., 2012). An example of a launch and recovery envelop of an aircraft is shown in Fig. 1.2. This latter type of work is necessary but extremely time consuming and in itself carries considerable risk for the aircrew.

Figure 1.2. An example of a launch and recovery envelope of a helicopter operating from a ship.

Because of the adverse operational and safety of fight implications of the DI, considerable previous research on the airwake and its associated problems has been conducted, and over several decades. This research has comprised both computational and experimental approaches, which have been used concurrently an attempt to unravel the intricacies of the ship airwake and better expose the true nature of the DI problem, mainly from an aircraft response and piloting perspective. Nevertheless, because of the complexity of the aerodynamic problem and the challenges in making the needed
experimental measurements, there is still a limited understanding of the details of the airwake and more research is needed. It is to this end that the present work is focused.

Specifically, the issues involving the aerodynamic characteristics of the airwake that still need to be addressed and understood include the degree of unsteadiness and turbulence scales, as well as the overall three-dimensionality of the flow in the airwake over the stern of the ship and its downstream wake. An assessment of prior work suggests that the level of fidelity needed to measure the most important airwake physics is more than what has been achieved so far, its understanding requiring much more comprehensive sets of unsteady flow measurements that have better spatial and temporal resolution. Another consideration toward this goal, is that the airwake is affected by the upstream atmospheric boundary layer (ABL), which contains gradients in wind speed as well nonuniform turbulence. The winds at sea are never calm, so the simulation of the ABL in the wind tunnel environment was also an important prerequisite to reach the goals of the present research.

1.2 Objectives of the Present Research

As previously alluded to, the first main objective of the present study was to perform wind tunnel measurements to better understand the details of the complex, unsteady and turbulent aerodynamic flows produced by superstructure of a generic Navy ship in the form of a simplified frigate shape. The research was performed using a combination of hot-wire anemometry (HWA) and particle image velocimetry (PIV) measurements, and specifically time-resolved PIV or TR-PIV. The work was also supported by flow visualization, which was used to help interpret the quantitative measurements.
HW A is a point measurement technique but has the capability of providing instantaneous velocity measurements in time with a relatively high frequency response thereby, allowing measurement of all the turbulence scales in the flow. In the present research, HW A was used mainly to help characterize the upstream flow characteristics as it approached the ship model, including the cases of the simulated ABL. However, HW A was also to measure the flows over selected points on the deck of the ship model. PIV measurements are planar measurements and are non-intrusive in nature (other than for seeding). PIV has the capability to measure over an area in the flow field with high spatial and good temporal resolution, and over a relatively large field of view (FOV). Both two-dimensional planar PIV as well as three-dimensional stereo PIV were performed in the present work, and the PIV measurements constitute the bulk of the results presented in this dissertation.

A second main objective of the present research was to better simulate the characteristics of an atmospheric boundary layer (ABL) in the wind tunnel environment, including the scaling, velocities, gradients and turbulence. The ABL was expected to have an important effect on the airwake developments, in that an ABL presents a velocity gradient in the oncoming flow to the ship as well as turbulence. The ABL was simulated in two different wind tunnels, namely a boundary layer wind tunnel (BLWT) and ERAU’s new low-speed wind tunnel (LSWT), and considerable effort was made in both cases to better represent actual ABL in the wind tunnel environment so as to conduct representative airwake measurements. To this end, measurements made of actual “real-world” ABLs were used to guide the research.
The value of these new measurements of the ship airwake to the community at large is both novel and profound. First, they help to provide much new insight into the complex, unsteady, turbulent flow physics that characterize a ship airwake. Second, the high spatial and temporal fidelity PIV measurements can provide a new benchmark for the verification and validation of advanced computational fluid dynamic (CFD) models that are being used to predict the flows about ships and the airwake developments. Third, the data can provide inputs needed to develop higher fidelity numerical models of the airwake for flight simulation and HQ assessments, and so can potentially contribute to improving the fidelity of flight simulators used by pilots for training purposes.

1.3 Technical Background and Literature Review

1.3.1 Ship Airwake

A detailed review of previous research on ship airwakes and the DI problem suggest that the field is extensive, and covers many different but closely related avenues of approach. Overall, the work can be categorized into four general approaches, namely 1. Sea trials with actual ships, 2. Numerical simulations using computational fluid dynamics, 3. Flight dynamic simulations and handling-qualities assessments using helicopters and other aircraft models programmed into simulators, 4. Wind tunnel measurements on scaled ship models, which is by far where the bulk of exiting knowledge of ship airwakes lies.

1. Sea trials have been used to measure the real airflows produced on the ship deck, examples including Refs. (Snyder et al., 2011; Luznik et al., 2013; Friedman et al., 2016). However, making at-sea measurements of the airwake has many challenges,
and the results obtained so far have been somewhat limited in both scope and in fidelity. One issue is the variability of winds and weather conditions at sea, which makes it difficult to acquire consistent and repeatable flow measurements. Another issue is that the sensors must be positioned in such a way that they do not pose a safety concern for operating aircraft, and so such measurements are inevitably somewhat sparse. Furthermore, it has not been possible to characterize the upstream flow (i.e., the ABL) in sea-trials, and this issue introduces significant uncertainties into the measurements.

Snyder et al. investigated the ship airwake with an operating helicopter aboard a patrol ship using various arrangements of three-axis acoustic anemometers as well as fog generators for flow visualization (Snyder et al., 2011). The at-sea measurements were made for three wind over deck (WOD) conditions, namely a headwind and beam winds of 15° and 30°. The study showed reasonable agreement with other measurements from wind tunnel testing and also CFD simulations for a headwind condition and for a beam winds 15° off the starboard bow. However, there were large differences in the results when compared to the at-sea measurements, most likely because the wind tunnel measurements and CFD simulations did not model the true nature of the winds and turbulence over the sea that were actually encountered by the ship.

Luznik et al. performed at-sea turbulence measurements behind the superstructure and flight deck region of a training vessel. This work was done using sonic anemometers placed at a few locations on the flight deck (Luznik et al., 2013). While useful, the measurements from such approaches do not provide anywhere
near the spatial detail to understand the flow physics of the airwake, nor do they provide sufficient quantitative data for validating computational models. However, at-sea measurements can be complementary to other types of measurements, if they are used carefully within the limitations of how they were actually made. Nevertheless, future at-sea measurements will be essential for the ultimate verification and validation of predictive methodologies of the airwake.

2. Numerical simulations of flows over ships using variations of CFD methods, e.g., (Polsky and Bruner, 2000; Polsky, 2002, 2003; Sezer-Uzol et al., 2005; Forrest and Owen, 2010; Polsky, 2010; Snyder et al., 2011; Brownell et al., 2012; Thedin et al., 2019). CFD simulations of the airwake are very useful and insightful, However, they require fine computational grids about the ship as well as time-accurate numerical techniques to resolve all the relevant spatial and temporal flow field scales of the airwake. The typically high dissipation of turbulence scales within most CFD simulations also pose many challenges in capturing the all-important unsteady effects that characterize an airwake (Syms, 2004). In general, the predictive capabilities with CFD still remains uncertain, partly because of the insufficient validation with detailed unsteady flow measurements of the detailed flow physics of the ship airwake. However, there are other issues too with CFD that bring into question the predictive confidence that is actually achievable with such computational methods.

Polsky performed time-accurate CFD computations to predict the coupled ship and aircraft aerodynamics (Polsky and Bruner, 2000; Polsky, 2002, 2003, 2010). This extensive study explored the importance of grid quality, geometric fidelity and
environmental modeling. In addition to the requirement of good grid quality to resolve areas of flow separation, the author also suggested that the proper representation of an atmospheric boundary layer was essential for predicting the ship airwake, especially in the case of beam winds. The author also mentioned the challenges in capturing the all-important unsteady effects that characterize the airwake because of the high dissipation of turbulence scales within the CFD codes. Synder et al. showed fair agreement when wind tunnel and at-sea results were compared to the CFD simulations. It was suggested that further improvements could be made by including ABL modeling both in the wind tunnel and CFD simulations (Snyder et al., 2011). A similar study performed by Brownell et al. compared CFD outcomes with measured airwake data for a Navy training vessel, and emphasized the importance of the knowing the characteristics of the upstream flow and ABL on the development of the airwake, as well as the ambient wind directions and an accurate ship headings (Brownell et al., 2012).

Kelly et al. validated CFD simulations against Acoustic Doppler Velocimetry (ADV) measurements, and suggested that CFD results with higher overall fidelity were needed such that they could be used confidently for flight simulation work (Kelly et al., 2016). However, to a large extent the predictive capabilities of ship airwakes using CFD still remains uncertain, in part because of insufficient validation with detailed unsteady flow measurements of the actual detailed flow physics of the ship airwake. The clear need for such experimental measurements, and under very controlled conditions, with a known upstream flow was a strong motivation for the present research.
More recently, Thedin et al. investigated one-way coupling of resolved atmospheric turbulence with the flight dynamics of a helicopter using CFD in the form of Large Eddy Simulations (LES) (Thedin et al., 2019). This type of CFD model is capable of identifying the energy scales between the ABL and the ship airwake. This study showed that the velocities in a ship airwake are considerably different when formed from the effects of an upstream atmospheric boundary layer versus that of an uniform flow, i.e., a ship sailing in a calm wind, which is an exceptional case. However, it was also suggested that one-way coupling was insufficient for predicting all the potential hazards associated with the airwake and the DI problem.

3. Flight dynamics and handling qualities assessments in flight simulators (Wilkinson et al., 2001; Bunnell, 2001; Bogstad et al., 2002; Zan, 2003; Lee, 2003; Lee et al., 2005; Wang et al., 2011; Hodge et al., 2012; Kääriä et al., 2012, 2013; Crozon et al., 2014; Kelly et al., 2016; Forrest et al., 2016; Oruc et al., 2017; Bae and He, 2017) used mathematical models of the spatial variation of the upwash/downwash flow field to represent the effects of the airwake. An example of a DI virtual environment is shown in Fig. 1.3, which is performed in a flight simulator. Thus far, such airwake models used in flight simulators appear to have been developed entirely from CFD simulations and not experimental measurements, in part because measurements have not yet been made so far with the necessary fidelity compared to what CFD has been able produce. Indeed, CFD has been used so far to help develop such DI simulation models, not because it has a verified and validated capability but because existing flow measurements have not yet reached the equivalent fidelity to create and/or validate any suitable airwake models.
For flight dynamic simulations of the DI, Bogstad et al. developed an extensive aerodynamic ship-airwake database for a ship-specific flight simulator (Bogstad et al., 2002). This simulator was used to help train helicopter pilots for landing and takeoff operations from various points on a ship. Lee et al. also developed helicopter/ship DI simulation tool for a helicopter operating near a ship (Lee et al., 2005). As previously mentioned, some of the outcomes from CFD have been used to create simplified numerical simulations of coupling effects on the airwake and rotor inflow (Zan, 2003; Crozon et al., 2014).

Wang et al. and Kääriä et al. suggested a flight simulation technique to quantify the unsteady aerodynamic loading imposed on a helicopter by an airwake (Wang et al., 2011; Kääriä et al., 2013). Kääriä et al. characterized the aerodynamic loading on a sub-scale helicopter immersed in the airwake of a frigate (Kääriä et al., 2012), similar to the experiments performed by Lee (2003) and Zan (2005). The results were obtained by integrating the effect of the unsteady airwake over the rotor disk and fuselage and quantifying the resulting aerodynamic loads. Polsky et al., Forrest et al. and Oruc et al. also developed an airwake analysis tool to model the handling
characteristics of an aircraft for use in future piloted simulation trials (Polsky et al.,
2016; Forrest et al., 2016; Oruc et al., 2017).

4. Model-scale testing of ships in wind tunnels using techniques such as
flow-visualization (Nolan, 1946; Ower and Third, 1959; Third and Ower, 1962;
Woolman and Healey, 1990; Reddy, 1992; Kulkarni et al., 2005; Vijayakumar et al.,
2008), multi-hole probes (White and Chaddock, 1967; Zan and Garry, 1994; Zan,
2001), hot-wire anemometry (HWA) (Garnett, 1979; Healey, 1986, 1991; Rhoades
and Healey, 1992; Healey, 1992; Zan et al., 1998; Lee, 2003; Snyder et al., 2010),
laser Doppler anemometry (LDA) (Bardera-Mora et al., 2015) and more recently
using variations of particle image velocimetry (PIV) techniques (Wadcock et al.,
Bardera and Meseguer, 2015; Rosenfeld et al., 2015; Bardera-Mora et al., 2016;
Sydney et al., 2016; Rahimpour and Oshkai, 2016; Khouli et al., 2016; Gallas et al.,
2017). The wind tunnel environment allows for a systematic study of the airwake
problem in a well-controlled environment, albeit on smaller models of the ship.
This is where (by far) the bulk of the published literature on ship airwakes is
derived from, and also where most of the fluid dynamic understanding of the the
airwake resides. For this reason, the next section of this dissertation is devoted
mostly to a discussion of prior wind tunnel measurements on ship airwakes.

1.3.2 Detailed Literature on Wind Tunnel Studies of Airwakes

Wind tunnel measurements of ship airwakes started in the 1950s, initially by using
various flow visualization techniques. If suitably performed, then flow visualization helps
in the qualitative understanding of airwakes and can determine the locations of dominant vorticity and turbulence being shed from the superstructure of the ship. Various flow visualization techniques have been used for airwake studies on ship models, including helium bubbles, hydrogen sulphide, surface oil flow, tufts and smoke. These flow visualization techniques have been used to garner flow information mostly only at specific points on the ship models (Shukla et al., 2019).

Nolan used mini-tufts and surface oil flow to understand the vortical topology of the airwake produced by a ship’s superstructure (Nolan, 1946). Ower and Third used smoke flow visualization to investigate the turbulent flow over the ship deck, in both the wind tunnel and in sea-trials (Ower and Third, 1959; Third and Ower, 1962). Reddy has compared and contrasted the usefulness of the various flow visualization techniques for understanding the ship airwakes (Reddy, 1992). More recently, Woolman and Healey, Kulkarni et al. and Vijaykumar et al. used smoke to study the flow around and downstream of a funnel and how it contributed to the nature of the airwake (Woolman and Healey, 1990; Kulkarni et al., 2005; Vijayakumar et al., 2008).

With further advancements in experimental techniques during the 1960s, multi-hole pressure probes were used by White and Chaddock to compare the full-scale and model-scale wind-over-deck measurements (White and Chaddock, 1967). In the wind tunnel, the measurements made were found to be inconsistent with the full-scale flow features, most likely because of the inadequate simulation of the ABL in the wind tunnel. Some other experiments were conducted in a water tunnel, but these did not give much further insight into the flow physics of the airwake. Notice that the pressure probes (no matter what type) cannot measure other than time-averaged flow effects, and so the important
turbulent aspects of the airwake cannot be resolved. Furthermore, the pressure probes are
unsuitable for use in unsteady flows, in general, because the unsteady pressure effects
manifest as a velocity error when time-averaging is performed (Shukla et al., 2019).

Despite this limitation, these early studies set the stage for the future model-scale
wind tunnel experiments on the problem of measuring ship airwakes. Later, Fortenbaugh
used the experimental measurements from the work of White and Chaddock to design the
first numerical model for the airwake specific classes of frigates (Fortenbaugh, 1977;
White and Chaddock, 1967). This work was aimed mainly at correlating the full-scale and
model-scale datasets and showing the validity of making ship airwake measurements in
the much more controlled environment of the wind tunnel.

Garnett and Rhoades performed time-dependent airwake measurements on both a
frigate and a destroyer model at a Reynolds number of $1.1 \times 10^4$ based on ship length
(Garnett, 1979; Rhoades and Healey, 1992). However, these authors did not simulate the
characteristics of an upstream ABL. Measurements were made using sulfur and helium
bubble flow visualization, as well as HWA measurements at selected points in the flow.
This latter study provided a database of mean and fluctuating velocities, turbulence
intensities and turbulence spectra at a specific location over the deck where a helicopter
might fly. This study was helpful in visualizing the three-dimensional behavior of the flow
in the vicinity of the superstructure area. However, in general the comparisons between
the full-scale and model-scale results showed significant discrepancies.

Healey examined ship airwakes and ship-helicopter flow interactions, extending
measurements included mean velocity profiles, turbulence intensities and turbulence
spectra at various locations on the flight deck with beam wind angles over the ship ranging between $\pm 30^\circ$. In addition, flow visualization were also performed to understand the flow characteristics over the deck. The results from Healey’s work showed vortices shedding from the sharp edges of the ship’s superstructure, and that the turbulent downstream wake increased in size when moving away from the bow of the ship. Also, the extent of the turbulent wake was shown to increase in size for beam winds. The studies showed the turbulence intensities were higher at the $30^\circ$ beam wind condition than at the $0^\circ$ headwind over the flight deck.

In further work, Healey and his group conducted a spectral analysis of the measurements, which showed that the levels of turbulence intensity were higher in the vertical velocity fluctuations above the flight deck and energy was in the range of 1–10 Hz (Healey, 1992). The general trend of turbulent energy confirmed that the flight deck regions experienced high-frequency energy, whereas in the regions away from the ship the flow contained relatively low-frequency energy. Overall, Healey’s group obtained reasonable correlations between the full-scale results and model-scale wind tunnel testing but only when simulating an ABL.

Zan and Garry performed experiments using HWA on a SFS1 generic ship model (Wilkinson et al., 1998) at Reynolds number of about $10^4$ based on ship length, emphasizing again the importance of the unsteady characteristics of the airwake (Zan and Garry, 1994). The authors recommended fully coupled spatial and temporal time-varying three-dimensional airwake investigations to obtain better data of the ship airwake flow physics that could best help in the modeling efforts.
Zan investigated the airwake with a frigate model in the wind tunnel and performed measurements using hot-film anemometers (Zan et al., 1998). The ABL was simulated using horizontal “Cowdrey” rods placed in the upstream flow before it entered the test section of the wind tunnel. This was the first attempt by researchers to investigate the “fully-coupled” ship airwake phenomena. The results showed encouraging levels of correlation when CFD results were compared to both wind tunnel measurements, as well as at-sea measurements on an actual ship.

Zan conducted experiments on a simplified frigate shape geometry using pressure probes and flow visualization techniques, the purpose being to help validate a companion CFD methodology (Zan, 2001). In follow-on work, Lee performed experiments on a scaled SFS2 ship model, including the effects of beam winds (Lee, 2003). Hot-film anemometers were used to obtain mean velocities and turbulence intensities at various locations on the flight deck. The experiments were conducted at a Reynolds number of $1.8 \times 10^5$ based on ship length for three WOD conditions, including a headwind. A spectral analysis showed that the main turbulence in the airwake was at low frequency in the range of 0.1–2 Hz and with magnitudes of same order (Healey, 1992) as previously reported by Healey. However, the magnitude of the frequency range was lower, which might be because of the smaller ship model and also the lower turbulence generated in the wind tunnel experiments.

In general, most of the experimental studies previously discussed have used pressure probes or hot-wire anemometry (HWA) to study the ship airwake phenomena. These devices are single point measurement methods, and their practical use means that the spatial fidelity of the measurements is usually rather limited (Shukla et al., 2019). HWA
gives good frequency response to flow field fluctuations, but it is somewhat intrusive in that the probe itself and its support can affect the flow. A more important issue is that hot wires have a directional ambiguity which, for example, means they cannot resolve the difference between the upstream and downstream flow directions.

Therefore, most researchers have come to the final realization that accurate ship airwake measurements can only be achieved by using advanced optical anemometry methods. To this end, the introduction of laser technology in the 1960s for laser Doppler velocimetry (LDV) and the more recent development in particle image velocimetry (PIV) techniques in 1980s, have paved the way for the development of advanced optical anemometry methods for use in ship airwake studies. Techniques such as LDV and PIV have since then become very useful in making non-intrusive three-dimensional flow measurements for many types of flows with the needed spatial and temporal resolutions.

Wadcock et al. performed “snap-shot” (i.e., not time-resolved) stereoscopic PIV measurements in the wind tunnel over the deck of a 1:48 scaled amphibious assault ship, although the PIV instrumentation had limited spatial resolution (Wadcock et al., 2004). Several small powered models of helicopters were positioned near the deck of the ship model, including a single rotor, a tandem rotor, and a tiltrotor, but aerodynamic scaling was not considered. Furthermore, an upstream ABL was not simulated. Nevertheless, the results showed the potential for aerodynamic interactions between a rotor wake and the development of the airwake. The data obtained were also compared to CFD but lacked the detail to quantify the unsteady, turbulent flow characteristics so to be used for proper verification and validation of CFD outcomes.
Shafer and Ghee investigated different active and passive flow control techniques on a ship model in the wind tunnel that might be used to mitigate adverse effects or improve the flow field characteristics at the flight deck (Shafer and Ghee, 2005). Experiments were conducted using HWA in a wind tunnel on a 1:144 scaled U.S. Navy Destroyer ship model. The passive control techniques that were studied included the replacement of the solid flight deck and hangar face with a porous material without changing the ship geometry, although this approach was shown to provide with a very small reduction in the flow unsteadiness. An active flow technique included mass injection through the porous hangar face, thereby slightly further decreasing the flow unsteadiness over the deck. The authors reported that both active and passive flow approaches significantly improved the flow characteristics over the flight deck.

Findlay and Ghee conducted wind tunnel experiments to investigate the effect of angle-serrated flaps when added to the hangar of the same 1:144 scale ship model (Findlay and Ghee, 2006). The objective of the study was to reduce the turbulence level on the flight deck. HWA was used to measure the flow variations to understand the effectiveness of fences to alter the mean and fluctuating velocities over the flight deck. The authors concluded that the addition of fences improved the flow over the flight deck by reducing the mean momentum and turbulence intensity in the local flow. However, it remains unclear how effective these flow control devices will be if tested on a full-scale ship.

Greenwell and Barrett investigated flow control modification devices on 1:90 scale SFS1 ship model using LDV in a wind tunnel (Greenwell and Barrett, 2006). The objective was to reduce the turbulence levels as well as the vertical velocity gradient of
the airwake over the flight deck area. The authors used a range of inclined porous screens that were mounted around the hangar door area, with the intention of reducing both turbulence levels and downwash velocities in the ship airwake. The measurements were conducted at two Reynolds numbers $3.3 \times 10^5$ and $5.65 \times 10^5$ based on ship length. This study concluded that the device effectiveness was strongly dependent on the flight deck regions, with the greatest improvement being obtained lower down in the lee of the hangar door. Progress was made towards understanding the relationship between flow structures and turbulence, but the important unsteady aspects of the flow field remained unresolved. The authors suggested PIV as a better technique to track the time-dependent behavior of the unsteady flow structures.

Nacakli and Landman were amongst the first to use PIV techniques to quantify ship airwake with rotor downwash interactions, but without simulating the characteristics of an ABL (Nacakli and Landman, 2011). Limited PIV measurements with low temporal resolution were conducted on a 1:50 scale SFS1 model in a low-speed wind tunnel by employing a ship and a small rotor in isolation, and then when coupled together. PIV measurement were made at two different rotor advance ratios, i.e., free-stream velocity to rotor tip speed ratios. Two-component PIV flow field analysis was analyzed over a set of longitudinal and lateral planes for headwind (WOD = 0°) condition. The study identified the ship airwake/rotor downwash coupling and how it might affect the CFD modeling. In addition, PIV surveys also helped to enhance the understanding of the changes in the thrust response as a function of rotor to ship proximity.

Herry et al. experimentally investigated the flow downstream of a backward facing double step on $Re$ (based on first step height) ranging from $5 \times 10^3$ to $8 \times 10^4$ and two
bow shapes before the step were tested (i.e., pyramidal and semicircular) (Herry et al., 2011). The flow was studied using laser tomography, oil-flow visualization, and PIV although the PIV measurements were made at relatively low temporal resolution. The study observed a form of bistable flow asymmetry over the flight deck flow and the zero sideslip angle seems to be a critical case where the flow switches randomly from positive drift angles to negative drift angles; this phenomenon was reproduced for the different bow shapes, wind tunnels, and Reynolds numbers.

Mora performed two-component LDV measurements on ship model and compared the results to full-scale wind over deck measurements (Mora, 2012). The full-scale measurements were made using three-component sonic anemometers located on the top of the hangar, which were placed 5 m above the deck level. The results showed good agreement between the smaller-scale and full-scale measurements, and also led to the development of safe Ship Helicopter Operational Limits (SHOLs) envelops for specific ships. The SHOL envelope is a polar plot that highlights the acceptable conditions of relative wind speed and wind direction for safe helicopter flight operation, as shown in Fig.1.4, and is unique for the operation of every ship and helicopter/rotorcraft combination.

Mora further discussed the investigation of ship airwakes on a SFS1 ship model using various experimental techniques, such as oil flow visualization, LDV and two-dimensional PIV (Mora, 2014). Overall, the comparisons showed that the simplified frigate geometry results predicted the full-scale frigate ship flow reasonably well over a wide range of WOD conditions, located approximately around zero wind incidence and at ±30–60°. The focus of the work was limited on the flight deck and, therefore, effects on
ship airwake from the superstructure and funnel were not discussed in detail.

Furthermore, the study strongly emphasized on the advantages of optical measurements such as PIV for future work.

Mora and Meseguer continued to investigate the possibility of modifying ship airwakes by means of geometric modifications to the hangar roof in front of the flight deck (Bardera and Meseguer, 2015). The flow measurements in the wind tunnel were made using PIV and surface pressure measurements on a scaled SFS2 ship model (Wilkinson et al., 2001). The purpose of using PIV was to provide more detailed insight into the flow conditions at the deck. The results showed reduction in the size of the shear layer and a significant movement relative to the hangar wall, thereby altering the airwake over the deck and potentially reducing the risks to on-board flight operations.
Furthermore, the authors proposed to optimize the hangar roof curvature to keep the flow more attached to the ship superstructure and so also potentially increasing safety during flight operations.

Rosenfeld et al. performed wind tunnel experiments on three different scaled SFS2 ship models at several Reynolds numbers (again, based on ship length) between 2.9–5.9 million (Rosenfeld et al., 2015). The scope of this study included Reynolds number effects and modeling of the ABL to better understand their effects on the development of the airwake. A representative ABL was generated using a Cowdrey grid, which is a relatively simple and effective way of producing a representative ABL in the wind tunnel. The flow measurements were performed using five-hole probes as well as with time-resolved PIV, albeit with limited resolution and fields of view. Nevertheless, the results from both methods showed good correlation in the streamwise direction, but with some lateral asymmetry in the flow over the deck. The similarities in the measurements suggested that the flow was insensitive to Reynolds number variations, as might be expected for a bluff body shape with angular surfaces that readily promote flow separation.

Mora et al. continued the investigation in an attempt to modify the unsteady separated flow over the downstream part of the deck by using plasma actuators as an active flow control device (Bardera-Mora et al., 2016). The dielectric plasma actuators were mounted on the hangar wall that generated a wall-bounded jet. Experiments were conducted on a SFS model settled at 0° WOD (wind directly down the deck) in a low-speed wind tunnel using PIV (albeit with low temporal fidelity) in the streamwise direction based on the guidelines established from the previous studies (Shafer and Ghee, 2005; Findlay and
Ghee, 2006). The PIV results showed significant reduction in flow unsteadiness and turbulence intensity over the flight deck region, which was consistent with the earlier studies. The authors suggested additional investigation were needed to optimize the plasma actuators so that they can be used as an effective device for flow control and also to determine their feasibility at full-scale.

Sydney et al. conducted two-dimensional and three-dimensional PIV experiments in the wind tunnel to investigate the turbulent flow features within the ship airwake. It was shown that the upstream structure of the ship produced strong levels of turbulence that effected the overall flow downstream (Sydney et al., 2016). However, these results still did not have sufficient spatial and temporal fidelity for CFD verification and validation. The authors have also recommended a Reynolds number of $5 \times 10^6$ or higher based on ship length to avoid scaling effects on the development of the airwake, although this recommendation is not entirely consistent with the work presented previously by Rosenfeld et al. (2015). The results also lacked temporal fidelity, and the number of PIV image pairs obtained were too low and insufficient to satisfy the statistical requirements for turbulent flow characterization.

Vidales experimentally investigated the airwake using time-averaged large scale Tomographic Particle Tracking Velocimetry (Tomo-PIV) on a ship model using helium filled soap bubbles as seed particles (Vidales, 2016), albeit at very low Reynolds numbers; the ABL was simulated using Cowdrey (1967) rods similar to that done by Rosenfeld et al. (2015). This study showed significant asymmetries in the flow at the flight deck for head-wind condition, with evidence also of bistable flow states. A low-order
reconstruction of the flow field was also performed using Proper Orthogonal Decomposition (POD).

Recently, Rahimpour and Oshkai investigated the airwake over a polar ice-breaker type of ship in the wind tunnel (Rahimpour and Oshkai, 2016). The experiments were performed using high-speed two-dimensional PIV on a small model at very low ship length Reynolds numbers of 47,900, 50,500 and 61,000, for a uniform upstream flow and also with a simulated ABL, and over a range of WOD conditions. However, their results mostly confirmed what is already known about the unsteady, three-dimensional vortical features of an airwake. The flow over the deck was suggested to be independent of the Reynolds number, which was consistent with the findings of Healey (1992) and Greenwell and Barrett (2006) and Rosenfeld et al. (2015). Higher turbulence intensities were observed in the case of the simulated ABL, which might be expected. Furthermore, the results showed that the spatial structures of the airwake were strongly dependent on the WOD angle and the highest turbulence levels were observed over the deck region for 60° WOD from starboard.

Khouli et al. experimentally investigated the large rotor blade movements found during rotor engagement/disengagement phase when a rotor is immersed in a ship airwake (Khouli et al., 2016), i.e., the phenomenon called blade sailing (Newman, 1999). The 1:12 scaled Froude-scaled rotor system was tested in the wind tunnel facility at simulated ship roll angles of 0° and −20° and also with a beam wind direction. The results from the experiments and simulations showed that the parameters of the rotor had minimal effect in the occurrence of large rotor blade motion that are sometimes observed in the full-scale
maritime helicopter rotor system when engaging and disengaging the rotor on the deck of a ship (Khouli et al., 2016).

Gallas et al. investigated the effect of active flow control system embedded in the hangar, which was aimed at improving the complex nature of the flow encountered during helicopter operations on the flight deck (Gallas et al., 2017). Active flow controls were provided by continuous steady flow through the slots made in the hangar periphery. The flow field above the flight deck was analyzed using stereo PIV (albeit at limited resolution), pressure sensors, and HWA. The results suggested that the recirculation region decreased in size such that covering only 25% of the flight deck, but making the turbulent fluctuations more intense.

1.4 Conclusions on Prior Experimental Research

Even with so much prior work on the ship airwake problem, there still remain many unanswered questions in understanding its characteristics, especially about the unsteady aspects and the various scales and energy of the numerous vortical structures. One of the biggest challenges is to perform higher spatial density and temporally correlated flow measurements on a representative ship shape at reasonably high ship length Reynolds numbers of near $10^7$. A complicating challenge in the wind tunnel is also the faithful simulation of the upstream ABL, which other authors have deemed as being a prerequisite to perform airwake measurements, both in terms of velocity profile and gradient but also in terms of turbulence.

To this end, the presently reported research work sets down new directions toward that end. Specifically, the present work involves the application of multi-camera,
time-resolved PIV to measure the unsteady nature of the airwake from a SFS2 frigate ship model encountering a simulated upstream ABL. Because an ABL is an important part of this problem, the following section discusses some of the characteristics of an ABL and the challenges in representing an ABL within the wind tunnel environment.

1.5 Atmospheric Boundary Layer (ABL)

The atmospheric boundary layer (ABL) is an essential part of understanding the flow over the deck and resulting airwake of the ship (Polsky, 2003). Therefore, one of the objective for the current research was to better simulate the characteristics of an atmospheric boundary layer (ABL) in the wind tunnel environment, including the scaling, velocities, gradients and turbulence. In the past, various methods have been studied to generate flows in wind tunnels that have similar properties to that of a turbulent atmospheric boundary layer (ABL), such as elliptical wedge generators, triangular spires, grids, and rods, as shown in Fig. 1.5. Counihan successfully simulated ABL using spires in the shape of quarter ellipsoid, combined with roughness elements to increase the thickness of turbulent boundary layer in the test section downstream of the obstacles (Counihan, 1969, 1970). This method was used by Cook (1978), Iyengar & Farell (2001), Wittwer & Möller (2000), Balendra et al. (2002), Kozmar (2011) and Varshney & Poddar (2011).

Cook simulated an ABL to understand the scaling factors using different design parameters, such as mean velocity profile, turbulence intensities, spectra and longitudinal integral lengths for Reynolds stresses (Cook, 1978). Cowdrey used horizontal circular rods that were placed parallel to the wind tunnel floor to produce a velocity and
momentum deficit in the flow to simulate a desired turbulent boundary layer that was representative of fully-developed turbulent boundary layer, i.e., one that conformed closely to a 1/7-th power law (Cowdrey, 1967). This latter method for creating an ABL in the wind tunnel has not been widely used, but it has been adapted by Barbosa et al. (2000) and others (Rosenfeld et al., 2015; Vidales, 2016).

Triangular spires were used by Campbell and Standen and also by Lopes to create an ABL (Campbell and Standen, 1969; Lopes et al., 2008). Cermak and Cochran used triangular spires with an addition of horizontal vanes (Cermak and Cochran, 1992), and Pires et al. used triangular spires with mesh screens (Pires et al., 2013). Triangular spires produced similar results to that of Counihan (1969), with an exception that the depth of the boundary layer was smaller than that produced by an equivalent height of elliptical vortex generator. Alternatives methods such as combinations of grids (Cook, 1975) and
screens (Elder, 1959) can be used to simulate an ABL, but such methods are not consistently used. However, an ABL generated using triangular spires showed significant lateral variations in the flow (Zan and Garry, 1994; Peterka and Cermak, 1974).

The Cowdrey grid method was used in the present research because it is based on a theoretical approach where the initial positions of the rods can be calculated a priori based on the diameter of the rod and spacing between the centerline of the rods. The Cowdrey method was used to address some of the shortcomings associated with previous methods. Firstly, how spanwise non-uniformities can effect the turbulence intensity. Secondly, in understanding the variations in the flow properties as the flow evolved downstream; it is important to quantify the development length and how rapidly the flow properties changed further downstream. Thirdly, how well an artificially-thickened ABL can resemble a turbulent ABL. And fourthly, how ABL can be simulated in a wind tunnel with an upstream contraction section.

### 1.6 Unanswered Questions About the Ship Airwake

Based on a thorough literature review of prior research work that has been conducted on the ship airwake problem, it became clear that there are many questions remaining about the physical nature of the airwake and its potential effects on a helicopter or other aircraft that encounters the airwake. Some of the questions that were posed and attempted to answer in the current research include:

1. *Spatial and Temporal Measurement Fidelity.* Prior wind tunnel experiments have not thoroughly described the airwake because the instrumentation limitations have not yet permitted measurements with the needed spatial detail and temporal fidelity.
Also, very few experiments have used PIV techniques (Wadcock et al., 2004; Bardera-Mora et al., 2015), and only two previous studies on the ship airwake problem (Rosenfeld et al., 2015; Rahimpour and Oshkai, 2016) have attempted to perform time-resolved PIV (TR-PIV), which is more difficult.

2. Effects of the ABL. Previous approaches that have been used to study the ship airwake have not simulated the proper characteristics of the upstream atmospheric boundary layer (Garnett, 1979; Wadcock et al., 2004; Snyder et al., 2011), or have not documented its characteristics in sufficient detail. This latter issue raises the question of the usefulness of prior wind tunnel results in understanding the physics of the ship airwake because a ship at sea only exceptionally encounters calm winds.

3. Effect of Scaling. Prior work does not have appeared to establish a clear relationship between the geometric and aerodynamic scaling of the ship model to the simulated ABL that was created in the wind tunnel environment. Obviously, at very least, the scaling of an actual ABL in the wind tunnel in terms of velocity profile and boundary layer thickness relative to the size of the ship is a prerequisite to obtaining the actual velocity gradients in the oncoming flow that are encountered by the ship.

4. Field of View. As the size of the ship model increases, in an attempt to achieve higher Reynolds numbers based on the ship length the regions (areas) of the flow that need to be examined also increases. This issue causes obvious challenges in making any type of flow measurements. For PIV, in particular, the needed fields of view become relatively large, with commensurate increases in the captured image.
sizes, data storage requirements, data throughput times, and in PIV image processing times.

5. **Spatial and Temporal Correlation.** The airwake is a three-dimensional flow problem, whereas PIV provides results in slices or two-dimensional planes. Volumetric PIV is not possible at this stage in its development (being restricted to very small volumes compared to what is needed here), so a challenge is to effectively synthesize three-dimensional flow measurements from measurements in two-dimensional planes that can, perhaps, be temporally correlated.

6. **Other Factors.** The structure of the airwake may also be affected by other factors that are not easy to account for such as the dynamic motion of the ship (e.g., heaving and rolling) and how an aircraft itself may modify the development of the airwake (e.g., the aerodynamic modifications to the airwake cause by a landing helicopter). However, these issues were not part of the present research work, but are likely to need some investigation in the future.

1.7 **Outline of this Dissertation**

Chapter 1 presents a detailed summary of the background to the present research and literature review pertinent to the current research work on the ship airwakes. The literature included the simulation of a turbulent atmospheric boundary layer in wind tunnels, numerical simulations of airwake flows over ships, flight dynamic simulations of landing aircraft operating in airwakes, and model-scale wind tunnel testing of ships and airwake measurements that have been made using a variety of methods.
Chapter 2 documents the details of the experimental facilities that were used for the present research, including details of the two wind tunnels and a description of the ship models. The Cowdrey grid method that was used to simulate an ABL in the wind tunnel is also discussed. In addition, this chapter also discusses the requirements of properly scaling the ABL parameters, which as had been described is a prerequisite to be able to study the effects of the ship airwake. The setup used for different measurement methods is discussed, including the hot-wire anemometry, the 7-hole pressure probe setup, and the PIV methods. Time-resolved PIV (TR-PIV) and stereo TR-PIV techniques were both used.

Chapter 3 documents the importance of a longer downstream development length for the simulation of an ABL and discusses in detail the results obtained from the PIV measurements, which were performed in both longitudinal planes and crossplanes. The second section compares the simulated ABL for both the BLWT and LSWT with other wind tunnel measurements in terms of mean velocity profiles and turbulence intensity profiles. The third section discusses the on-surface flow measurements that were supported by surface oil flow visualization, which was used to help interpret the flow features over the stern of the ship. The fourth section discusses the results obtained from “Snap-shot” (i.e., not time-resolved) PIV measurements in the BLWT. The fifth section discusses the effects of ABL by comparing the results obtained with uniform flow and with ABL. The sixth section discusses the results obtained from TR-PIV and stereo-PIV measurements, which are presented in terms of time-averaged mean velocities, turbulence intensities, Reynolds shear stresses, and turbulent kinetic energy. The seventh section quantify the effects of Reynolds number (based on ship length) on the airwake in the
range of 0.6–6.2 million. The eight section discusses the flow frequencies associated with
the ship airwake, which are relevant to the handling qualities assessments of landing
aircraft passing into the airwake. Finally, reduced-order modal analysis techniques
including Proper-Orthogonal Decomposition (POD) and Spectral POD (SPOD) were
discusses that were used to examine the underlying structure and dynamics of the
turbulent flow, and are also discussed in this chapter.

Chapter 4 concludes the present research study by summarizing the key conclusions
and contributions. This final chapter also includes several suggestions for follow-on
future work. The measurements that were made showed large regions of unsteady flow
separation, dominant vortical flows, and significant wall-normal flows over the flight deck
regions caused, in part, by the irregular shedding of vorticity and turbulence from the
upstream funnel and superstructure of the ship. The measured flows also suggested the
existence of asymmetric, intermittent flow in the near-wall regions of the deck, and some
evidence of bistable fluctuations in the recirculation region behind the hangar and the
stern of the ship. In addition, the results showed the development of a shear layer
originating at the corners of the flight deck on both port and starboard sides, and a set of
counterrotating vortices at the edge of the flight deck, which resulted in higher turbulence
over the flight deck. An energy spectrum analysis showed the flow frequencies in the
regions where the shear layer was developed behind the funnel and above the flight deck.
The SPOD analysis revealed that most of the larger energetic coherent flow structures
were at low frequency in both the streamwise and wall-normal directions, and primarily in
the near-wall regions of the flight-deck.
Appendix A discusses the theoretical method used to calculate the position of the Cowdrey rods used to simulate the ABL in both the BLWT and the LSWT. Appendix B discusses specifics of the method used for the calibration of the hot-wire sensors. Appendix C discusses the measured ABL profiles relative to the other wind tunnel measurements in the form of log scales. Finally, Appendix D discusses the two-dimensional mean velocity magnitude and turbulence intensity profiles that were extracted from the TR-PIV measurements at various flight deck locations for an $Re$ of 6.2 million.
2. Experimental Setup

For the present research, a campaign of wind tunnel experiments were conducted to study the ship airwake problem. The first set of preliminary experiments were conducted in ERAU’s Boundary Layer Wind Tunnel (BLWT), and then the second set of measurements were conducted in ERAU’s new Low-Speed Wind Tunnel (LSWT). The BLWT is an open return wind tunnel and the LSWT is a closed-return tunnel. The ship model used was a geometrically simplified but representative Navy frigate, the details of which are described in this chapter.

Particle Image Velocimetry (PIV), as well as time-resolved PIV (TR-PIV) and stereo TR-PIV, were used to study the flow in the ship airwake. An overview of the methods of PIV along with the details of the different experimental setups will be discussed in this chapter. The setup used for the hot-wire anemometry (HWA) and the surveys using the 7-hole pressure probes are also described. Finally, this chapter discusses the requirements for scaling of the parameters of the simulated atmospheric boundary layer (ABL), which as described in Chapter 1, is a prerequisite to be able to study the effects of the ship airwake, as well as how the ABL was practically simulated in the two wind tunnels.

2.1 Simple Frigate Shape (SFS2)

The ship model used for measurements of the airwake was the Simplified Frigate Shape No. 2 or SFS2, which is a geometrically simplified but a representative Navy frigate. The SFS1 and SFS2 geometries were originally developed under the auspices of an international collaborative research program with the U.S. Navy (Wilkinson et al.,
The sharp angular lines of these simplified ship shapes were designed mainly to minimize the effort required to generate the computational grid for CFD studies (Zan, 2001; Tai, 2003), but the SFS2 shape is also well-suited for the construction of wind tunnel models.

Figure 2.1 shows the geometric shapes of the SFS1 and SFS2 simplified frigates. Figure 2.2a shows the 1:90 scale SFS2 ship model, and Fig. 2.2b shows the 1:235 scale SFS2 ship model, as they were constructed and used in the present wind tunnel tests. The ship models were constructed using high-density PVC plastic mounted to a precision ground aluminum plate, followed by CNC machining. The 1:90 scale model was 1.54 m (5.05 ft) long and its surface was painted in a deep matt-black finish to minimize surface reflections from the laser sheets. This ship model, as tested, had an equivalent surface roughness of between 600 and 800 grit. The 1:235 scale model was 0.59 m (1.94 ft) long and its surface was also painted in a deep matt-black finish with a slightly rough surface. In some cases, rhodamine dye was spray-applied to the surface of the models to minimize surface reflections from the laser sheets, although its effectiveness was really rather limited and was not used in the LSWT. Table 2.1 gives the primary dimensions of the SFS2 ship models at the different scales and is also shown in Fig. 2.3.

<table>
<thead>
<tr>
<th>Scale</th>
<th>$SH$ (ft)</th>
<th>$BW$ (ft)</th>
<th>$SL$ (ft)</th>
<th>Deck (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>55.0</td>
<td>45.0</td>
<td>455.0</td>
<td>90.0</td>
</tr>
<tr>
<td>1:90</td>
<td>0.61</td>
<td>0.5</td>
<td>5.05</td>
<td>1.0</td>
</tr>
<tr>
<td>1:235</td>
<td>0.23</td>
<td>0.19</td>
<td>1.94</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Figure 2.1. Definition of the SFS2 ship geometry. The SFS1 is the shaded part only. Note: Dimensions are given in feet (Zan and Garry, 1994).

(a) 1:90th-scaled ship model, as constructed.

(b) 1:235th-scaled ship model, as constructed.

Figure 2.2. Photos of the Simple Frigate Shape 2 (SFS2) ship models.

2.2 ABL Simulation

The atmospheric boundary layer (ABL) is an essential part of understanding the flow over the deck and resulting airwake. Winds always blow over the sea, so a representative
The scaling of the upstream ABL parameters in the wind tunnel is a prerequisite to study the effects on the airwake (Zan, 2002). The creation of a mean velocity profile (i.e., a velocity gradient with a reduction in the flow velocity near the ground) for a simulated ABL in the wind tunnel is a necessary but insufficient condition because the simulated ABL must also have some representative turbulence intensity. A representative peak turbulence goal in the present experiments was up to 10% of the free-stream velocity. However, it should be noted that the generation of higher turbulence levels causes many issues for a closed-return wind tunnel facility, including high cyclic loads on the fan blades.
For modeling and simulation purposes, the mean velocity profile of an ABL is usually described by using one of two models, namely a power law and a logarithmic law (log-law) model. Both models are also useful goals for generating ABLs in wind tunnel experiments. The power law is given by

$$\frac{u}{U_\delta} = \left(\frac{z_g}{\delta}\right)^{1/n}$$

(2.1)

where $U_\delta = 0.99U_\infty$ is the flow velocity at the edge of the boundary layer and $\delta$ is the height for $U_\delta$ (Schlichting and Gersten, 2016). Usually $n = 7$ is a reasonable approximation for a fully developed turbulent ABL in equilibrium conditions.
The log-law also includes a roughness length, $z_0$, which represents the characteristics of the interface between the wind and the surface, such that

$$\frac{\bar{u}}{U_\delta} = \frac{\ln(z_g/z_0)}{\ln(\delta/z_0)} \quad (2.2)$$

Figure 2.4 shows the mean velocity profiles for the 1/7-th power law as well as the log-law model at roughness length scales of $z_0 = 0.005, 0.001$ and $0.002$. The closest match to the 1/7-th power law was obtained for the log-law model with a roughness length scale of $(z_0 = 0.005)$. These cases were used as a reference for comparing with the simulated ABL, which will be discussed in Chapter 3.

### 2.2.1 ABL Scaling

A proper scaling of the ABL parameters is required to study the effects of the ship airwake (Zan, 2002). The ABL scaling must include the ratio of the height of the ship model (from the waterline to the top of the funnel) to the thickness of the incoming ABL, $\delta$, which must be matched in terms of the variation of the mean velocities with height as well the turbulence intensities. The thickness of an actual ABL over the ocean is usually considered to have an integral scale of 300 m (approximately 1,000 ft) (Counihan, 1975).

Considering the height of the test section for the wind tunnel, the boundary layer thickness for an actual ship on the ocean was taken to be approximately 4 to 5 times of the full-scale ship height ($FSH$) such that the ship was completely submerged in the velocity gradient of the boundary layer, as shown in Fig. 2.5. The present approach parallels the study performed by Zan (2002) and Rosenfeld et al. (2015). Therefore, in both the LSWT a 1:90 scale SFS2 model and the BLWT a 1:235 scale SFS2 model
needed at least to have an equivalent simulated ABL thickness of 0.745 m (29.32 in) and 0.28 m (11.24 in), respectively, which is four times the height of the scaled ship height ($SH$), a goal that was obtained with the final positions of the Cowdrey rods.

Notice that in the wind tunnel environment, it is important to try to scale both the velocity profile and turbulence within the ABL profiles. In fact, the creation of a mean velocity profile for a simulated ABL, which is usually all that is done, is a necessary but insufficient condition because the simulated ABL must also have representative turbulence intensity profiles. Over the surface of a rough sea, the turbulence intensities in the wind are known to be substantial and may vary from 13–17% of the mean wind flow near the surface but they also rapidly diminish away from the surface (Healey, 1992; Peña et al., 2009; ESDU, 2010).
2.3 Boundary Layer Wind Tunnel Facility

The Boundary Layer Wind Tunnel (BLWT) at ERAU, which is shown in Fig. 2.6, is an open-return, drawdown, low-speed tunnel with a 0.61-by-0.61 m (2-by-2 ft) cross-section, a test section length of 1.82 m (6 ft), and an overall length of 7.32 m (24 ft). The corner fillets are present throughout the length of the BLWT. This wind tunnel is driven by a 0.25 kW three-phase electric motor with a centrifugal fan, which is controlled by a variable frequency industrial drive. The tunnel can achieve a free-stream flow speed of up to 25 m s$^{-1}$ (82 ft s$^{-1}$) and a Reynolds number of up to $5.16 \times 10^5$ per foot or $1.7 \times 10^6$ per meter of model length. The reference dynamic pressure and flow speed was measured using a pitot-static tube at the entrance to the tunnel.

The BLWT was constructed for the present research for two reasons. The first reason was because the new ERAU Low-Speed Wind Tunnel was not yet commissioned and available for use. The second reason is that preliminary PIV experiments were needed to work out many details of simulating an ABL in a wind tunnel and also in measuring the
Figure 2.7. Parts of the Boundary Layer Wind Tunnel (BLWT).

airwake. These preliminary measurements helped in resolving various issues such as setting up PIV cameras for capturing larger fields of view, focusing issues, and alignment of the laser sheets. These tests also explored various paints and surface finishes for the
ship model that were suitable for PIV measurements so as to obtain minimum surface reflections from the laser sheets.

By design, the BLWT has a 5.67 m (18.6 ft) long upstream section before the flow reaches the test section. The purpose was to allow for a faithful simulation of a thick atmospheric boundary layer (ABL) prior to reaching the ship model. Honeycomb sheets were installed in the inlet of the wind tunnel to straighten the incoming flow, reduce the swirl, and also to obtain lower values of the test section turbulence. The inlet boundary layer was tripped with 80 grid sandpaper.

The long upstream section of 7.32 m (24 ft) was constructed using MDF boards and aluminum frames with T-slots, as shown in Fig 2.7b. There were three windows of cross-section 1.22-by-0.61 m (4-by-2 ft) for accessing the upstream sections at three different locations in the wind tunnel. The inlet section and the power system as shown in figs. 2.7a and 2.7e, respectively were from another low-speed wind tunnel. A transition duct, as shown in Fig. 2.7d, was designed to connect the test section to the fan stage. The transition duct was fabricated out of fiberglass to provide both transitional shape and strength to the section.

The test section itself, as shown in fig. 2.7c, was constructed such that PIV measurements can be readily conducted; most of the test section was made of cast acrylic sheet, which gave a reasonable optical access for lasers and cameras. Free-stream turbulence intensities at the entrance to the test section were measured to be < 0.08% as determined using HWA.
2.3.1 Cowdrey Grid in the BLWT

As previously mentioned, an atmospheric boundary layer (ABL) is an essential part of understanding the flow over the deck and resulting airwake of the ship. Various techniques such as elliptical wedge generators, triangular spires, grids, and rods have all been used to simulate an ABL in wind tunnels. In particular, Rosenfeld et al. (2015) and Vidales (2016) have used horizontal Cowdrey (1967) rods with good success in a large, short-test section LSWT, so this approach was also used in the present work.

Figure 2.8. Cowdrey grid setup and schematic showing the positions of the rods in the BLWT. (All dimensions are in inches).

In the BLWT, Cowdrey grid was installed just downstream of the intake section to produce the needed velocity gradients and turbulence to form a representative ABL at the test section. The advantage of the BLWT is that there was also a longer mixing length available downstream of the rods. The initial positioning of all the Cowdrey grids was based on the theory of Cowdrey, but judicious changes were made to these positions to
simulate a turbulent ABL that corresponded closely to a 1/7-th power law (Wiernga, 1993; Zhou and Kareem, 2002; Rosenfeld et al., 2015) at the entrance to the test section. The Cowdrey grid (Cowdrey, 1967) consisted of four rods that were placed 0.61 m (2 ft) downstream of the inlet to the tunnel, as shown in Fig. 2.8. Each rod was 0.61 m (2 ft) long and was 1.27 cm (0.5 in) in diameter. The distance between the Cowdrey rods and the ABL measurement location upstream of the ship model was $393d$ rod diameters. The theory supporting the positioning of the rods is given in Appendix A.

2.3.2 HWA Measurements in the BLWT

Figure 2.9 shows a schematic of the HWA setup used in the BLWT. The HWA setup was located 5.61 m (18.4 ft) from the inlet to the tunnel and 0.30 m (1 ft) upstream of the bow of the ship. A Velmex BiSlide motor-driven traverse was mounted vertically to hold a streamlined strut with a hot-wire probe at the needed position to traverse a vertical flow velocity profile in the tunnel. The motion of the traverse was tracked using an incremental linear magnetic encoder system with a resolution of 10 $\mu$m.
The HWA was calibrated using a calibration jet before each run (pre-calibration) at
the same nominal temperature as for the actual test because of the dependence of the
heat-transfer from the wire on fluid properties. Details of the calibration jet are given in
Appendix B. A third order polynomial curve was used to fit the calibration data. Various
MATLAB scripts were used to communicate with all devices and to automate the process
where necessary. All the measurements were conducted in the wall-normal direction for
60 points that were logarithmically spaced with respect to each other. HWA
measurements were sampled at a rate of 20 kHz using a data acquisition board. During
the scans the atmospheric temperature and pressure were monitored using a thermocouple
and a pressure transducer.

2.3.3 PIV Setup in the BLWT

PIV was performed in the centerline plane on the 1:235 scaled SFS2 ship model.
Figure 2.10 shows a schematic of the “snap-shot” (non-time-resolved) PIV setup. This
PIV technique uses high power pulsed lasers (Class 4b laser) to illuminate the seed
particles in the measurement plane. In the present research, one double-pulsed 350
mJ/pulse Nd:YAG laser was used to generate laser sheet at a 15 Hz repetition rate. An
articulated optical arm was used as an integrated light guide for delivering controlled laser
illumination safely to the measurement plane in the wind tunnel. The raw laser beams
passed through an optics head with a 20 mm cylindrical lens and spherical lens
combinations, thereby expanding each beam into a thin sheet. The sheet thickness was
measured to be less than 1 mm (0.039 in) using burn paper.
The necessary regions of interest over the SFS2 ship model were covered by the two, fully-programmable, high-resolution 29 Mpx CCD cameras. These CCD cameras have a rectangular pixel array with a resolution of 6600-by-4400 px that can capture raw images at a rate of 0.88 Hz at full pixel resolution. The cameras had 14-bit digital outputs and were also equipped with a Gigabit Ethernet interface for rapid data transfer to the computer.

The overall field of view was 24.96 cm (9.8 in) long in streamwise direction and 9 cm (3.5 in) high in the wall-normal direction, as shown in Fig. 2.10. Camera 1 was used to capture the funnel and superstructure and Camera 2 was used to capture the flight deck and downstream wake. Camera 1 used a 200 mm lens with a f-stop of 4 while Camera 2 used a 105 mm lens with a f-stop of 2.8. Camera 2 was fitted with a customized front mounting plate to allow a Scheimpflug mount adapter to be attached to the camera; this mount was used for the adjustment of the angle between camera and its lens to avoid oblique distortion.
The laser and the cameras were triggered simultaneously through a Programmable Timing Unit (PTU). The PTU generated precise trigger pulses for the cameras and lasers under the control of the software. The time interval between image acquisition was set to $\Delta t = 15 \mu s$, so that the distance traveled by the seed particle in the image pairs was approximately 10 pixels. Typically, 1,000 image pairs were obtained from the two cameras at 0.88 Hz with small sets because of the internal memory limitation of the CCD cameras, amounting to some 136 GB of raw PIV image data for each run.

The acquired images were preprocessed to correct some oblique distortion resulting from the use of cameras at an angle. A calibration plate with a dot spacing of 5-by-5 mm and dot diameter of 2 mm was placed in the measurement plane, and the images were recorded by both the cameras. 1,000 PIV image pairs were obtained in the centerline plane to satisfy the statistical requirements for turbulent flow characterization. The raw images were then processed using commercial PIV software in which pixel-wise mapping was performed according to the given flow field and pixel intensity using bi-linear interpolation. This approach helped to obtain a better signal-to-noise ratio of the correlation function with an increased accuracy of velocity measurements and, thereby, a reduction in peak locking that might be caused from using relatively small seed particles.

Surface reflections in the raw PIV images were minimized by using masking and background subtraction techniques. The quality of the final processed results depends on a number of factors such as particle seeding density, camera alignment, camera focus, and magnification factor, etc. It is necessary to obtain a strong correlation peak (better signal to noise ratio) from the cross-correlation algorithm to obtain high quality processed PIV images. The 1,000 image pairs were post-processed with two interrogation windows.
starting with 64 \times 64 and ending at 32 \times 32 with an overlap region of 50% at the centerline case. To obtain the needed region of interest, the vector fields derived from each camera were numerically mosaiced using cubic interpolation with overlap averaging to provide a nominally seamless vector field. Interpolation was used to fill in any missing vectors, but these were typically less than 3% of the total number of flow vectors.

### 2.3.4 Seeding in the BLWT

In PIV, the velocity of the seed particles is used as a surrogate to estimate the velocity of the flow. Therefore, it is necessary that particles follow the flow closely under all conditions. In general, the size of the seed particles need to be small enough to faithfully follow the flow but large enough to create enough Mie scattering to be recorded on the images. The seeding particles for the PIV in the BLWT were generated using oil-based ViCount Compact 1300 smoke generator system to create vaporized particles that were nominally 0.2 \( \mu m \) in diameter based on calibration.

The Stokes number can be used to estimate how closely the seed particles follow the flow, which is a measure of the ratio of inertial forces on the particle to its viscous forces. For the particles to follow the flow, the Stokes number should be much less than 1. If the Stokes number is greater than 1, then the particles will not follow the fluid during accelerations or decelerations. The particle Stokes number (\( Stk \)) can be defined as

\[
Stk = \frac{\tau U}{L}
\]

where \( \tau \) is relaxation time of the particle, \( U \) is the flow velocity in the mid flight deck region and \( L \) is the characteristic length dimension of the problem, which was decided in
the present case to be the hangar height of the ship model, $HH$. The relaxation time $\tau$ can be defined as

$$\tau = \frac{\rho d_p^2}{18 \mu}$$

(2.4)

where $d_p$ is the particle diameter, and $\rho$ and $\mu$ are the density and dynamic viscosity of the flow. Based on the seed particles of diameter of 0.2 $\mu$m, the hangar height of 0.026 m (1.02 in) for the 1:235 scale ship model used in the experiments, flow velocity of 7.5 m $s^{-1}$ (24.60 ft $s^{-1}$) near the mid-deck region and assuming ISA MSL standard values for density and viscosity, then the Stokes number is

$$Stk = \frac{1.225 (0.2 \times 10^{-6})^2 7.5}{18 (1.789 \times 10^{-5}) 0.026} = 4.4 \times 10^{-8}$$

(2.5)

Because the Stokes number was much less than 1, it was determined that particles will follow closely the motion of the flow over the ship model.

### 2.3.5 Measurements Performed

Some of the work in the BLWT included the use HWA to measure the development of simulated turbulent ABL for various Cowdrey grid configurations and downstream distances. The goal was find a combination of conditions that produced velocity gradients that was representative of a 1/7-th power law as well as sufficient turbulence to represent an ABL. HWA measurements were made at three downstream locations in the BLWT, namely at 120$d$, 240$d$ and 393$d$ rod diameters (as shown previously in Fig. 2.11) to understand the effect of downstream development length on the boundary layer.
Figure 2.11. A schematic showing the locations of the HWA measurements at three downstream development lengths, namely 120\(d\), 240\(d\) and 393\(d\) rod diameters in the BLWT. (Not to scale.)

Figure 2.12 shows the measurement plane used for the PIV in the streamwise (\(x-z\)) direction for the centerline plane. In the contour plots obtained from these PIV measurements which will be shown in Chapter 3, all lengths were normalized by the model ship height (\(SH\)) and the velocity components were normalized by the free-stream velocity, \(U_\infty\), in keeping with the conventions established by Rosenfeld et al. (Rosenfeld et al., 2015) and others.

Figure 2.12. Schematic showing the measurement plane for PIV using the 1:235 scale ship model in the BLWT.
HWA was also used to collect flow field data at four locations (A–D) near the center of the flight deck at \( x/SH = 1.84 \), and four locations (E–H) near the trailing edge of the deck at \( x/SH = 2.53 \), as shown in Fig. 2.13. For consistency, these are the same locations previously used by Rosenfeld et al. to survey the ship deck (Rosenfeld et al., 2015). Locations A–D were located 57% of the rear deck length behind the superstructure. Locations A and D lie on Plane 4, which is at the edge of the ship at the port sides, whereas locations D and H lie on Plane 1 at the edges of the ship at the starboard sides. Plane 2 (containing locations C and G), and Plane 3 (containing locations B and F), which were equispaced from the ship edges.

Figure 2.13. Flight deck locations where the mean velocity profiles and turbulence intensity profiles were obtained for the 1:235 scale SFS2 ship model in the BLWT.
2.3.6 Test Conditions in the BLWT

Table 2.2 shows the test cases used for the measurements in the BLWT. The experiment was performed at a constant upstream dynamic pressure equivalent to a nominal flow speed in the test section of $15 \text{ m s}^{-1}$ (49.2 ft s$^{-1}$), giving a Reynolds number based on ship length (0.59 m, 1.94 ft) of 0.6 million.

![Image Number of Measurement](Image)

Table 2.2. Test matrix for the airwake measurements of the 1:235 scale SFS2 ship model.

<table>
<thead>
<tr>
<th>$U_\infty$ (ft s$^{-1}$/m s$^{-1}$)</th>
<th>$Re$ (millions)</th>
<th>$\Delta t$ ($\mu$s)</th>
<th>Image rate (Hz)</th>
<th>Number of images</th>
<th>Measurement Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.2/15</td>
<td>0.6</td>
<td>15</td>
<td>0.4</td>
<td>1000</td>
<td>Centerline</td>
</tr>
</tbody>
</table>

2.4 Low-Speed Wind Tunnel Facility

The low-speed wind tunnel (LSWT) at the Embry-Riddle Aeronautical University (ERAU) Micaplex Research Annex is a newly commissioned, state-of-the-art, closed-return wind tunnel facility, as shown in Fig. 2.14. The LSWT has excellent flow quality and has many unique features and capabilities (Staff, 2019), including a seed injection and purge system. The test section of the LSWT has a nominally 1.8-by-1.2 m (6-by-4 ft) cross-section with tapered corner fillets, and has a length of 3.7 m (12 ft).

The entire test section is within the calibration specifications for flow uniformity ($<0.1\%$ of free-stream) and flow angularity ($<\pm 0.2^\circ$). Tapered corner fillets ensured that there was essentially no longitudinal pressure gradient over the length and immediate downstream wake of the ship model, which was verified by the empty test section
calibration measurements. The free-stream flow was pre-conditioned by a heat exchanger system and anti-turbulence screens; the heat exchanger control system maintains the assigned flow temperature in the test section to hold constant the air density and viscosity.

![Figure 2.14. Closed-return low-speed wind tunnel (LSWT) facility at ERAU.](image)

The test section of the ERAU LSWT is comprised 65% of area of optical grade glass with an anti-reflective optical coating, thereby giving excellent options for the positioning of lasers and cameras needed for PIV. The extended length of the test section is well-suited for ship airwake studies because the downstream wake from the ship can properly develop inside the test section before entering the high-speed diffuser section, a concern with many previously published ship airwake measurements.

The free-stream turbulence intensities at the entrance to the test section were measured to be < 0.1% for flow speeds at or below 45.7 m s\(^{-1}\) (150 ft s\(^{-1}\)) and < 0.25% for flow speeds up to 107 m s\(^{-1}\) (350 ft s\(^{-1}\)), as determined by both hot-wire anemometry and turbulence sphere tests. The LSWT also has a seed purging system, which can be
operated with the tunnel running, which was helpful in controlling the concentration of seed particles in the test section for the PIV measurements.

2.4.1 Cowdrey Grids in the LSWT

The Cowdrey grid method was also used in the LSWT because good success was achieved in simulating an ABL in the BLWT; see Appendix A. The LSWT, however, has a contraction section before the test section so in this case it was found that two sets of Cowdrey rods were needed to produce the needed velocity gradients and turbulence to form a representative ABL at the test section. Figure 2.15 shows a schematic of the positions of the Cowdrey grid for both first and second Cowdrey grids in the LSWT. One set of Cowdrey rods were placed in the stilling chamber and another set was located about two ship model lengths upstream of the bow of the ship, as shown in Fig. 2.16.

The first grid located in the stilling chamber of the LSWT consisted of five rods stacked near the floor with a separation of 0.05 m (2 in), each rod being 4.39 m (14.4 ft) long and 0.11 m (4.5 in) in diameter, as shown in Fig. 2.15a. This first set of Cowdrey rods created the initial velocity gradients and turbulence in the low-speed flow. The second downstream grid consisted of seven rods placed 1.95 m (6.4 ft) before the inlet of the test section, each rod being 1.52 m (60 in) long with a diameter of 0.027 m (1.05 in), as shown in Fig. 2.15b.

The initial positioning of the Cowdrey grids was again based on the theory (Cowdrey, 1967) as also described in detail Appendix A, but judicious changes were made to these positions to simulate a turbulent ABL that corresponded closely to a 1/7-th power law (Wiernga, 1993; Zhou and Kareem, 2002; Rosenfeld et al., 2015) at the entrance to the
test section. The second set of rods was fitted with a turbulence screen, which was found effective in enhancing the overall mixing in the flow in the simulated ABL before it reached the ship model. The distance between the secondary Cowdrey rods and the ABL
measurement location was about 100d rod diameters, and although shorter than obtained in the BLWT, a reasonable turbulence spectrum was obtained suggesting that there was good mixing in the flow.

2.4.2 Measurement of the Simulated ABL

Both 7-hole probe rake and hot wire anemometry (HWA) were used to measure the simulated ABL in the LSWT; a schematic of the setup is shown in Fig. 2.17. Both the 7-hole probes and hot wires were placed on a rake that was located 0.518 m (1.7 ft) from the inlet and 0.152 m (6 in) upstream of the bow of the ship model. The rake consisted of four, laterally-spaced, 7-hole pressure probes that could measure both flow velocity and flow angularity, as shown in Fig. 2.18a.

Figure 2.17. Schematic showing the 7-hole probe rake and HWA setup for measuring the ABL in the LSWT. (Not to scale.)
Each 7-hole probe consisted of seven small 0.794 mm (1/32-inch) internal diameter tubes that were connected to a multi-channel Scanivalve pressure transducer block that had a measurement range of about 7 kPa (1 lb/in\(^2\)) and accuracy of \(\pm 2\) Pa (\(\pm 0.0003\) lb/in\(^2\)). Each probe was pre-calibrated in pitch and yaw using established procedures (Gerner and Maurer, 1982), and had a measurement resolution of \(\pm 0.03\)% of the free-stream and a flow angularity of \(\pm 0.1^\circ\).

The true dynamic pressure was measured at the centerline of the test section using a pressure probe rake, which was mounted on a streamlined strut connected to a precision overhead instrumentation traverse system; the turbulence profile was measured using the pre-calibrated hot wire probe on the same traverse. Various LabVIEW scripts were used to communicate with all the devices and to automate the process where necessary.

The turbulence was measured using the HWA setup, the single component hot-wire probe being mounted on the same traverse. Measurements were made with a sampling rate of 20 kHz in the wall-normal direction for 35 points that were logarithmically spaced with respect to each other. The HWA was calibrated using a calibration jet before each run (pre-calibration) at the same nominal temperature as for the actual test because of the dependence of the heat-transfer from the wire on fluid properties. Again, details of the calibration jet are given in Appendix B.

### 2.4.3 Time-Resolved PIV Setup

Figure 2.19 shows the high-speed, time-resolved PIV (TR-PIV) setup in the LSWT. A dual-head, 30 mJ/pulse at a wavelength of 527 nm Nd:YLF high-speed, diode-pumped, solid-state laser having an energy per flash in a range of 1–10 kHz repetition rate was
(a) The 7-hole probe rake consisted of four, laterally-spaced, pressure probes.

(b) 7-hole probe rake mounted on the streamlined strut.

Figure 2.18. 7-hole pressure rake and traverse system used in the LSWT.

used. The lasers constitute a complete system that included a beam combination optics, laser heads, power supply and a chiller with iced water to cool the laser heads.

Cylindrical lenses were used to spread the laser beam into a planar sheet, which then illuminates the seed particles in the desired field of view within the test section. A compact integrated and fully adjustable light sheet optics package was used, which has two sets of cylindrical lenses that allows maximum control over the sheet divergence and thickness. The raw laser beams were passed through an optical head with cylindrical and
spherical lens combinations, thereby expanding the beams into thin sheets. With a final –10 mm focal length diverging lens, the sheet thickness was measured to be less than 1 mm (0.039 in) for the streamwise planes. The laser sheets entered the test section from the top through an optical grade glass window. The sheet thickness was measured to be less than 1 mm (0.039 in) using burn paper.
The necessary regions of interest were covered by 4 Mpx CMOS cameras with a 2560-by-1600 px array. Two cameras were needed to capture the relatively large field of view (FOV) at the required spatial resolution for all streamwise planes. The overall FOV over the ship deck and its immediate wake was 53.34 cm (21 in) long in the streamwise direction and 10.16 cm (4 in) high in the wall-normal direction, giving a spatial resolution of approximately 0.1 mm (0.004 inches) per pixel for the streamwise planes. Camera 1 was used to capture the rear of the superstructure, funnel and flight deck, with Camera 2 being used to capture the flight deck and the downstream wake, as shown in Fig. 2.19a. Both cameras used 105 mm lenses with an f-stop of 2.8 and were fitted with Scheimpflug mounts.

For the crossplane PIV measurements, which were performed in stereo mode, the laser beams passed through a final −25 mm focal length diverging lens and expanding them into thicker sheets of 3 mm (0.12 in) to better capture the out-of-plane particle movement. Two, 4 Mpx CMOS cameras were again used to capture the crosswise FOV. The three-dimensional displacement field was constructed from the two projected, planar displacement fields. To this end, the combination of both camera projections were used to obtain reconstruction of the two-dimensional, three-component particle displacement inside the required FOV. The two cameras used a 200 mm lens with an f-stop of 4, again with Scheimpflug mounts, giving a net FOV of 19.05-by-10.16 cm (7.5-by-4 in) for the crossplanes.

The PTU timing hub was used to synchronize the cameras and lasers. The straddling time $\Delta t$ between PIV image pair acquisition was set such that the distance traveled by the seed particles in the image pairs were approximately 10 px; $\Delta t = 8–20 \mu s$ was typically
typically, 5,000 image pairs were obtained from the two cameras at 500 Hz for a contiguous period of 10 s, amounting to some 144 GB of raw image data for each run. Other sampling frequencies and record lengths were studied, but the frequency content of the unsteady flow was found to be negligible above 200 Hz and so to minimize data storage then 500 Hz was subsequently used.

The acquired PIV images were pre-processed using a calibration plate to correct for oblique distortion resulting from the axis of the lens being at an angle to the measurement plane. Surface reflections in the raw PIV images were minimized by using masking and background subtraction techniques. The quality of PIV processed results strongly depends on a large number of factors such as particle seeding density, camera alignment, camera focus and magnification factor, etc. It is always necessary to obtain a strong correlation peak (better signal to noise ratio) from the cross-correlation algorithm in order to obtain high quality processed images.

The raw images obtained were processed using commercial PIV software in which pixel-wise mapping was performed according to the given flow field and pixel intensity using bi-linear interpolation. This approach helped obtain a better signal-to-noise ratio of the correlation function with an increased accuracy of velocity measurements and, thereby, a reduction in peak locking that might be caused from using relatively small seed particles. The acquired PIV images were pre-processed using a calibration plate to correct for oblique distortion resulting from the axis of the lens being at an angle to the measurement plane. Surface reflections in the raw PIV images were minimized by using masking and background subtraction techniques.
For TR-PIV, calibration plate with a dot spacing of 10-by-10 mm and dot diameter of 5 mm were placed in all the longitudinal measurement planes. TR-PIV measurements were performed at five longitudinal planes, as shown in Fig. 2.20a. For consistency, the measurement planes were made at the same locations as Rosenfeld et al., who used 5-hoe probes (Rosenfeld et al., 2015). Planes 1 and 4 were at the edges of the ship at the starboard and port sides, respectively. For all longitudinal planes, 5,000 PIV image pairs were obtained from the two cameras at 500 Hz for a contiguous period of 10 s.

The 5,000 image pairs were then post-processed with the two interrogation windows starting with $64 \times 64$ and ending at $32 \times 32$ with an overlap region of 50% at the centerline case. For all the other streamwise planes, images were processed starting with $96 \times 96$ and ending at $48 \times 48$ with an overlap region of 50% for Planes 1 and 2, and an overlap region of 75% for Planes 3 and 4. To obtain the needed region of interest, the vector fields derived from each camera were numerically mosaiced using cubic interpolation with overlap averaging to provide a nominally seamless vector field. Interpolation was used to fill in any missing vectors, but these were typically less than 3% of the total number of flow vectors.

For stereo-PIV, a three-dimensional calibration plate with a dot spacing of 15-by-15 mm, dot diameter of 3 mm and plane-to-plane distance of 3 mm were placed in all cross-plane measurement planes to obtain images from the cameras. 5,000 image pairs from two cameras were obtained for each crossplane at 500 Hz for a contiguous period of 10 s. These data were post processed with two interrogation windows, starting with $98 \times 98$ and ending at $48 \times 48$ with an overlap of 75%.
Again, the vector fields derived from each camera were numerically mosaiced together. Some of the challenges faced during the crossplane measurements were the oblique viewing angles for the cameras, and the more rapid out-of-plane particle movement because of the relatively high streamwise flow velocities. Again, the vector fields derived from the two cameras were numerically mosaiced together.

2.4.4 Seeding Particles in the LSWT

The seeding particles in the LSWT were generated using oil-based ViCount Compact 5000 smoke generator system to create vaporized particles that were nominally 0.2 µm in diameter based on calibration. The seed particles were introduced in the stilling chamber, and the tunnel was filled until an acceptable seed particle density was achieved to perform PIV. To this end, the wind tunnel was run at low speed until the concentration in the test section became homogeneous; this was decided based on visual observations.

Using Eqs. 2.3 and 2.4, and again based on a seed particle diameter of 0.2 µm, a hangar height of 0.067 m (2.67 in) in this case for the 1:90 scale ship model, flow velocity of about 15 m s\(^{-1}\) (49.2 ft s\(^{-1}\)) at the mid-deck and assuming ISA MSL standard values for density and viscosity, then the Stokes number for the experiments conducted at the LSWT is

\[
Stk = \frac{1.225 \times (0.2 \times 10^{-6})^2 \times 15}{18 \times (1.789 \times 10^{-5}) \times 0.067} = 3.4 \times 10^{-8}
\]  

(2.6)

Because the Stokes number was much less than 1, it was determined that particles will also follow closely the motion of the flow over the ship model.
2.4.5 PIV Measurements Planes

Figure 2.20 shows the measurement planes for the TR-PIV in the streamwise \((x-z)\) and stereo TR-PIV in crosswise \((y-z)\) directions. TR-PIV measurements were made at five longitudinal planes namely, centerline, Planes 1 and 4 are over the ship edges on both starboard and port side and Plane 2 and Plane 3 are equally-spaced from the ship edges.

Figure 2.20. Schematic showing the measurement planes in the streamwise and crosswise directions.

Stereo PIV measurements were performed at three locations in the cross-plane namely, rear edge of superstructure (above the hangar), rear edge of the flight deck and 15.24 cm (6 in, i.e is the half the deck length) behind the flight deck. In the contour plots
obtained from these TR-PIV and stereo TR-PIV measurements which will shown in Chapter 3, all lengths were normalized by the model ship height \((SH)\) and the velocity components were normalized by the free-stream velocity, \(U_\infty\), in keeping with prior convention (Rosenfeld et al., 2015).

### 2.4.6 Test Conditions in the LSWT

Table 2.3 shows the measurement cases used for PIV measurements in the LSWT. The experiments were performed at a constant upstream dynamic pressure equivalent to a nominal flow speed in the test section of 30.5, 45.7, 61.0 and 76.2 m s\(^{-1}\) (100, 150, 200 and 250 ft s\(^{-1}\)), giving a Reynolds number range based on ship length (1.54 m, 5.05 ft) of 3.1 million to 7.7 million.

Table 2.3. Test matrix for the airwake measurements of the 1:90 scale SFS2 ship model.

<table>
<thead>
<tr>
<th>(U_\infty) (ft s(^{-1}) / m s(^{-1}))</th>
<th>(Re) (millions)</th>
<th>(\Delta t) ((\mu s))</th>
<th>Image rate (Hz)</th>
<th>Number of images</th>
<th>Measurement Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 / 30.5</td>
<td>3.1</td>
<td>20</td>
<td>500</td>
<td>5,000</td>
<td>Centerline, Planes 1–4 (\text{Crossplanes 1–3})</td>
</tr>
<tr>
<td>150 / 45.7</td>
<td>4.7</td>
<td>15</td>
<td>500</td>
<td>5,000</td>
<td>Centerline, Planes 1–4</td>
</tr>
<tr>
<td>200 / 61.0</td>
<td>6.2</td>
<td>10</td>
<td>500</td>
<td>5,000</td>
<td>Centerline, Planes 1–4</td>
</tr>
<tr>
<td>250 / 76.2</td>
<td>7.7</td>
<td>8</td>
<td>500</td>
<td>5,000</td>
<td>Centerline</td>
</tr>
</tbody>
</table>

### 2.5 Uncertainties in the PIV Measurements

There are several sources of measurement uncertainty that arise when using PIV to measure a complex flow. These sources include seeding density, laser reflections, out-of-plane motion, background noise, laser pulse separation time (from uncertainties in
the software), and interrogation window size. Calibration misalignment was eliminated with the help of LaVision’s self-calibration routine and sub-pixel displacement measurement accuracy by sophisticated sub-pixel interrelates and correlation peak finding routines. Background noise, which may result in inaccurate cross-correlations and erroneous vectors, were reduced by implementing a strict signal-to-noise ratio range when assessing vector validity during both “snap-shot” PIV and TR-PIV measurements.

The values can be used to determine the total uncertainty in measurements of flow velocity \( U \) by using the equation

\[
\Delta U = \sqrt{ \left( \Delta \varepsilon_{\Delta x} \frac{\partial U}{\partial \Delta x} \right)^2 + \left( \Delta \varepsilon_{\Delta t} \frac{\partial U}{\partial \Delta t} \right)^2 + \left( \Delta \varepsilon_M \frac{\partial U}{\partial M} \right)^2 } \tag{2.7}
\]

where \( \varepsilon_{\Delta x}, \varepsilon_{\Delta t}, \) and \( \varepsilon_M \) are the pixel displacement, pulse separation time, and magnification factor, respectively. The interrogation window size and pulse separation time were chosen such that there was minimal flow curvature shearing within each window. The interrogation windows were sized to be as small as possible such that they resolved the velocity gradients in the flow. The smallest window size \( (32 \times 32 \text{ px}) \) were found to contain about 8–15 seed particles. A assumption for the magnitude of error from these sources is 0.1 px, giving a 1.5% error in the resulting flow velocities.

The uncertainty of the laser pulse separation is usually treated as a Type B uncertainty (i.e., it cannot be retrieved from data statistics on repeated observation) and its quantification relies upon the information provided by the manufacturer or dedicated experiments (Bardet et al., 2013), yielding a negligible relative uncertainty of about 0.005% for the experiments. The estimated uncertainty of the magnification factor was
calculated by considering the uncertainties associated with the size of the camera view in the object plane and that of the digital image, which was about 0.8%. When combining all the uncertainties from pixel displacement, pulse separation time, magnification factor, the total uncertainty for the velocity measurements was estimated to be about 1.7%.
3. Results and Discussion

The results obtained from the present research into the ship airwake problem are discussed in this chapter of the dissertation. The first and second sections of this chapter discusses the characteristics of the simulated ABL in terms of mean velocity and turbulence intensity profiles that were obtained in both the Boundary Layer Wind Tunnel (BLWT) and the Low-Speed Wind Tunnel (LSWT). It also compares results to actual ABLs measured in the field as well as other simulated ABLs obtained in other wind tunnels. The third section discusses the on-surface flow measurements that were supported by surface oil flow visualization, which was used to help interpret the flow features over the stern of the ship. The fourth section discusses the results obtained from the “snap-shot” (non-time-resolved) PIV measurements in the BLWT, which include presentations of time-averaged mean velocities, turbulence intensities, Reynolds shear stresses, and turbulent kinetic energy.

The fifth section discusses the effects of the ABL on the airwake developments by comparing the results obtained with the simulated ABL to those done in an uniform free-stream flow. The sixth section discusses the results obtained from the time-resolved PIV (TR-PIV) and stereo PIV measurements, which are also discussed in a similar manner to those for the BLWT and as will be discussed have exposed some additional unsteady flow aspects of the airwake problem. The last section in this chapter is a detailed analysis of the airwake and discusses the flow frequencies that are associated with the ship airwake, which are relevant to understanding what might happen to an operating aircraft that passes into the airwake. To this end, reduced-order modal analysis techniques
including Proper-Orthogonal Decomposition (POD) and Spectral POD (SPOD) were used to examine in considerable detail the underlying structure and temporal dynamics of the turbulent airwake.

### 3.1 Simulation of an ABL in the BLWT

Measurements were first made in the BLWT to determine the mean velocity and turbulence profiles of the simulated ABL. In this wind tunnel, the Cowdrey grid was installed just downstream of the intake section to produce the needed velocity gradients and turbulence to form a representative ABL at the test section. As discussed previously in Chapter 2, the Cowdrey grid consisted of four rods that were placed 0.30 m (2 ft) downstream of the inlet to the wind tunnel and well upstream test section. Each rod was 0.30 m (2 ft) long and 1.27 cm (0.5 in) in diameter.

Several combinations of Cowdrey rod locations were tried before settling on a combination that best replicated the velocity gradient and turbulence characteristics of an representative ABL (Peña et al., 2009) in the test section, as previously explained in Chapter 2. The initial positioning of all the rods was based on the theory of Cowdrey (Cowdrey, 1967), as discussed in Appendix A. However, judicious changes were still needed to the rod positions to achieve the desired outcomes, which also consumed significant wind tunnel and measurement time.

As also previously discussed, a reasonable scaling of the ABL parameters is required to study the effects of the ship airwake (Zan, 2002). For the BLWT, a 1:235 scale SFS2 model needed (at least) to have an equivalent ABL thickness of up to 0.28 m (11.24 in),
which is four times the height of the scaled ship height ($SH$). This goal was achieved with a final Cowdrey grid consisting of just four rods.

A challenge in developing an artificially thick boundary layer in a wind tunnel is for it to reach a reasonable equilibrium state with good mixing before it reaches the test section. Therefore, it was important to understand the effect of development length on the resulting boundary layer as it formed downstream of the rods flowed toward the test section. To this end, HWA measurements were made at three downstream locations in the BLWT, namely at distances of $120d$, $240d$ and $393d$ rod diameters, as shown previously in the schematic of Fig. 2.11.

Figures 3.1a and 3.1b detail the mean velocity profiles and turbulence intensities that were measured at the three downstream development lengths. For all of these plots, the ordinate was normalized by the estimated boundary layer thickness $\delta$ and the abscissa was normalized by the velocity at the reference boundary layer thickness, $U_\delta$. It should be noted that because of the single component hot-wire used, all the HWA measurements presented here measured the streamwise velocity ($u$). However, along with the actual flows in streamwise direction, some flows and fluctuations in other directions are also picked up in other direction.

Table 3.1. Measurement values of the simulated ABL at three downstream locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>$U_\infty$ (ft s$^{-1}$)</th>
<th>q (psi)</th>
<th>$\rho$ (lb ft$^{-2}$)</th>
<th>$\delta$ (in)</th>
<th>$U_\delta$ (ft s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$120d$</td>
<td>49.2</td>
<td>0.02</td>
<td>0.074</td>
<td>9.3</td>
<td>46.8</td>
</tr>
<tr>
<td>$240d$</td>
<td>49.2</td>
<td>0.02</td>
<td>0.074</td>
<td>10.3</td>
<td>48.9</td>
</tr>
<tr>
<td>$393d$</td>
<td>49.2</td>
<td>0.02</td>
<td>0.074</td>
<td>10.1</td>
<td>48.6</td>
</tr>
</tbody>
</table>
Figure 3.1. Mean velocity and turbulence intensity profiles of the simulated ABL in the BLWT for different downstream development lengths.

HWA measurements were made to determine the mean velocity and turbulence profiles for the simulated ABL for a flow velocity of 15 m s$^{-1}$ (49.2 ft s$^{-1}$) corresponding
to a Reynolds number (based on the ship length) of 0.6 million. Table 3.1 shows the boundary layer values obtained from the hot-wire measurement scans. At 120\(d\) of downstream development length, the results showed fairly irregular mean velocity and turbulence profiles. This behavior can be attributed to the signatures of an insufficiently mixed turbulent flow downstream of the individual Cowdrey rods, which is expected. Each rod produces initially its own turbulent wake with discrete, almost stratified layers or bands of turbulence, and some downstream distance is needed before the turbulence in the layers started to mix. Below \(z_g/\delta = 0.3\) the turbulence intensities were up to 8\%, and were less than 1\% when moving further away from the wall toward the free-stream region.

At a downstream development length of 240\(d\), the mean velocity and turbulence profiles started to smooth out, thereby reducing the more irregular features observed in the profiles at the 120\(d\) location. Again, the turbulence intensity was up to 8\% in the near-wall region and less than 1\% in the free-stream region. However, some bands were still observed in the turbulence intensity profile because of the continuing transitional mixing of the flow downstream of the Cowdrey rods, especially in the height range \(z_g/\delta = 0.2–0.7\).

At a downstream development length of 393\(d\), the mean velocity and turbulence profiles were found to be much smoother. This is was because the wake flows from the individual rods were now better mixed at this location. The turbulence intensity was still up to 8\% in the near-wall region and about less than 1\% in the outer free-stream region. CFD simulations of the BLWT with Cowdrey grid performed by partner colleagues at Pennsylvania State University (David et al., 2020) also showed similar results, as shown
in Fig. 3.2, which confirms the aforementioned hypothesis of the progressive mixing process produced by the rods. Both the experiments and the CFD confirmed that at $393d$ location the turbulence generated using Cowdrey grid had mixed well, as shown in Fig. 3.9a. The energy spectrum in this simulated ABL is discussed later in this chapter.

![Figure 3.2. A schematic showing the CFD simulation (David et al., 2020) of the downstream development of the ABL at $120d$, $240d$ and $393d$ along with the ABL profiles obtained using HWA measurements at these locations.](image)

### 3.2 Simulation of an ABL in the LSWT

Similar challenges were found in the LSWT in developing an artificially thick boundary layer that simulated an ABL in reasonable equilibrium state with good mixing before it reached the test section. An additional challenge in the LSWT was the presence of the contraction section before the test section, as well as the shorter available mixing length downstream of the Cowdrey rods in terms of rod diameters, i.e., 100 diameters in the LSWT versus 393 diameters in the BLWT.
In the LSWT, 7-hole pressure probe and HWA measurements were made to determine the mean velocity and turbulence profiles for the simulated ABL for three flow velocities, namely 30.5, 45.7 and 60.9 m s\(^{-1}\) (100, 150 and 200 ft s\(^{-1}\)) corresponding to Reynolds numbers (based on the ship length) of 3.1 million, 4.7 million and 6.2 million, respectively. Notice that the Reynolds numbers obtained in the LSWT were up to an order of magnitude higher than for the BLWT. As before, in all of the plots showing ABL profiles then the ordinate was normalized by the estimated boundary layer thickness \(\delta\) and the abscissa was normalized by the edge velocity \(U_\delta\).

The results measured using both the 7-hole probe pressure rake and HWA measurements for all the three flow speeds were seen to match well, as shown in Fig. 3.4. Figure 3.4b shows the turbulence intensity comparison for the simulated ABL in the LSWT. As was found in the BLWT, the turbulence intensity was up to 8\% in the near-wall regions and about less than 1\% in the free-stream regions. These trends were found to be similar for all three flow speeds/Reynolds number cases.

Figure 3.3. Comparison of the simulated ABL measured using the 7-hole pressure rake and HWA for three flow speeds.
(a) Mean velocity profile in the simulated ABL.

(b) Turbulence intensity for the simulated ABL.

Figure 3.4. Mean velocity and turbulence intensity profiles of the simulated ABL in the LSWT.
3.2.1 Comparison of Simulated ABL with an Actual ABL

Figure 3.5 shows a comparison of the ABL mean velocity profiles generated in both the BLWT and LSWT with actual ABL profiles that were measured in the field. The results shown here come from the work of Pena et al., Vickery et al. and Hutchins et al., although there are probably an infinite number of possible ABL profiles, depending on weather, surface terrain, atmospheric stability, etc (Peña et al., 2009; Vickery et al., 2009; Hutchins et al., 2012).

Pena et al. made ABL measurements taken off the coast of Denmark, near the Horns Rev wind farm (Peña et al., 2009). They used LiDAR and cup anemometers, and obtained the velocity profiles measured at three mast locations. The dataset used here for the ABL comparison was the one in which the masts were not affected by the wakes of the turbines and/or nearby terrain, which is referred to as “open sea”. The data were presented as ensemble time-averages, which were recorded for 10 minute windows. It was also mentioned that during the time of year in which the measurements were made, the atmospheric state over the sea was generally considered to be unstable, which produces some additional mixing within the ABL.

The study by Vickery et al. used a fitting technique to model the shape of the vertical profiles of mean horizontal wind speeds in a hurricane boundary layer, the measurements being made using dropsondes (Vickery et al., 2009). The dropsonde data were obtained from the Atlantic Oceanographic and Meteorological Laboratories Hurricane Research Division (AOML HRD), and consisted of all vertical profiles of wind speed collected during the 1997 and 2003 hurricane seasons. Hutchins et al. measured the atmospheric
boundary layer in the western salt flats of Utah over a period of 9 days in 2005; three-component sonic anemometers were used to measure the mean velocity profile (Hutchins et al., 2012).

Figure 3.5. Comparison of the ABL mean velocity profiles obtained in the BLWT and LSWT with open-sea and hurricane profiles.

Notice that actual ABLs show a wide variation of velocity gradients, and basically it would seem that an ABL can have an unlimited number of profiles. It was also observed, however, that all the ABL profiles followed the same trend in that there was a steep velocity gradient near the surface. It is also important to recognize that an actual ABL does not exactly conform to a 1/7th-power law or a log-law, as commonly assumed for a variety of industrial aerodynamic applications, but these mathematical relationships serve as references as being typical of fully developed turbulent boundary layers.
3.2.2 Simulated ABL Compared Results from Other Wind Tunnels

Figure 3.7a shows the mean velocity profiles for the simulated ABL made using the HWA in both the BLWT and LSWT as well as the 7-hole probe rake in the LSWT. There were no significant lateral variations in the flow velocities upstream of the ship model based on the simultaneous velocity scan in the LSWT using the 7-hole probe rake, as shown in Fig. 3.6. Furthermore, the mean velocity profiles and turbulence intensity profiles of the simulated ABL were seen to matched well for both the BLWT and LSWT.

Figure 3.7a also shows a comparison of the measurements to a 1/7th-power law and a logarithmic law (log law) model; the log law model was calculated for \( z_0 = 0.0005 \) (Letchford and Zachry, 2009; Holmes, 2001) and is equivalent to a relatively calm sea state with low waves. The thickness of the simulated ABL obtained in the LSWT was \( \delta = 0.76 \) m (30 in), which is about four times the ship height (\( SH \)) and \( SH/\delta = 0.244 \) whereas the thickness of the simulated ABL obtained in the BLWT was \( \delta = 0.26 \) m (10.1 in), which is almost four times the ship height (\( SH \)) and \( SH/\delta = 0.28 \).

For the BLWT, the value of \( U_\delta \) at the edge of the boundary layer as obtained from the hot-wire measurements was 14.8 m s\(^{-1}\) (48.6 ft s\(^{-1}\)). For \( z/\delta \leq 0.28 \) (i.e., up to the ship height) the simulated ABL matched to within ±3% of the power law profile and to within ±8% of the log law profile. Whereas for the LSWT, \( U_\delta \) obtained from both the 7-hole probe and hot-wire measurements was 27.46 m s\(^{-1}\) (90.09 ft s\(^{-1}\)) and 28.35 m s\(^{-1}\) (93 ft s\(^{-1}\)), respectively. For \( z/\delta \leq 0.244 \) (i.e., up to the ship height) the simulated ABL matched to within ±2% of the power law profile and to within ±5% of the log law.
Figure 3.6. Flow velocities simultaneously measured by the four probes of the 7-hole pressure probe rake for the 30.5 m s$^{-1}$ (100 ft s$^{-1}$) case.

Figure 3.7b shows the mean ABL velocity profiles obtained from the present results in both the BLWT and LSWT versus the results of Vidales, Rosenfeld et al., Zan and also Peterka and Cermak, which again are presented as a reference rather than as a basis for comparison (Vidales, 2016; Rosenfeld et al., 2015; Zan and Garry, 1994; Peterka and Cermak, 1974). The more undulating velocity profile obtained by Rosenfeld et al. can be attributed to the signature of an insufficiently mixed flow downstream of the individual Cowdrey rods based on the results shown in the BLWT (Rosenfeld et al., 2015).

Peterka and Cermak simulated an ABL using vertical spires, without and with additional roughness elements (Cases 1 & 2 in Fig. 3.7b, respectively) (Peterka and Cermak, 1974). Spires by themselves (Case 1) tend to simulate an ABL with a velocity profile similar to that obtained with the Cowdrey rods. With the addition of extra
roughness elements on the tunnel floor (Case 2), the effects obviously become much more severe on both the velocity profile and the turbulence, the turbulence intensities being discussed next.

Figure 3.7. Mean velocity profiles of the simulated ABL.
Figure 3.8 shows the corresponding turbulence intensities of the simulated ABL as obtained using HWA in both the BLWT and LSWT. The turbulence in the free-stream measured without the Cowdrey rods was <0.1%. The turbulence intensity profile for the BLWT was smoother as compared to the one obtained in the LSWT. This was because of the longer mixing length downstream of the Cowdrey grid. As expected, the turbulence was found to be higher near the floor of the tunnel compared to the outer free-stream region, which is because of the closer spacing of the Cowdrey rods there.

Notice that the turbulence intensity was relatively modest but realistic for the simulation of an ABL with a relatively low effective roughness height, and is similar to the turbulence distribution obtained by Peterka & Cermak using plain spires (Peterka and Cermak, 1974). Again, it is important to appreciate that all of these results are presented simply as a reference and not as a basis for comparison. It should be noted that Rosenfeld et al. did not make turbulence measurements of their simulated ABL (Rosenfeld et al., 2015). A comparison of these mean velocity and turbulence intensity profiles relative to the other wind tunnel measurements in the form of log scale are shown in Appendix D.

3.2.3 Further Analysis of the Cowdrey Rod Measurements

The time-averaged turbulence spectrum for the simulated ABL in both the BLWT and LSWT was found to follow a $-5/3$ Kolmogorov scaling slope of the energy cascade in the inertial sub-range, as shown in Fig. 3.9. This is an expected outcome for a turbulent boundary layer that is mostly in equilibrium. The energy spectrum from both the wind tunnel compares well, and also both the ABLs contain turbulent motions that span a wide
Figure 3.8. Turbulence intensity profiles of the simulated ABL relative to the other wind tunnel measurements.

It is interesting to note that for the Cowdrey rods then the downstream mixing scales of the flow can be measured in terms of distance and/or time. In terms of distance, then the number of rod diameters traveled by a fluid element is one measure. In terms of time, then the diameter of the rods divided by the flow velocity is another measure. Therefore, a measure of mixing was also calculated in terms of time for both the BLWT and LSWT, as shown below.
Figure 3.9. Energy spectrum for the ABL that was simulated in both the BLWT and LSWT.
The time traveled by a fluid particle in the flow in the BLWT was determined by the
distance traveled in terms of rod diameters, where $d_{BLWT} = 393 \times 0.013 \text{ m} (393 \times 0.5 \text{ in})$
divided by the value of free-stream flow velocity $U_\infty = 15 \text{ m s}^{-1} (49.2 \text{ ft s}^{-1})$, which gives

$$t_{BLWT} = \frac{d_{BLWT}}{U_\infty} = \frac{393 \times 0.013}{15} = 0.34 \text{ s} \quad (3.1)$$

Similarly, the time traveled by a fluid particle in the flow in the LSWT was determined
by the distance traveled in terms of rod diameters for the second grid, where $d_{LSWT} =
100 \times 0.027 \text{ m} (100 \times 1.05 \text{ in})$ divided by the value of free-stream flow velocity $U_\infty =
30.5 \text{ m s}^{-1} (100 \text{ ft s}^{-1})$, which gives

$$t_{LSWT} = \frac{d_{LSWT}}{U_\infty} = \frac{100 \times 0.027}{30.5} = 0.09 \text{ s} \quad (3.2)$$

Notice, that the transit time of the flow particles in the flow was higher for the BLWT
as compared to the LSWT. Therefore, the simulated ABL profile simulated of the BLWT
is smoother and more homogeneous when compared to the one simulated in the LSWT.
However, despite the relatively short mixing length downstream of the second set of
Cowdrey rods of just 100 rod diameters, the results confirmed the efficacy of the dual
Cowdrey rod method, and that the simulated ABL gives reasonably acceptable velocity
gradient and turbulence characteristics of an actual ABL to study the development of the
ship airwake.
### 3.3 Surface Oil Flow Visualization

The surface oil flow technique was used as a qualitative method to identify the topological structures on the aft portion of the ship model, including the funnel, flight deck, and behind the stern of the ship model. Oil was also applied to the floor of the wind tunnel to identify the signature of the airwake well behind the ship. The oil mixture consisted of a low viscosity, clear mineral oil with suspended Titanium Dioxide (TiO\(_2\)). TiO\(_2\), a bright white powder, which gives good contrast on the black surface of the ship model. A slight amount of oleic acid (olive oil) was added to the mixture, which helps to dissolve the TiO\(_2\).

This oil mixture was then applied liberally to the ship model with the wind off. After the wind was turned on, the oil was moved by the effects of the boundary layer surface shear stress, leaving behind streaks of TiO\(_2\) in surface patterns that help identify the signatures of main topological flow patterns. In regions of low surface shear, higher accumulations of oil and TiO\(_2\) tend to develop, which helps in identifying the points of flow separation, separation bubbles, and stagnation points. The resulting patterns can then be photographed under normal lighting conditions. Most of the photos were taken with an SLR camera using various lens combinations.

There are several challenges with the surface oil flow method. The biggest challenge is in determining the best oil mixture, which requires trial and error to find one that is not too viscous or not too fluid, and also contains the optimum concentration of TiO\(_2\). The viscosity of the oil is particularly important for vertical surfaces, where higher fluidity will cause the oil mixture to run off too quickly. Nevertheless, there is always a challenge...
with interpreting the flows on vertical surfaces in that there is some vertical bias to the results because of the effects of gravity. If the oil is too viscous, then the patterns will take a longer time to develop and the results are usually less satisfactory as the oil does not follow the flow as well.

The TiO$_2$ powder must also contain small enough particles that the particles themselves do not alter the boundary layer flow. To this end, cosmetic grade rather than paint grade TiO$_2$ was used, which has much smaller particles and are more easily dissolved. Other challenges with the method include dealing with large regions of flow separation and separation bubbles, where the oil tends to pool and then periodically break away, possibly destroying adjacent flow patterns. In this latter case, the tunnel must be run long enough to reach an equilibrium state, which can take considerable time. However, this latter approach becomes problematic for the situations in which unsteady or bistable flow states exist because the flow never reaches one steady state pattern, and so the final results tend to represent neither one state or the other.

### 3.3.1 Fundamental Airwake Flow Physics

An overview of the flow over the stern of the ship is now presented, mainly for orientation. The purpose of this is to outline the primary flow features from different parts of the ship and to describe how these features combine to produce an airwake. A schematic of the basic flow structures over the ship is shown in Fig. 3.10, which was based on the interpretations obtained from both the flow visualization as well as the PIV.

Overall, the resulting airwake was found to exhibit many of the characteristics of flow over three dimensional rearward-facing steps, as reported by other investigators (Healey,
However, the flow visualization and TR-PIV measurements of the airwake showed that it was substantially more complicated than has hitherto been reported. There was also significant flow separation and recirculation over the stern of the ship, and much turbulence in the downstream wake.

The flow around the funnel resulted in a scarf vortex that extended over the top of the superstructure and well downstream over the deck, as shown in Fig. 3.11. In addition, a standing pair of counterrotating vortices downstream of the funnel along with flow separation on the surface on either side of the funnel was also observed.

Recirculation regions behind the funnel (the first step), the ship deck (the second step) and the flight deck of the ship (the third step) were evident. Notice that the face of a hangar door would typically be located at the upstream edge of the flight deck. The development of two primary standing vortices were also observed on the deck itself. The flow reattached near the center of the mid-deck and was then shed off as counterrotating
(a) Upstream funnel flow.

(b) Downstream funnel flow.

Figure 3.11. Development of the flow around the funnel of the ship.

Figure 3.12. Signature of the arch-shaped flow separation line formed because of the separation zone on the flight deck.

vortices near the edges of the deck. Similar vortex patterns were also seen downstream behind the flight deck at the stern of the ship. The signature of the arched shape
separation line on the hangar door was observed, as shown in Fig. 3.12; this was a result of the large flow separation region seen to develop over the flight deck near the hangar.

An unsteady, bistable movement in the flow reattachment point on the flight deck and also behind the stern of the ship was also observed. However, for 0° yaw case (flow directly onto the bow) it was not possible to get a steady flow pattern because the flow tried to alternate between the two states. Therefore, the flow visualization was performed with ±0.5° yaw (i.e., slight beam winds) to force the flow states to be just one or the other so that the flow patterns reached a steady state to be photographed, the resulting images being shown in Fig. 3.13.

Notice that in both the cases, asymmetric flow differences were observed between the flow recirculation regions on the deck and behind the stern of the ship. For the −0.5° case, the recirculation region was larger on the port side of the flight deck while the recirculation region was larger on the starboard side behind the stern of the ship. Whereas for +0.5° case, the recirculation region was larger on the starboard side on the flight deck while behind the stern of the ship it was higher on the port side. Furthermore, it was also observed that with 0° case (wind directly down the deck), the flow tried to alternate from one state to the other but stayed mostly at the state obtained for the +0.5° case.

Along with the appearance of bistable recirculation region on the flight deck, other complex flow structures were also observed, as shown in Fig. 3.14. The flow over the stern of the ship combines with the trailing flow from the side to form a recirculation region behind the stern of the ship, which also showed some evidence of a bistable flow state. Downstream of the recirculation region, there appeared to be a saddle point beyond which the flow diverges. The analysis of downstream airwake is important because of the
Figure 3.13. Development of the flow over the flight deck region at ±0.5° beam wind angles.

potential effects on approaching aircraft, a behavior also noted in the PIV measurements (discussed later).

3.4 Flow Measurements in the BLWT

“Snap-shot” (i.e., not time-resolved) PIV measurements and HWA measurements were performed on the 1:235 scale SFS2 ship model in the BLWT. PIV measurements
were made in the streamwise centerline plane, and HWA measurements were made at various selected points over the flight deck.

Figure 3.15 shows contour plots of the time-averaged streamwise and wall-normal velocities in the centerline plane. The three recirculation regions behind the funnel, on the flight deck and behind the stern of the ship are now evident in these PIV measurements. Moving outward from the hangar to the rear edge of the ship the recirculation region decreased in size and reattachment moved closer to the superstructure. Similar trends were seen behind the funnel and stern of the ship. The recirculation region on the flight deck was about 75% of the flight deck length. A turbulent free-shear layer was seen to overlay this flow recirculation region on the flight deck, which originated mostly from the flow structures shed off the funnel.

Figure 3.16 shows contour plots of the streamwise and wall-normal turbulence intensities in the centerline plane. The turbulence intensity fluctuations were about 10% in
the near the near-wall region of the funnel, which is consistent with the results obtained from the hot-wire measurements, which are shown later in Section 3.7. Figure 3.17 showed that the TKE were higher in the near-wall regions of the flight deck, especially in the region $x/SH = 1–2$. This outcome was observed because of the shedding of vortices and turbulence from the funnel and upstream superstructure of the ship model. Lower levels of TKE were observed when moving away from the flight deck.

![Contour plots showing time-averaged streamwise and wall-normal velocities in the centerline plane.](image)

Figure 3.15. Contour plots showing time-averaged streamwise and wall-normal velocities in the centerline plane.

Although the results from “snap-shot” PIV do not provide a temporal evolution of the flow structures, they were still able to provide a basic understanding of the flow physics of the airwake. In addition to this, the preliminary measurements in the BLWT were also
helpful in resolving many of the issues related to making PIV measurements, such as setting up cameras for capturing larger fields of view, focusing issues, alignment of lasers, seeding, and dealing with surface reflections. These issues were better understood and resolved before the TR-PIV measurements were performed in LSWT, in part because of the better options for the positioning of lasers and cameras.

3.4.1 Velocity Profiles on the Deck in the BLWT

Figure 3.18 compares the mean velocity profiles $\bar{u}$ measured using HWA (1:235 scale SFS2, $Re = 0.6$ million, $U_\infty = 15$ m s$^{-1}$/49.2 ft s$^{-1}$) in the BLWT with the Rosenfeld et al. (1:50 scale SFS2, $Re = 2.9$ million, $U_\infty = 15.43$ m s$^{-1}$/50.62 ft s$^{-1}$). Rosenfeld et
al. used 5-hole pressure probes to make measurements at four locations (A–D) near the center of the flight deck at $x/SH = 1.84$, and four locations (E–H) near the trailing edge of the deck at $x/SH = 2.53$ (Rosenfeld et al., 2015). All the profiles shown in Figs. 3.18 were normalized by ship height $SH$ in the $z$-axis and by free-stream velocity $U_\infty$ in the $x$-axis. It should be noted that the surface of the flight deck corresponds to a normalized value of $z/SH = 0.273$, where the height of the 1:235 scale ship model is $SH = 71.4$ mm (2.81 in).

The results show that the trends are same, but the magnitudes shown in Rosenfeld et al.’s data were up to 20% higher than the HWA measurements, except for profile D and C. Such offsets are known artifacts of measuring highly unsteady and/or separated flows with
a pressure probe (Bennett, 1976), and so quantitative comparisons must be made with caution. The velocity profiles were generally mirror-symmetric with respect to the centerline for profiles E–H in both the HWA and probe measurements. However, the mid-deck profiles A–D showed the largest deviations with respect to the other profile locations were observed for both Rosenfeld and BLWT data because of their closer proximity to the recirculation region. The results showed that within regions $z/SH < 0.5$, the flow velocities were up to 80% of the free-stream velocity, with the exception of profiles A, E and H.
3.5 Effects of ABL

Simulating an ABL is an essential part of understanding the flow over the deck and resulting airwake of the ship. With the previously published experimental and CFD results (Healey, 1992; Polsky, 2003; Zan and Garry, 1994) it was clear that the ABL is important in terms of its effect on the airwake. However, some measurements were performed with and without ABL flow in the LSWT to study how the ABL affected the airwake. In this regard, TR-PIV results on the centerline plane of the flight deck region and stereo TR-PIV results on the flight deck edge of the 1:90 scaled SFS2 model to study the effects of ABL on the ship airwake.

Figures 3.19 and 3.20 show the flow in a centerline streamwise plane over the flight deck with a uniform upstream flow and with the ABL, the former being performed without the Cowdrey rods installed. They show the time-averaged flow velocities and turbulence intensities ensemble averaged over 5,000 PIV realizations, respectively. In Fig. 3.19a, which is with the uniform flow, the results showed a well-defined shear layer with relatively high flow velocities in the near-wall regions of the flight deck. However, with the ABL present the results shown in Fig. 3.20 suggest slightly lower flow velocities and also with a somewhat more diffused shear layer. This behavior occurs, at least in part, because of the lower flow velocities in the simulated ABL, as well as the additional turbulence introduced into the incoming flow. The results in Fig. 3.20 suggested that the turbulence intensities in both the streamwise and wall-normal direction were up to 10% lower with the ABL when compared to those with the uniform flow, especially in the near-wall regions of the flight deck.
(a) Time-averaged streamwise velocities, with and without the effects of the ABL.

(b) Time-averaged wall-normal velocities, with and without the effects of the ABL.

Figure 3.19. Time-averaged streamwise and wall-normal velocities over the flight deck, with and without the effects of the ABL.

Figures 3.21 and 3.22 show the flow in the Crossplane 1 with a uniform upstream flow and also with the ABL, the former being performed without the Cowdrey rods installed. They show the time-averaged flow velocities and turbulence intensities ensemble averaged over 5,000 PIV realizations for Crossplane 1, respectively. Figure 3.21c shows well-defined shear layer for the flow velocities in the wall-normal direction with ABL. Figure 3.21 shows that with the ABL, lower flow velocities were observed in streamwise, spanwise and wall-normal directions in the near-wall regions above the hangar, which were similar to the results obtained in the centerline longitudinal plane Fig 3.19. This
behavior occurs because of the lower flow velocities in the simulated ABL, as well as the additional turbulence introduced into the incoming flow. Figure 3.22 also suggested that the turbulence intensities in all the streamwise, spanwise and wall-normal direction were up to 15% lower with the ABL when compared to those with the uniform flow, especially above the hangar.

Two-dimensional mean velocity magnitude and turbulence intensity profiles were extracted from the above centerline plane TR-PIV measurements at the center of the flight deck at $x/SH = 1.84$, and near the trailing edge of the deck at $x/SH = 2.53$. Figures 3.23
(a) Time-averaged streamwise velocities, with and without the effects of the ABL.

(b) Time-averaged spanwise velocities, with and without the effects of the ABL.

(c) Time-averaged wall-normal velocities, with and without the effects of the ABL.

Figure 3.21. Time-averaged streamwise, spanwise and wall-normal velocities over the flight deck at Crossplane 1, with and without the effects of the ABL.

and 3.24 compare the mean velocity and turbulence intensity profiles at two locations for
(a) Streamwise turbulence intensities, with and without the effects of the ABL.

(b) Spanwise turbulence intensities, with and without the effects of the ABL.

(c) Wall-normal turbulence intensities, with and without the effects of the ABL.

Figure 3.22. Streamwise, spanwise and wall-normal turbulence intensities over the flight deck, with and without the effects of the ABL.
with and without the effects of ABL in the streamwise direction, where the mean velocity was calculated using

\[ U = \sqrt{u^2 + w^2} \]  

(3.3)

and the turbulence intensity was calculated using

\[ U'_{\text{rms}} = \sqrt{U'_i^2} \]  

(3.4)

where \( U = \sqrt{u^2 + w^2} \) and the prime represents the fluctuating part of the flow velocity.

All the profiles shown in Figs. 3.23 and 3.23 were normalized by ship height \( SH \) in the \( z \)-axis and by free-stream velocity \( U_\infty \) in the \( x \)-axis. It should be noted that the surface of the flight deck corresponds to a normalized value of \( z/SH = 0.273 \), where the height of the 1:90 scale ship model is \( SH = 186.26 \text{ mm} \) (7.33 in).

The results showed similar trends in terms of both the mean velocity profiles and turbulence intensity profiles for both with and without ABL flow, but the magnitudes for both the velocity magnitude and turbulence intensity profiles without ABL were up to 20% higher than with ABL. In addition, below \( z/SH = 0.6 \) the turbulence intensities were much higher at \( x/SH = 1.84 \) because of the close proximity to the recirculating flow region.

Overall, the results measured with and without the ABL in both the streamwise and crossplanes showed that the effects of the ABL were important in determining the details of the flow over the deck, but the flows were still qualitatively very similar. Indeed, the results with and without the ABL suggested that the ship shape itself was responsible for producing most of the turbulence over the deck and the effects of the upstream turbulence
in the ABL itself were somewhat secondary. Therefore, results from the flow measurements in the LSWT are now presented as obtained with the simulated ABL.

3.6 Flow Measurements in the LSWT

The bulk of the measurements made in the present research were obtained using Time-Resolved PIV (TR-PIV) in the LSWT. The TR-PIV used a dual-head, Nd:YLF high-speed, diode-pumped, solid-state laser with an energy of 30 mJ/pulse at a wavelength of 527 nm. Cylindrical lenses were used to spread the laser beam into a planar sheet, which then illuminated the seed particles in the desired field of view within the test
Figure 3.24. Comparison of normalized turbulence intensity profiles \( U'_{\text{rms}} / U_\infty \) at locations \( x/SH = 1.84 \) and \( x/SH = 2.53 \) for the centerline plane, with and without effects of the ABL.

section. The necessary fields of view were covered by using two, 4 Mpx CMOS cameras with 2560-by-1600 px arrays.

### 3.6.1 Streamwise TR-PIV Measurements in the LSWT

For the streamwise planes, the overall FOV over the ship deck and its immediate wake was 53.34 cm (21 in) long in the streamwise direction and 10.16 cm (4 in) high in the wall-normal direction, giving a spatial resolution of approximately 0.1 mm (0.004 inches) per pixel for the streamwise planes. Camera 1 was used to capture the rear of the superstructure, the funnel and the flight deck, with Camera 2 being used to capture the flight deck and the downstream wake.
Figure 3.25 details the velocity field at the centerline plane in the streamwise directions for four consecutive instantaneous PIV realizations. The three flow recirculation regions are now eminent clear, which are behind the funnel, the flight deck, and off the stern of the ship. In particular, the results show the development of the previously noted large flow recirculation region (i.e., a separation bubble) over most of the flight deck behind the hangar. However, the TR-PIV showed that the actual size of this bubble was rather dynamic in that the points of reattachment varied somewhat. The flight deck was overlaid with a constant stream of fairly large-scale turbulent eddies, much of which seemed to originate from the funnel and upstream superstructure of the ship.

While the foregoing instantaneous PIV realizations show the inherent unsteadiness of the airwake problem, their value can be enhanced after further analysis, such as time-averaged velocities, turbulence intensities, Reynolds shear stress and turbulent...
kinetic energy in both streamwise and wall-normal direction. These analysis will enable to understand and visualize the important structures that are developed over time on the stern of the ship, especially on the flight deck.

Figures 3.26 and 3.27 show contour plots of the time-averaged streamwise and wall-normal flow velocities. The mean flow values clearly showed the formation of the previously noted flow recirculation regions behind the superstructure, the flight deck, and downstream behind the stern of the ship. Moving outwards towards the lateral edges of the ship, the recirculation regions were seen to decrease in size. Also, the recirculation zone was noted to be fairly symmetric on the port and starboard sides, at least in a time-averaged sense. Notice that the velocity deficit created by the superstructure extended well above the height of the superstructure ($z/SH = 0.6$).

At the centerline of the ship, the flow was found to separate at the top edge of the hangar and then extended downwards, reattaching at about $x/SH = 2$. Notice from Fig. 3.26 that the recirculation regions extended almost the 75% of the length of the flight deck. A turbulent free-shear layer was seen to overlay this flow recirculation region on the deck, which originated mostly from the funnel. The instantaneous velocity field showed that the overall flow was not only unsteady but also somewhat bistable, i.e., in the time-resolved PIV measurements the flow reattachment point, for example, was not fixed and its location aperiodically jumped from one stable location to another, i.e., a bistable behavior also seen in the flow visualization as shown in Fig. 3.13. The bistable behavior was present on both the flight deck as well as behind the stern of the ship; in this case the bubble on one side seemed to grow in length and burst and then repeat on the other side.
Moving outward from the centerline of the ship, as shown in Fig. 3.26, this recirculation region decreased in size and the reattachment point moved closer to the hangar.

Figure 3.26. Contours of the time-averaged streamwise flow velocities in the longitudinal planes.

Figure 3.27. Contours of the time-averaged wall-normal flow velocities in the longitudinal planes.
The turbulence intensities were higher in the near-wall regions of the flight deck, as shown in Figs. 3.28 and 3.29. The wall-normal turbulence intensity was about 15% of the free-stream velocity in the centerline plane. Moving outward toward the lateral sides of the ship, the turbulence intensity region decreased in size and moved closer to the hangar. The centerline plane showed the highest levels of turbulent kinetic energy (TKE), as shown in Fig. 3.31, which was calculated using

\[ k = \frac{1}{2} (u'^2 + w'^2) \]  

(3.5)

This outcome occurs mainly because of the higher turbulence produced by the funnel and upstream superstructure of the ship, as shown in Figs. 3.30 and 3.31. The other measurement planes were laterally offset from the funnel and superstructure and, therefore, were further outside of the flow recirculation region. The results in Planes 1 and 4 were seen to contain significantly lower levels of TKE. But the TKE was higher in the near-wall region of the flight deck, especially in the region \( x/SH = 1–2 \), which was consistent with the results of shown by Sydney et al. using the SFS2 ship model (Sydney et al., 2016). Lower levels of TKE were generally obtained when moving out of the direct downstream wake of the funnel.

### 3.6.2 Stereo TR-PIV Crossplane Measurements in the LSWT

For the crossplane PIV measurements, two, 4 Mpx CMOS cameras were again used to capture the FOV. The three-dimensional displacement field was constructed from the two projected, planar displacement fields. The combination of both camera projections were used to obtain reconstruction of the two-dimensional, three-component particle
Figure 3.28. Contours of the streamwise turbulence intensities in the longitudinal planes.

Figure 3.29. Contours of the wall-normal turbulence intensities in the longitudinal planes.

displacement inside the required FOV. The two cameras used 200 mm lenses with an
Figure 3.30. Contours of the Reynolds shear stress in the longitudinal planes.

Figure 3.31. Contours of the turbulent kinetic energy (TKE) in the longitudinal planes.

f-stop of 4, again with Scheimpflug mounts, giving a net FOV of 19.05-by-10.16 cm (7.5-by-4 in).
Figure 3.32 shows examples of the crossplane flow velocities for four consecutive instantaneous PIV realizations. There were many challenges in obtaining these measurements, including the rapid out of plane movement of the seed particles through the light sheet. Nevertheless, measurements were made possible in stereo mode, partially by using a thicker laser sheet.

These instantaneous realizations showed the convection of large-scale turbulent eddies at about one ship height over the flight deck. On one hand, above $z/SH > 0.6$ the development of larger scale turbulence eddies were observed, much of which seemed to originate from the funnel and upstream superstructure of the ship. On the other hand, much smaller scale turbulent eddies were observed in the near-wall regions of the flight deck. The flow in the crossplanes was confirmed to be highly unsteady, with irregular bursts of turbulence being shed into the flow, as suggested in the streamwise measurements. A further analysis such as time-averaged velocities, turbulence intensities, Reynolds shear stress and turbulent kinetic energy in both streamwise and wall-normal direction of these instantaneous PIV realizations better brings out the key structures in this crossplane flow.

The time-averaged velocities in the streamwise and wall-normal directions were lower in the near-wall regions of the flight deck at all crossplanes, and were also seen to increase in magnitude when moving outward, as shown in Figs. 3.33 and 3.35. Figure 3.34 shows oscillating features of the mean velocity in the spanwise direction in all of the crossplanes. Again, this outcome was the signature produced mostly because of the shedding of vortices and turbulence from the funnel, as well as the other unsteady flow features produced by the upstream superstructure of the ship.
Figure 3.32. Plots showing four consecutive instantaneous flow realizations in Crossplane 2. Background contours are in terms of velocity magnitude $U = \sqrt{u^2 + v^2 + w^2}$.

The turbulence intensities among the streamwise, spanwise and wall-normal directions were found to be higher near the centerline for all of the crossplanes, and were seen to decrease in magnitude when moving outward, as shown in Figs. 3.36–3.38. Turbulence intensities in Crossplanes 1–3 were up to 8% of the free-stream velocities in both the spanwise and wall-normal directions, and up to about 12% in the streamwise direction, as shown in Figs. 3.36–3.38. However, an asymmetry in the turbulence levels were observed across the flight deck, especially in the streamwise and wall-normal
Figure 3.33. Contours of the time-averaged streamwise flow velocities in the crossplanes.

directions for both Crossplanes 1 and 3, as shown in Figs. 3.36 and 3.38. Interestingly, the turbulence was seen to be notably higher on the port side when compared to the starboard side shown in Crossplane 1, whereas in Crossplane 3 the turbulence was higher on the starboard side, as shown in Figs. 3.36–3.38. This behavior seems to occur because the flow tried flip-flopping in the bistable state over the flight deck.

Figures 3.39–3.40 show the three components of Reynolds shear stress in the crossplanes; the red and blue regions of the contours indicate turbulent shear stresses in opposite directions. It can be seen for all planes and for all three components of Reynolds shear stress that their magnitudes were symmetric about z-direction. The $u'v'$ and $v'w'$ stresses were higher in the wake of the funnel at Crossplane 1 when compared to the measurements in the other planes, as shown in Figs. 3.39 and 3.41. The $u'w'$ stresses were found to be relatively constant and did not vary in the crossplanes, as shown in Fig. 3.40.
Figure 3.34. Contours of the time-averaged spanwise flow velocities in the crossplanes.

Figure 3.35. Contours of the time-averaged wall-normal flow velocities in the crossplanes.
The contribution of the scarf vortices from the funnel, superstructure and flight deck led to higher TKE levels in the near-wall regions of the flight deck, as shown in Fig. 3.42.
Notice that for these measurements then the TKE levels were calculated using all three velocity components, i.e.,

\[ k = \frac{1}{2} (u'u' + v'v' + w'w') \]  

These results from the TR-PIV measurements in the all the longitudinal planes and stereo TR-PIV measurements in the crossplanes conducted in the LSWT shed light on the development on the ship airwake. The time-averaged velocities showed symmetry across all the planes. However, asymmetry was observed in the turbulence intensities across all the streamwise and crossplanes. The existence of bistable movement on the flight deck were also observed in the flow over the flight deck. It may also be taken into consideration that if the amplitudes and frequencies involved in these random flip-flopping states can lead to hazardous launches and recoveries of helicopters on ships. A helicopter approaching the flight deck of the ship for landing generates a rotor
Figure 3.39. Contours of the $u'v'$ shear stress in the crossplanes.

downwash flow field, which is influenced by the unsteady ship airwake. As the helicopter operates in these complex unfavourable asymmetric perturbations, it may lead to higher induced pilot workload, a behavior observed from previous at sea-trial testings. For this
reason, the velocity amplitudes as well as the frequency of these complex unsteady aerodynamic perturbations are particularly of interest for the launch and recovery issue.
In this regard, further analysis was performed on the data obtained from these measurements in order to identify the energy level and frequency content in the airwake, which is discussed in section 3.8.

3.7 Reynolds Number Effects

This section compares the results obtained from PIV measurements in both the BLWT and the LSWT at a Reynolds number of 0.6 million and 6.2 million, respectively. The results were ensemble averaged over 1,000 PIV realizations in the centerline plane for both the “snap-shot” PIV and TR-PIV. Figures 3.43 show contour plots of the time-averaged streamwise and wall-normal flow velocities for both cases. The flow features in the streamwise PIV measurements showed very good agreement, suggesting little Reynolds number dependency at least for this component of the flow. The reattachment points and sizes of the separated flow regions behind the funnel, behind the superstructure, and also behind the stern of the ship were nearly identical for both Reynolds number cases.

Figure 3.44 shows contour plots of the streamwise and wall-normal turbulence intensities in the streamwise centerline plane. The turbulence intensities were found to be higher along the entire length of the flight deck in both the streamwise and wall-normal direction for $Re = 6.2$ million when compared to the results for $Re = 0.6$ million. The shear layer also covered the entire landing zone on the flight deck for the higher Reynolds number case. This might be because of the higher vortices shedding from the funnel and superstructure, as shown in Fig. 3.45a. Furthermore, the TKE levels were also found to be higher in the near-wall regions along the length of the flight deck for 6.2 million case.
when compared to the 0.6 million case, as shown in Fig. 3.45b. This outcome most likely can be associated with the Reynolds number effects.

Figure 3.43. Contour plots showing the time-averaged streamwise and wall-normal velocities in the streamwise centerline plane for a $Re$ of 0.6 million and 6.2 million.

Two-dimensional mean velocity magnitude and turbulence intensity profiles were extracted from the above “snap-shot” PIV and TR-PIV measurements at the center of the flight deck at $x/SH = 1.84$, and near the trailing edge of the deck at $x/SH = 2.53$.

Figures 3.46 and 3.47 compare the mean velocity and turbulence intensity profiles at two locations for with and without the effects of ABL in the streamwise direction, where the mean velocity was calculated using

$$\overline{U} = \sqrt{\overline{u}^2 + \overline{w}^2}$$  \hspace{1cm} (3.7)

and the turbulence intensity was calculated using
(a) Streamwise turbulence intensities.

(b) Wall-normal turbulence intensities.

Figure 3.44. Contour plots showing streamwise and wall-normal turbulence intensities in the streamwise centerline plane for a $Re$ of 0.6 million and 6.2 million.

(a) Reynolds Shear Stress.

(b) Turbulence kinetic energy.

Figure 3.45. Contour plots showing Reynolds shear stress and TKE in the streamwise centerline plane for a $Re$ of 0.6 million and 6.2 million.
\[ U'_{\text{rms}} = \sqrt{U'_i^2} \]  

(3.8)

where \( U = \sqrt{u^2 + w^2} \) and the prime represents the fluctuating part of the flow velocity.

All the profiles shown in Figs. 3.46 and 3.49 were normalized by ship height \( SH \) in the \( z \)-axis and by free-stream velocity \( U_\infty \) in the \( x \)-axis. It should be noted that the surface of the flight deck corresponds to a normalized value of \( z/SH = 0.273 \), where the height of the 1:90 and 1:235 scale ship models are \( SH = 186.26 \) mm (7.33 in) and \( SH = 71.4 \) mm (2.81 in), respectively. The mean velocities almost showed no sensitivity to the Reynolds number. However, the turbulence intensities showed some variation to the Reynolds number.

Further two-dimensional mean velocity and turbulence intensity profiles were extracted from the above TR-PIV measurements at four locations (A–D) near the center of the flight deck at \( x/SH = 1.84 \), and four locations (E–H) near the trailing edge of the deck at \( x/SH = 2.53 \), as previously shown in Fig. 2.13; a reminder that for consistency these are the same locations previously used by Rosenfeld et al. using 5-hole probe measurements (Rosenfeld et al., 2015). Figures 3.48 and 3.49 compare the mean velocity and turbulence intensity profiles at locations A–D and E–H for a \( Re \) of 6.2 million obtained from the TR-PIV measurements and \( Re \) of 0.6 million obtained from the HWA measurements.

The mean velocity was denoted by \( \bar{u} \) and the turbulence intensity was obtained using

\[ u'_{\text{rms}} = \sqrt{u'_i^2} \]  

(3.9)
where the prime represents the fluctuating part of the streamwise flow velocity. On one hand, the mean velocity profiles showed clear variations with distance from the deck but did not show much sensitivity to Reynolds number, as shown in Fig. 3.48. On the other hand, the turbulence intensity profiles, as shown in Fig. 3.49, indicated somewhat greater sensitivity to Reynolds number, the profiles also showing higher variations in the turbulence when moving away from the deck. However, above $z/SH = 0.6$, turbulence variations significantly reduced among both the cases. Higher overall levels of turbulence were observed near the mid-deck at locations A–D when compared to those downstream at E–H, which were between 9–12% of the free-stream velocity because of the close
Figure 3.47. Comparison of the normalized turbulence intensity profiles ($U_{\text{rms}}/U_\infty$) at $x/SH = 1.84$ and $x/SH = 2.53$ for the centerline plane for a $Re$ of 0.6 million and 6.2 million.
proximity to the recirculation regions. However, a sudden increase in the turbulence intensity of up to 18% was observed at location D, below $z/SH < 0.4$.

Figure 3.48. Comparison of the normalized mean velocity profiles ($\bar{u}/U_\infty$) at the prescribed flight deck locations for a $Re$ of 0.6 million and 6.2 million.

It is significant to note that the results compared were from the measurements made in two separate wind tunnels namely, BLWT and LSWT with two different type of measurements. Although, the turbulence intensity profiles showed some sensitivity to Reynolds number, specially near the mid-deck region, it was clear that the ship airwake is mostly independent of Reynolds number, especially above Reynolds numbers of near $10^6$. Similar suggestions regarding the effects of Reynolds number have been made by other
Figure 3.49. Comparison of the turbulence intensity profiles \(\frac{u'_{rms}}{U_{\infty}}\) at the prescribed flight deck locations for a \(Re\) of 0.6 million and 6.2 million.
studies performed by Zan and Healey but never confirmed (Zan and Garry, 1994; Healey, 1992).

3.8 Energy Spectrum Analysis of the Airwake

It is known that airwake flow frequencies below 2 Hz generally have the most significant impact on the workload of a pilot landing a helicopter on a ship (Wilkinson et al., 2001). This is a consequence of low frequency aerodynamic perturbations at the rotor blades causing large amounts of blade flapping and disk tilt. Therefore, a frequency scaling is necessary to understand how the frequencies observed in a sub-scale test can be directly related to the unsteady aerodynamic effects in the ship airwake over the desired full-scale bandwidth (Lee and Zan, 2002).

To this end, a Strouhal number can be defined as

\[ St = \frac{f \, SH}{U_{\infty}} \]  

where the characteristic length is the ship height \( SH \) and the flow velocity is the free-stream velocity \( U_{\infty} \). The frequency scaling as suggested by Lee and Zan is given by (Lee and Zan, 2002)

\[
\left( \frac{f_{fs}}{f_{ms}} \right) \left( \frac{L_{fs}}{L_{ms}} \right) \left( \frac{U_{ms}}{U_{fs}} \right) = 1 \]  

where the subscript \( fs \) and \( ms \) refer to the full-scale and the model-scale respectively. A geometric scaling \( (L_{ms}/L_{fs}) = 1/90 \) was fixed by the present ship model. The scaling of \( (U_{fs}/U_{ms}) = 10/30.5 \) was governed by the test conditions and the sailing speed of typical
Figure 3.50. Energy spectrum at two locations above the flight deck, namely Location A \((x/SH = 2.53, z/SH = 0.58)\) and Location B \((x/SH = 2.25, z/SH = 0.45)\).

A frigate of about 19 knots or 10 m s\(^{-1}\) (32.8 ft s\(^{-1}\)) Therefore, Eq. 3.11 yields a frequency scaling of \(f_{fs}/f_{ms} = 0.0036\).
A Fourier analysis was used to calculate the energy spectrum across the entire FOV in the longitudinal measurement planes. The maximum resolvable frequency was half of the sampling frequency \( f_{\text{max}} = f_s/2 = f_N/2 \); the limiting Nyquist frequency was 250 Hz in this case. The resolution was determined by the duration of the data set \( \Delta f_s = f_{\text{max}}/N = 0.1 \) Hz, where the maximum frequency was \( f_{\text{max}} = 500 \) Hz and the number of data points \( N = 5,000 \). A representation of the energy spectrum at both Locations A and B are shown in Fig. 3.50.

![Figure 3.50. A representation of the energy spectrum at both Locations A and B.](image)

The flow frequencies were found to be notably higher in the wall-normal direction compared to the streamwise (longitudinal) direction, as shown in Figs. 3.51 and 3.52, which are represented in terms of Strouhal number. The frequencies were higher in the regions where the shear layer was clearly developed, which is behind the funnel and above the superstructure and flight deck.

![Figure 3.51. Contours showing the flow frequencies in the streamwise direction in the longitudinal planes.](image)
Figure 3.52. Contours showing the flow frequencies in the wall-normal direction in the longitudinal planes.

For the crossplanes, the flow frequencies were also found to be notably higher in the wall-normal and spanwise direction compared to the streamwise direction in the near-wall region of the flight deck, as shown in Figs 3.53–3.55, which are represented in terms of Strouhal number. The frequencies were higher in the wall-normal direction, especially in the near-wall region of the flight deck centerline, $y/SH = 0$ because of the shedding from the funnel and upstream superstructure. In addition, higher frequencies were found in the spanwise direction over the complete extent of the flight deck.

The frequencies near the flight deck were found to be in the range up to 50 Hz ($St$ up to 0.3) and up to 100 Hz ($St$ up to 0.6) in the streamwise and wall-normal directions, respectively. However, above $z/SH = 0.8$, frequencies were found to be in the lower range of below 30 Hz ($St$ up to 0.2). It is significant to note again that these aerodynamic perturbation frequencies both in the longitudinal and crossplanes span the blade flap
Figure 3.53. Contours showing the flow frequencies in the streamwise direction in the crossplanes.

frequencies of a typical helicopter rotor in that they will cause the rotor disk to tilt (Bridges et al., 2007).

Quon and Smith showed a shedding frequency of about 7.8 Hz in both the streamwise and wall-normal directions (Quon and Smith, 2015). In addition, a spectral analysis of flow measurements over a flight deck by Healey reported a frequency range of 1–10 Hz in all the streamwise, wall-normal and spanwise directions (Healey, 1992). The spectral analysis by Zan revealed that most of the turbulent energy was in the range 0.1–2 Hz in both the streamwise and wall-normal directions (Zan and Garry, 1994). However, the frequency range could be lower in Zan’s case because of the simpler ship geometry. But the bottom line is that it is the turbulent eddies related to these low-frequency ranges that directly affects aircraft response and piloting reactions in the airwake, as alluded to previously.
Figure 3.54. Contours showing the flow frequencies in the spanwise direction in the crossplanes.

Figure 3.55. Contours showing the flow frequencies in the wall-normal direction for the crossplanes.
3.9 Two-Point Correlation of the Airwake

A two-point correlation method was used to calculate time-averaged estimate of the flow structures at specific reference locations in the airwake; the coherent structures can be determined by performing two-point correlation of the fluctuating velocities $u'$ and $w'$. The two-point correlation also allows the determination of the length scales associated with the coherent turbulent structures in the flow. The two-point correlation is defined as (Gnanamanickam et al., 2020)

$$R_{ik}(\Delta x, z; x_r, z_r) = \frac{\overline{u_i(x_r + \Delta x, z_r) u_k(x_r + \Delta x, z)}}{\sigma_i(z_r) \sigma_k(z)} \quad (3.12)$$

where $u_i$ and $u_k$ are the $i$-th and $k$-th fluctuating velocity component respectively, $\Delta x$ the spatial separation in the streamwise direction, $z_r$ is the wall-normal reference location and $x_r$ is the reference streamwise location. The normalization factors are

$$\sigma^2_i(z_r) = \overline{u_i^2(x_r + \Delta x, z_r)} \quad \text{and} \quad \sigma^2_k(z) = \overline{u_k^2(x_r + \Delta x, z)}; \quad \text{the overline indicates a time-average.}$$

Figure 3.56 shows two points of interest near the flight deck. Figure 3.57 and 3.58 shows the contour plots $R_{uu}$ and $R_{ww}$ for the normalized two-point correlation function for both the streamwise and wall-normal fluctuating velocities at Location A ($x/SH = 2.53$, $z/SH = 0.58$) and Location B ($x/SH = 2.25$, $z/SH = 0.45$), which are both at the centerline plane. Notice that the positive and negative regions are indicative of the spatial and temporal motion of the flow. The size of the correlated motions at Location A were larger compared to Location B. The correlated flow motions for both $R_{uu}$ and $R_{ww}$ at Location B were flattened by the presence of the flight deck.
The values of $R_{uu}$ showed large region containing coherent structures with positive correlation values near the flight deck and the correlated motions decreased when moving away from the flight deck. The flow structures were also more uniform across $R_{uu}$ at both Locations A and B, which was indicative of a higher streamwise uniform flow. This outcome was also indicative of only limited variations in the spanwise direction. However, the contours of $R_{ww}$ still suggested significant correlated motions toward or away from the flight deck. This latter observation suggests that a landing aircraft will likely be subjected to large-scale motions in the streamwise direction as it approaches the flight deck. There were also significant changes in the scale of the correlated values in the wall-normal direction $R_{ww}$.

Overall, the two-point correlation analysis suggested that these correlated structures were large-scale structures having low frequency content. The regions behind the hangar clearly showed higher shedding frequencies, which results in a reduction of the length scale of all coherent structures. Overall, these foregoing results help to explain the production of the intense zones of unsteady upwash/downwash that are known, from practical flight operations, to exist over the flight deck.

![Figure 3.56. Locations of interest for the two-point correlation at the centerline plane.](image-url)
3.10 Proper Orthogonal Decomposition (POD)

POD is a powerful mathematical technique used to extract energetically and dynamically important features of non-homogeneous turbulent flows (Wang et al., 2019; Tinney et al., 2019). The spatial features of the flows are accompanied by characteristic values, which are represented either based on kinetic energy levels or their growth rates and frequencies (Chen et al., 2012; Singh et al., 2018; Taira et al., 2017).
3.10.1 Mathematical Model of POD

POD decomposes a complicated high dimensional system into a finite number of basis functions or modes that are empirically based on maximizing their energy content. The POD was originally proposed to the turbulence community by Lumley. POD was used in the present work to extract the physically important modes from the PIV measurements to better understand the complex three-dimensional, spatially turbulent structures exhibited in the airwake (Lumley, 1967, 2007).
The POD analysis (Meyer et al., 2007) was applied to two-dimensional instantaneous velocity fluctuations, for each instantaneous measurement is given as

$$u'(x, z) = u(x, z) - \bar{u}(x, z) \quad (3.13)$$

where $x, z$ are the indices of the measurement grid in the centerline longitudinal PIV measurement plane. All the fluctuating component from $M$ snapshots are arranged in the matrix $U$ as

$$U = [u'_1, u'_2, \ldots, u'_M] \quad (3.14)$$

The velocity fluctuations are decomposed into orthonormal basis functions or modes $\phi_j$, where $j = 1, \ldots, M$, by solving an eigenvalue problem ($\tilde{C}A_j = \lambda_jA_j$) of the auto covariance matrix ($\tilde{C} = U^TU$). The resulting eigenvalues $\lambda_j$ represent the relative fluctuating kinetic energy and are arranged in descending order, $\lambda_1 > \lambda_2 > \ldots > \lambda_M = 0$. The POD modes $\phi_j$ are then constructed using the eigenvectors $A_j$, which are given by

$$\phi_j = \frac{\sum_{j=1}^{M} A_j u'_j}{\| \sum_{j=1}^{M} A_j u'_j \|} \quad (3.15)$$

The dynamics and temporal evolution of the modes is given by the temporal coefficients $a_j$, which are calculated by projecting the fluctuating component of the velocity to the modes $[\Phi = \phi_1, \phi_2, \ldots, \phi_M]$, i.e.,

$$a_j(t) = u'(x, t)\phi_j(x) \quad (3.16)$$
Finally, POD produces a linear basis set consisting of $M$ basis functions $\phi_j$ and corresponding coefficient $a_j$, that is used to reconstruct velocity distributions using

$$u(x,t) = \bar{u} + \sum_{j=1}^{M} a_j(t) \phi_j(x)$$  \hspace{1cm} (3.17)

where $j$ is the mode index and the total number of modes being equal to the total number of snapshots, i.e., $M$.

### 3.10.2 POD Analysis of the Airwake

Figures 3.59 and 3.60 show the eigenvalues as a function of mode number and also the energy content of the first 100 modes, respectively. The eigenvalues decay slowly and hence, give no indication of low-rank behavior. It was also observed that the leading mode contains the highest energy and the energy decreases with the increase in the mode number. Furthermore, all of the modes contain contributions from a wide range of frequencies, i.e., each mode represents the behavior at many different time scales.

Figures 3.61 and 3.62 show contour plots with the first 8 POD modes of both the streamwise and wall-normal fluctuating velocities at the centerline plane of the airwake. The modal shapes showed the presence of large-scale oscillating structures in the flow; notice that the number of oscillations in the sign of the modes increases with an increase in the mode number.

Mode 1 resembles the ensemble time-average of the velocity in both the streamwise and wall-normal directions. Modes 2–8 contain the larger scale structures that are present in the unsteady turbulent flow, and were comprised of at least 50% of the total kinetic energy. The spacing between the signs of the oscillations are indicative of the size of the
Figure 3.59. POD eigenvalues as a function of mode number.

Figure 3.60. Energy content of the first 100 modes normalized by the total flow energy.
vortices in the shear layer formed behind the superstructure and over the flight deck. The wavelength of the shear layer was seen to decrease with the increasing mode number, which shows the presence of smaller turbulent structures in the airwake, especially in the near-wall regions of the flight deck. Although with the higher modes present even smaller structures started to appear that were indistinguishable from the original flow structures.
Figure 3.62. Contours showing the first 8 POD modes in the wall-normal direction at the centerline plane.

To further understand the dynamics of the ship airwake flow and the contribution of the POD modes, reduced-order flow fields were reconstructed using Eq. 3.17 for both the streamwise and wall-normal directions, as shown in Fig. 3.63 and 3.64. These reconstructions are based on the energy content within the modes, which was obtained by
taking the 5, 25, 50 and 100 modes that approximately comprise of 50.3%, 63.3%, 72.5% and 79.3%, respectively, of the total kinetic energy of the flow.

The ensemble average of the velocities in both the streamwise and wall-normal directions can be observed when the flow field was reconstructed using the first mode alone, but this result does not show any of the temporal flow dynamics. When reconstructed with 79.3% of the kinetic energy, a small number of variations started to appear in the wall-normal flow velocities especially above the flight deck. These features can be associated with the higher frequencies and wavelengths that are important features associated with the time-dependent flow dynamics of the airwake; note that these effects are not captured in the first mode of a purely spatial decomposition.

Figure 3.63. Comparison of the reduced-order ship airwake flow field as reconstructed using POD modes with a full-rank velocity field in the streamwise direction at the centerline plane.
Figure 3.64. Comparison of the reduced-order ship airwake flow field as reconstructed using POD modes with a full-rank velocity field in the wall-normal direction at the centerline plane.

POD modes can be useful in constructing the reduced-order model for the flow field because POD modes can remove the stochastic turbulence from the PIV data sets; it is based on a second-order correlation so higher-order correlations are ignored. However, this foregoing analysis suggested that several POD modes combinations will be required to capture and design a numerical model that can represent any unsteady aspects of an airwake. Furthermore, the temporal coefficients of the spatial POD modes contain a mix of frequencies and are arranged in the order of the energy content, and not in the order of dynamic importance. This latter issue can be resolved by determining spectral POD...
modes, where the modes can be calculated based on their frequency and optimally represent second-order, space-time flow statistics.

3.11 Spectral Proper Orthogonal Decomposition (SPOD)

SPOD analysis is a frequency domain form of POD modes (Towne et al., 2018), which used TR-PIV data to estimate the flow scales evolving coherently in space and time. The first space-time formulation of POD for statistically stationary flows (Lumley, 1967, 2007) was introduced by Lumley.

3.11.1 Mathematical Model of SPOD

In this formulation (Towne et al., 2018), the POD is applied to decompose the flow individually at each frequency. This method solves for the eigenvalues and eigenvectors of the cross-spectral densities (CSD) of each block of data following Welch’s method (Welch, 1967). Because of this, modes and their energies are a function of both frequency and POD mode number. The goal was to represent the velocity field in low-rank $u'(x,t) = \sum_{j=1}^{M} a_j^n(t)\phi_j(x,t)dx$ (Singh et al., 2018)

$$u'(x,t) = \sum_{j=1}^{M} \int_{\Omega} a_j^n(t)\phi_j(x,t)dx$$  \hspace{1cm} (3.18)

where $a_j^n$ are the expansion coefficients and $\phi_j$ are eigenfunctions based on spatial modes with an associated frequency.

Using these definitions, for any frequency $f'$, the function $\phi(x,t) = \psi(x,f')e^{i2\pi f't}$ is the solution to the eigenvalue problem with $\lambda(f')$, where $\psi(x,f')$ and $\lambda(f')$ satisfy
spectral eigenvalue problem. The Fourier modes of each flow realization can be optimally expanded as

\[ \hat{u}(x, f) = \sum_{j=1}^{M} a_j(f) \psi_j(x, f) \]  

(3.19)

where \( a_j(f) = \hat{u}(x, f) \psi_j(x, f) \).

Considering the instantaneous state of \( U(x, t) \) at time \( t_k \) on a discrete set of point in the spatial domain \( \Omega \). The total length \( N \) of the vector is equal to the number of grid points times the number of flow variables, as all these values have been stacked into the vector \( u_k \). If these data are available for \( M \) equally spaced time instances, \( t_{k+1} = t_k + \Delta t \), the data set can be compactly represented as

\[ U = [u_1, u_2, \ldots, u_M] \]  

(3.20)

The first step is to partition the data matrix into a set of smaller, possible overlapping, blocks. Each block is given by

\[ U^{(n)} = [u_1^{(n)}, u_2^{(n)}, \ldots, u_{N_f}^{(n)}] \]  

(3.21)

then \( k \)th entry in the \( n \)th block is \( u_k^{(n)} = u_{k+(n-1)(N_f-N_o)} \), where \( N_f \) is the number of snapshots in each block, \( N_o \) is the number of snapshots by which the blocks overlap and \( N_b \) is the total number of blocks. By the ergodicity hypothesis, each of these blocks can be regarded as a member of an ensemble of realizations of the flow. The DFT is then computed for each block, i.e.,

\[ \hat{U}^{(n)} = [\hat{u}_1^{(n)}, \hat{u}_2^{(n)}, \ldots, \hat{u}_{N_f}^{(n)}] \]  

(3.22)
with
\[
\hat{u}_k^{(n)} = \frac{1}{\sqrt{N_f}} \sum_{j=1}^{N_f} w_j u_j^{(n)} e^{-i2\pi(k-1)((j-1)/N_f)}
\] (3.23)

for \( k = 1, \ldots, N_f \) and \( n = 1, \ldots, N_b \). The scalar weights \( w_j \) are the nodal values of a window function that can be used to reduce spectral leakage due to non-periodicity of the data in each block. \( u_k^{(n)} \) is the Fourier component at frequency \( f_k \) in the \( n \)th block and the resolved frequencies are

\[
f_k = \begin{cases} 
  \frac{k - 1}{N_f \Delta t} & \text{for } k \leq N_f/2, \\
  \frac{k - 1 - N_f}{N_f \Delta t} & \text{for } k > N_f/2 
\end{cases}
\] (3.24)

The cross-spectral density tensor can be estimated at frequency \( f_k \) by the average

\[
S_{f_k} = \frac{\Delta t}{s N_b} \sum_{n=1}^{N_b} \hat{u}_k^{(n)} (\hat{u}_k^{(n)})^* 
\] (3.25)

where \( s = \sum_{j=1}^{N_f} w_j^2 \). This can also be rewritten by arranging the Fourier coefficients at frequency \( f_k \) from each block into the new data matrix, which is given by

\[
\hat{U}_{f_k} = \sqrt{k} \begin{bmatrix} \hat{u}_k^{(1)} \hat{u}_k^{(2)} \ldots \hat{u}_k^{(N_b)} \end{bmatrix}
\] (3.26)

where \( k = \Delta t/(s N_b) \). Furthermore, the estimated cross-spectral density tensor at frequency \( f_k \) can be written as

\[
S_{f_k} = \hat{U}_{f_k} \hat{U}_{f_k}^* 
\] (3.27)
The cross-spectral density estimate converges as the number of blocks $N_b$ and number of snapshots in each block $N_f$ are increased together. The infinite-dimensional SPOD eigenvalue problem reduces to $N \times N$ matrix eigenvalue problem, i.e.,

$$ S_{fk} W \psi_{fk} = \psi_{fk} \lambda_{fk} \quad (3.28) $$

where $W$ is the positive-definite Hermitian matrix that accounts for weight $W(x)$ and the numerical quadrant of integral on the grid. The approximate SPOD modes are given by the columns of $\psi_{fk}$ and are ranked according to their corresponding eigenvalues by the diagonal matrix $\lambda_{fk}$.

### 3.11.2 SPOD Analysis of the Airwake

The SPOD modes of the ship airwake at the centerline longitudinal ($x$-$z$) plane and Crossplane 2 were calculated using the method and code of Towne et al. The 5,000 PIV image pairs were divided into $N_b = 38$ blocks, with each block containing $N_f = 256$ snapshots with an 50% overlap (Towne et al., 2018).

The eigenvalues are depicted in two ways for both the longitudinal centerline plane and Crossplane 2, as shown in Figs. 3.66 and 3.65. Figures 3.66a and 3.65a show the eigenvalue as a function of mode number for $St = 0.13$ for both centerline plane and Crossplane 2. The eigenvalues are normalized by the total flow energy at this frequency, such that each scaled eigenvalue represents the fraction of the energy at $St = 0.13$ described by that mode.

The leading mode is substantially more energetic than the other modes and captures approximately 21% and 18% of the flow energy at this frequency for the centerline plane
and Crossplane 2, respectively. The low-rank behavior observed at $St = 0.13$ were indicated by a large gap between first and second SPOD eigenvalues for both centerline plane and Crossplane 2. Figures 3.65b and 3.66b show the full spectrum of SPOD eigenvalues as a function of frequency in both the centerline plane and Crossplane 2. All the eigenvalues have been normalized by total flow energy, such that each one can be interpreted as a fraction of the total energy described by that mode. The curves were seen to vary linearly as the mode number increases from 1 to $N_b = 38$.

Figures 3.67–3.68 show the contour plots showing the first two SPOD modes that occur at various flow frequencies near the flight deck, i.e., at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz corresponding to $St = 0.01, 0.06, 0.13, 0.31$ and 0.61, and for both the streamwise and wall-normal flow velocities. In addition, figures 3.69–3.71 show the contour plots showing the first two SPOD modes that occur at various flow frequencies at the flight deck edge, i.e., at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz corresponding to $St = 0.01, 0.06, 0.13, 0.31$ and 0.61, and for all the streamwise, spanwise and wall-normal flow velocities at Crossplane 2.

The most energetic scales structures were at low frequencies in the range up to 99.6 Hz ($St$ up to 0.61) in both the longitudinal and crossplanes. Also, these are the regions that consists of counterrotating vortices, as shown in Figs. 3.39–3.41. Furthermore, these sub-scale frequencies, when converted using Eq. 3.11, give values up to 0.3 Hz, which lie within in the range of the full-scale airwake flow frequency range of up to 2 Hz, as previously mentioned. The harmonics/sub-harmonics of these frequencies are such that they may then couple with the rotor wake and so may also affect the rotor (flapping) response.
Tables 3.2 and 3.3 show the flow energy content for first two modes at various frequencies in both the centerline plane and Crossplane 2. It is evident that the first mode for each frequency contains the largest energy content of the flow, and the energy content
Figure 3.66. The SPOD eigenvalues depicted in two ways at Crossplane 2.

(a) SPOD eigenvalues at $St = 0.13$, normalized by the total flow energy at that frequency.

(b) SPOD eigenvalues as a function of frequency.

decreases with a higher number of modes. However, the energy content of Modes 1 and 2 were found to be less than 6% for $St = 1.53$ (250 Hz) and so the SPOD modes for this frequency are not shown in Figs. 3.67 and 3.68.
Figure 3.67. Contour plots showing the first two SPOD modes at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz ($St = 0.01, 0.06, 0.13, 0.31$ and $0.61$) in the streamwise direction at the centerline plane.

The SPOD modes allow for a decoupling of the airwake flow phenomena at different time scales, another outcome that can be very helpful for understanding the airwake and
Figure 3.68. Contours of the first two SPOD modes at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz ($St = 0.01, 0.06, 0.13, 0.31$ and $0.61$) in the wall-normal direction at the centerline plane.

perhaps gives a new basis for verification and validation of CFD models. Although the concentration of the energetic modes in the airwake were seen to be at low frequencies,
Figure 3.69. Contours of the first two SPOD modes at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz ($St = 0.01, 0.06, 0.13, 0.31$ and $0.61$) in the streamwise direction at Crossplane 2.
Figure 3.70. Contours of the first two SPOD modes at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz ($St = 0.01, 0.06, 0.13, 0.31$ and 0.61) in the spanwise direction at Crossplane 2.
Figure 3.71. Contours of the first two SPOD modes at 1.95, 9.76, 21.5, 50.8 and 99.6 Hz ($St = 0.01, 0.06, 0.13, 0.31$ and 0.61) in the wall-normal direction at Crossplane 2.

the overall energy content was still rather broadband in both longitudinal and crossplanes, as shown in Fig. 3.72.
Table 3.2. Combined flow energy content of the first two modes at the centerline plane.

<table>
<thead>
<tr>
<th>$St$</th>
<th>$f$ (Hz)</th>
<th>Mode 1 (%)</th>
<th>Mode 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1.95</td>
<td>51.0</td>
<td>13.6</td>
</tr>
<tr>
<td>0.06</td>
<td>9.76</td>
<td>16.0</td>
<td>15.2</td>
</tr>
<tr>
<td>0.13</td>
<td>21.5</td>
<td>21.1</td>
<td>12.2</td>
</tr>
<tr>
<td>0.31</td>
<td>50.8</td>
<td>16.2</td>
<td>12.2</td>
</tr>
<tr>
<td>0.61</td>
<td>99.6</td>
<td>11.5</td>
<td>8.0</td>
</tr>
<tr>
<td>1.53</td>
<td>250</td>
<td>5.5</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 3.3. Combined flow energy content of the first two modes at Crossplane 2.

<table>
<thead>
<tr>
<th>$St$</th>
<th>$f$ (Hz)</th>
<th>Mode 1 (%)</th>
<th>Mode 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1.95</td>
<td>33.3</td>
<td>23.3</td>
</tr>
<tr>
<td>0.06</td>
<td>9.76</td>
<td>14.3</td>
<td>10.9</td>
</tr>
<tr>
<td>0.13</td>
<td>21.5</td>
<td>18.1</td>
<td>11.45</td>
</tr>
<tr>
<td>0.31</td>
<td>50.8</td>
<td>12.8</td>
<td>10.5</td>
</tr>
<tr>
<td>0.61</td>
<td>99.6</td>
<td>9.4</td>
<td>8.3</td>
</tr>
<tr>
<td>1.53</td>
<td>250</td>
<td>5.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

The oscillating turbulent vortical structures were seen to increase with the number of modes for each frequency. At lower frequencies, large-scale structures were observed in both the streamwise and wall-normal directions in the near-wall regions of the flight deck. Furthermore, at lower frequencies the magnitudes of the turbulent structures were also lower, whereas at higher frequencies their magnitudes were higher.

The foregoing is a significant finding that suggests caution in the approach to airwake modeling in that many modes will likely required to create a flow model of any significant fidelity. It should also be emphasized that such models will also have to be in the mathematical form that will ultimately have to interface with existing flight simulation methodologies (Theodore et al., 2014). Although, SPOD has been proven to be a very
Figure 3.72. Contour plot showing the energy content of the SPOD modes as a function of $St$ and the number of modes at the centerline plane and Crossplane 2.

useful analysis tool on the study of the air-wake flow dynamics. It will also be useful if the spatial structure obtained from these SPOD along with the temporal dynamics of these structures can be identified, which can be used to model real-time airwake.
4. Conclusions and Recommendations for Future Work

Experimental investigations in the wind tunnel were conducted to better characterize the complex, three-dimensional, unsteady aerodynamic flows produced by the superstructures of a scaled ship model, i.e., the airwake. The type and scope of the measurements that were conducted, as well as the methods used for analysis, have provided a deeper and broader insight into the detailed aerodynamic characteristics of the airwake. Generic SFS2 frigate models at two scales were tested in two different wind tunnel facilities, in part to quantify the effects of Reynolds number (based on ship length) on the airwake in the range of 0.6–6.2 million.

Measurements were also performed with and without a simulated atmospheric boundary (ABL). The ABL was simulated using the Cowdrey grid method, which comprises of horizontal rods placed in the wind tunnel upstream of the test section to produce a thick boundary layer with reasonably high turbulence. The measurements were performed using a combination of hot-wire anemometry (HWA) and time-resolved particle image velocimetry (TR-PIV), but the bulk of the measurements were made using TR-PIV. These off-surface flow measurements were also supported by surface oil flow visualization, which was used to help interpret the flow features over the stern of the ship. Various types of reduced-order modeling was also used to extract the dominant energy modes from the flow measurements to better understand the type and frequency of the unsteady flow structures in the airwake.

The outcomes from the work, in part, set benchmarks for future verification and validation of computational models that are used to predict the airwake. The results could
also be used as a basis for the development of flight dynamics models for handling qualities assessments in flight simulators, although this is a longer term goal and was not part of the present effort. Nevertheless, the techniques used in the present research to analyze the measurements expose a new understanding of the airwake and give good directions toward that end.

4.1 Conclusions

Based on the results obtained in the present work, the following key observations and primary conclusions have been drawn:

1. At the outset of the research, it was clear from the literature that the effects of an ABL, which is usually thought of as a mean velocity profile, was an essential part of understanding the development of the airwake. However, the creation of a mean velocity profile for a simulated ABL in the wind tunnel is a necessary but insufficient condition because the simulated ABL must also have some representative turbulence intensity. To this end, an ABL velocity profile in the Boundary Layer Wind Tunnel (BLWT) was successfully simulated with the use of a Cowdrey rod method. Several sets of measurements were made to understand the effectiveness of the Cowdrey rods in producing a specific velocity profile and turbulence levels representative of an ABL. In the Low-Speed Wind Tunnel (LSWT), two sets of Cowdrey rods were needed to obtain the required velocity gradients and turbulence levels representative of an ABL, one in the settling chamber before the contraction and the other upstream just before the entrance to the test section. Overall, the results confirmed the efficacy of the dual Cowdrey rod
method, and that the simulated ABLs gave reasonably acceptable velocity gradients and turbulence characteristics of an actual ABL to be able to study the development of the ship airwake.

2. Surface oil flow visualization on the ship model was conducted, and this technique was shown to be very useful in identifying points of flow separation, recirculation regions, and stagnation points on the ship. A development of standing horseshoe or scarf vortex around the funnel was observed, which trailed downstream over the flight deck. A large flow separation region with an overlying shear layer produced by the funnel was also seen to develop over the deck, as well as the development of two primary standing vortices on the deck itself, one on each corner in front of the hangar. Vortical structures trailing along the sides of the ship and a broad downstream wake were also observed, which not only affected the flow on the flight deck but also had effects well downstream.

3. The ABL was shown to be important in terms of its effect on the airwake. In this regard, quantitative TR-PIV measurements were performed with and without ABL flow in the LSWT. With the simulated ABL, a more diffused shear layer downstream of the funnel with lower flow velocities was found to develop over the flight deck. Also with the ABL present, the turbulence intensities decreased up to 10% when compared to the case with uniform flow. Overall, the TR-PIV results measured with and without the ABL showed that the effects of the ABL were important in determining the details of the flow over the deck, but overall the airwake flows were qualitatively very similar. Indeed, the results with and without the ABL suggested that the ship shape itself produced most of the turbulence over
the deck and the effects of any upstream turbulence inside the ABL itself were somewhat secondary.

4. An extensive amount of TR-PIV measurements were performed to better understand the ship airwake, including detailed measurements in several streamwise and crosswise. The mean flow properties in the airwake confirmed the formation of recirculation region behind the funnel, flight deck, and stern of the ship that were seen in the flow visualization. The size of the recirculation region extended up to 75% of the length of flight deck but the reattachment point was not steady in time. The recirculation bubble reduced in size and moved closer to the hangar when moving laterally outward. Turbulence intensities were found to be higher in the near-wall regions of the flight deck, which were about up to 12% in the streamwise direction and about up to 8% in the spanwise and wall-normal direction. This behavior was correlated to the shedding of vortices from the funnel and turbulence from the upstream superstructure of the ship. The measurements also showed the development of a shear layer originating at the corners of the flight deck on both port and starboard sides, and a set of counterrotating vortices at the edges of the flight deck.

5. Asymmetric flow differences were observed between the flow recirculation regions on the deck and behind the stern of the ship, which was traced to a form of bistable flow state. However, with 0° yaw case, it was not possible to get a steady flow pattern because the flow tried to alternate back and forth between the bistable states, a behavior seen in the TR-PIV data. Therefore, to force the flow states to be just one state or the other for flow visualization the ship model was yawed very slightly
to ±0.5° yaw cases. In this case, clearer asymmetric differences were observed in both cases between the flow recirculation regions on the deck and behind the stern of the ship, although the flow was still very unsteady. With −0.5° yaw, the recirculation region (on average) was larger on the port side on the flight deck, but behind the stern of the ship the recirculation region was larger (on average) on the starboard side. Whereas with +0.5° yaw, the recirculation region was larger on the starboard side on the flight deck and larger on the port side behind the stern. While unsteadiness in the airwake is the primary contributor to the upwash/downwash over the flight deck, this bistable flow characteristic of the flow over the deck introduces another degree of complexity into characterizing the airwake problem.

6. To help understand the Reynolds number effects, the flow measurements were compared between the Reynolds numbers of 0.6 million and 6.2 million. The mean velocity profiles showed very good agreement, suggesting very low sensitivity to the Reynolds number. The reattachment points and sizes of the separated flow regions behind the funnel, behind the superstructure, and also behind the stern of the ship were nearly identical for both the lowest and the highest Reynolds numbers. However, the turbulence intensity profiles showed some differences depending on the Reynolds number, which suggests that from this perspective the Reynolds number does matter. Overall higher levels of turbulence were observed near the mid-deck locations, which were between 9–12% of the free-stream velocity because of the close proximity to the recirculation regions. Although, the turbulence intensity profiles showed some variations with Reynolds number, overall
the results showed relatively low sensitivity to Reynolds number above a Reynolds number of $10^6$.

7. Spectral Proper Orthogonal Decomposition (SPOD) was used to extract the dominant energy modes from the TR-PIV measurements to better quantify the complex unsteady flow structures exhibited in the airwake. The SPOD analysis showed that most of the large energetic scale structures were at low frequency in the near-wall regions of the flight-deck, which were also in the regions that consisted of counterrotating vortices. Higher frequencies in the flow were observed in the wall-normal direction as compared to the streamwise direction in the regions where the shear layer was developed, which was behind the funnel and above the flight deck. The flow frequencies near the flight deck were in the lower range in the streamwise direction but higher in the wall-normal direction. These sub-scale frequencies observed near the flight deck region lie within the range of the full-scale airwake flow frequencies, which for a helicopter, for example, may couple with the rotor wake and may affect the rotor response. Furthermore, it was also observed that the first mode of each frequency contained the largest energy content of the flow, and the energy content decreases with a higher number of modes. Although, the concentration of the higher energetic modes were seen at low frequencies, the overall energy content in the flow was still rather broadband.

4.2 Recommendations for Future Work

The new measurements of the ship airwake presented in this dissertation have profound value to the research community. First, the results help to provide new insight
into the complex, unsteady, turbulent flows that characterize a ship airwake. Second, the high spatial and temporal fidelity PIV measurements provide a new benchmark for verification and validation of advanced CFD models that are being used to predict the flows about ships and the airwake developments. Third, the new data may provide the necessary inputs needed to develop higher fidelity numerical models of the airwake for flight simulation and handling qualities assessments, and can potentially contribute to improve the fidelity and accuracy of flight simulators used by pilots for training purposes. Nevertheless, further work is appropriate and needed, and to conclude this dissertation a few suggestions are now given in the following paragraphs.

1. One of the major challenges in measuring a ship airwake is that it is inherently a three-dimensional flow. Currently, the TR-PIV data are not temporally correlated, i.e., they are made up of planes and were not all obtained at the same instants in time. It might be useful to identify if a correlation exists between the time dynamics of different coherent structures, especially on the flight deck. Temporal correlation among the measurements could be achieved, for example, by synchronizing to a well-defined characteristic event in the flow, and use this as a trigger to make simultaneous flow measurements over several planes. The results from temporally correlated off-surface flow measurements may provide further insights as to how these flow structures interact with each other.

2. The new data obtained in this dissertation provide a new opportunity for verification and validation of various types of CFD models used to predict the ship airwake. While a direct, side-by-side comparison of the CFD with the TR-PIV measurements is valuable in itself, the use of the SPOD analysis could also be a important type
of future validation. To this end, SPOD analysis of the TR-PIV measurements has been shown in this dissertation to provide new insight into the characteristics of the airwake, and SPOD could also be performed on the CFD data (if available at comparable resolution) to compare with the measurements. The outcomes of these types of future comparisons may offer further opportunities in understanding of the ship airwake.

3. Currently, models of the airwake for use in the flight dynamic simulations import data from CFD and not from the measurements. But now, with the availability of measurements of higher spatial and temporal fidelity obtained from this research (which are at least as good in terms of resolution as CFD), these data could be used as an input to develop higher fidelity numerical models of the airwake. Most such airwake models need to be in relatively parsimonious mathematical (and numerical) form to be included inside flight dynamic simulation codes, so some form of reduced-order model of the airwake is probably necessary. As previously suggested, the SPOD analysis can be used to identify the coherent structures in the airwake based on the energy levels and frequency content. Although the airwake has been shown to have flow frequencies that are relatively broadband, there is significant energy at low frequency and this is important for modeling because it is the low frequency modes that will affect rotor response and piloting inputs.

4. It is always tempting to suggest taking “more data,” although there is always a place for more data if that can be justified. For example, in the present research it was not possible to take crosswise plane PIV measurements at the center of the flight deck (where a helicopter might actually land) because of various physical and optical
constraints in the wind tunnel in regard to laser and/or camera placement.

Nevertheless, if these constraints could be overcome, which might also require moving the position of the ship model in the test section, then the additional flow information at this plane, especially at 25%, 50% and 75% of the length of the flight deck would be useful.

5. This research has also suggested some irregularly occurring flow states on the flight deck, including some form of potential bistable flow state. To investigate this further then it would be desirable to make flow measurements in a horizontal plane \((x,y)\), which would allow the flow on both sides of the flight deck to be imaged simultaneously. While this would require the physical movement of lasers, cameras, optics, etc., and is certainly a significant undertaking in the wind tunnel, the benefits would be worthwhile.
REFERENCES


A. Cowdrey Theory

This appendix discusses the theoretical aspects of the method that was used to calculate the position of the horizontal rods to form the simulated atmospheric boundary layer (ABL) in both the Boundary Layer Wind Tunnel (BLWT) and the Low-Speed Wind Tunnel (LSWT). The Cowdrey method was developed as a convenient way of obtaining the positions of a grid of horizontal bars or rods that could generate specified simulated ABL profiles (i.e., a wind gradient and associated turbulence) in a wind tunnel, especially for industrial aerodynamic investigations such as estimating wind forces on buildings and other terrestrial structures (Cowdrey, 1967). This method draws on the earlier work of Cockrell and Lee, as well as the work of Elder, who examined pressure drops over grids and rods (Cockrell and Lee, 1966; Elder, 1959).

The Cowdrey grid method is a relatively straightforward mathematical method in which the diameter and vertical spacing between a set of horizontal placed cylindrical rods can be calculated to generate a specific boundary layer velocity profile downstream of the rods. There are some initial assumptions in the theory, i.e.,

1. There is a uniform flow before the grid of rods.

2. The boundary layer velocity profile downstream of the rods is based on a classic \(1/n\) power law.

3. The turbulent boundary layer that is produced is completely developed immediately downstream of the grid.

4. The static pressure is same everywhere downstream of the grid.
5. The flow is incompressible, inviscid, and steady.

A.1 Derivation

The overall pressure drop $\Delta p$ along any streamline that passes through the grid is given with the application of Bernoulli equation with a local pressure drop, i.e.,

$$\Delta p = \frac{1}{2} \rho \overline{u}^2 - \frac{1}{2} \rho U_\delta^2 + \frac{1}{2} \rho \overline{u}^2 K = \text{constant} \quad (A.1)$$

where $\rho$ is the density of air, $\overline{u}$ is the local velocity in the boundary layer profile at height $z_g$, $\delta$ is the boundary layer thickness, $U_\delta$ is the velocity at the edge of the boundary layer, $K$ is the local pressure drop coefficient over the grid.

Dividing Eq. A.1 by $1/2 \rho U_\delta^2$ gives

$$\frac{\Delta p}{\frac{1}{2} \rho U_\delta^2} = \frac{\overline{u}^2}{U_\delta^2} - 1 + \frac{\overline{u}^2}{U_\delta^2} K = K_1 \quad (A.2)$$

where

$$K_1 = \frac{\Delta p}{\frac{1}{2} \rho U_\delta^2} \quad (A.3)$$

is the overall pressure drop coefficient produced by the grid of rods in the flow.

Substituting the non-dimensional velocity $u^* = \overline{u}/U_\delta$ into Eq. A.2 gives

$$K_1 = u^{*2}(K + 1) - 1 \quad (A.4)$$
Rearranging the above equation gives $u^*$ in terms of $K$ and $K_1$, which is

$$u^* = \left( \frac{\bar{u}}{U_\delta} \right) = \left( \frac{1 + K_1}{1 + K} \right)^{1/2} \quad \text{(A.5)}$$

The above equation relates $\bar{u}/U_\delta$, $K$ and $K_1$, where the local pressure drop coefficient $K$ can be determined by assuming a value of $K_1$ for a desired velocity profile $\bar{u}/U_\delta$. $K_1$ is a constant value that can be assumed to lie within the range of 0.2–1 (Cowdrey, 1967).

Furthermore, according to Cowdrey, the value of the local pressure drop coefficient $K$ is a function of the diameter of the rod, $d$ and spacing between the centerline axis of the rods, $l$, which is derived from earlier work (Elder, 1959) and is given as

$$K = \frac{d}{l} \left( 1 - \frac{d}{l} \right)^{1/2} \quad \text{(A.6)}$$

This particular result is derived from the result for a pressure drop over a turbulence screen with a wire diameter $d$ and wire grid spacing $l$ (Elder, 1959). Notice that in this case, the value of $K$ pertains to the local pressure drop coefficient behind and between any two rods that are separated by a distance $l$.

Considering a power law velocity profile for the boundary layer then

$$\bar{u} = z^{1/n}_g \quad \text{(A.7)}$$
where $n$ is the index of the power law profile. A 1/7-th power law was used as a reference ABL profile for the present research, so $n = 7$. Therefore, for any value of $z_g$ then

$$\frac{\bar{u}}{z_g^{1/n}} = \text{constant} \quad (A.8)$$

Figure A.1. Control volume analysis applied to the flow through the Cowdrey grid.

Consider a wind tunnel with Cowdrey rods where the control volume is drawn around the flow through the Cowdrey grid, as shown in Fig. A.1. Applying the continuity equation in the flow and assuming per unit depth, then the mass flow rate entering the control volume is

$$\dot{m}_{in} = \rho U_\delta \delta \quad (A.9)$$

The corresponding mass flow rate leaving the control volume in the boundary layer is found by integration, i.e.,

$$\dot{m}_{out} = \rho \int_0^\delta \bar{u} \, dz \quad (A.10)$$
Therefore, conservation of mass gives

\[ m_{\text{in}} - m_{\text{out}} = \rho \ U_\delta \ \delta - \rho \ \int_0^\delta \ \bar{u} \, dz = 0 \]  

(A.11)

Rearranging the above equation gives a relationship between the inlet (before the grid of rod) and outlet (after the rods) conditions, i.e.,

\[ \rho \ U_\delta \ \delta = \rho \ \int_0^\delta \ \bar{u} \, dz \]  

(A.12)

Because an incompressible flow is assumed then

\[ U_\delta \ \delta = \int_0^\delta \bar{u} \, dz \]  

(A.13)

Multiplying by \( z_g^{1/n} \) and dividing by \( z_g^{1/n} \) on the right-hand side of the above equation gives

\[ U_\delta \ \delta = \int_0^\delta \frac{\bar{u}}{z_g^{1/n}} z_g^{1/n} \, dz \]  

(A.14)

From the power law profile then using Eq. A.8 then

\[ U_\delta \ \delta = \frac{\bar{u}}{z_g^{1/n}} \int_0^\delta z_g^{1/n} \, dz \]  

(A.15)

Performing the integration between the limits (the floor to the top of the boundary layer) gives

\[ U_\delta \ \delta = \frac{\bar{u}}{z_g^{1/n}} \left[ \frac{z_g^{1/n+1}}{n+1} \right]_0^\delta \]  

(A.16)
and introducing the limits gives

\[ U_\delta \delta = \frac{\bar{u}}{z_g} \frac{\delta^{1/n+1}}{(n+1)} \]  

(A.17)

Simplifying the foregoing equation gives

\[ U_\delta = \frac{\bar{u}}{z_g} \left( \frac{n}{n+1} \right) \left( \frac{\delta^{1/n+1}}{\delta} \right) \]  

(A.18)

and rearranging in terms of \( \bar{u}/U_\delta \) gives

\[ \frac{\bar{u}}{U_\delta} = \left( \frac{z_g}{\delta} \right)^{1/n} \left( \frac{n+1}{n} \right) \]  

(A.19)

Substituting \( \bar{u}/U_\delta \) from Eq. A.5 and solving for \( z_g/\delta \) gives

\[ \frac{z_g}{\delta} = \left( \frac{n}{1+n} \right)^n \left( \frac{1+K_1}{1+K} \right)^{n/2} \]  

(A.20)

Finally, substituting \( K \) from Eq. A.6 gives a relationship between \( z_g, d, n, K_1 \) and \( l \), i.e.,

\[ \frac{z_g}{\delta} = \left( \frac{n}{1+n} \right)^n \left[ \frac{1+K_1}{d/l} \left( \frac{d/l}{(1-d/l)^2} \right) \right]^{n/2} \]  

(A.21)

This latter equation can now be used to construct a relationship between \( z_g \) as a function of \( d, l, \) and \( K_1 \), which can then be used to calculate the height of the rods \( h \). The detailed explanation on calculating the heights of the rods using Eq. A.21 will be discussed later in Section A.3.
A.2 Selection of the $K_1$ Value

The value of $K_1$ suggested by Cowdrey should be in the range of 0.2–1 (Cowdrey, 1967). There can be certain amount of latitude in the choice of value of $K_1$, but there are practical limits to the rod spacing. Some of the issues that can occur if the $K_1$ value is chosen improperly can be:

1. Flow separation will occur at the walls of the wind tunnel if the rods are placed too close to each other.

2. If the rods are placed too far apart, the wakes of individual rods will persist downstream to give rise to irregular velocity profiles.

3. Larger values of $K_1$ will result in greater turbulence in the boundary layer, but which can also give some control over the intensity and scale of the needed turbulence.

A.3 Computation of the Heights of the Rods

Figure A.2 shows the spacing between the centerline axes of the rods, $l$, and diameter of the rod, $d$ as a function of height above the ground, $z_g$, which was calculated using Eq. A.21 for various values of $K_1$, namely 0.2, 0.4, 0.6 and 0.8. To keep the value of $z_g$ within the practical height limits of both the BLWT and LSWT and also, to keep the turbulence in the reasonable range of 8–10% in the near-wall regions of the tunnel floor, a value of $K_1 = 0.2$ was selected to calculate the rod spacing. Other parameters used for the calculations were $d = 1.27$ cm (0.5 in), and $n = 7$. Rod diameters of 1 in and 0.25 in were also considered, however 0.25 in was too small for installation in the wind tunnel and 1 in
was tested but it was determined to be too big for the BLWT, which had a height only of 0.61 m (2 ft).

![Graph](image)

(a) Spacing between the centerline axes of the rods, $l$ (in) as a function of height above the ground, $z_g$ (in), for the BLWT.

![Graph](image)

(b) Spacing between the centerlines of the rods $l$ (in) as a function of height above the ground, $z_g$ (in) for the second grid of the LSWT.

Figure A.2. Spacing between the centerlines of the rods $l$ (in) as a function of height above the ground, $z_g$ (in) for the grid used in both the BLWT and the LSWT for various values of $K_1$. 
The following is an example for calculating the position of the rods for the Cowdrey grid in the BLWT. From the graph shown in Fig. A.2a, then at $z_g = 0$ (which is the tunnel floor) then $l$ is equal to the diameter of the rod, i.e., $l = d$. This means the first rod is placed on the tunnel floor. An initial approximation to $z_g$ for the second rod is one rod diameter, i.e., $d = 0.5$ in. The corresponding value of $l$ is read from the graph shown in Fig. A.2a, and by adding half of this value to the height of the axis of the first rod, the new value $z_g'$ is obtained, which is then used for the second iteration. The process is repeated iteratively until the differences between the values of $z_g$ and $z_g'$ converges to $10^{-6}$, as shown in Fig. A.3a. Figure A.3b shows the convergence for the value of $z_g$ when calculating the height of the second rod for the BLWT Cowdrey grid.

A.4 Cowdrey Grid Combinations for the BLWT

Table A.1 shows the parameters used to calculate the Cowdrey rod positions for the BLWT. Table A.2 shows the initial height (C1 case) of the rods which was obtained using the process as described previously. The corresponding boundary layer profile generated by C1 case is shown in Fig. A.4. It can be seen that the boundary layer profile generated by the C1 grid arrangement did not match well with the 1/7-th power law profile. As such, several variations of the grid arrangement was conducted until the boundary layer profile matched better with the 1/7-th power law, which is shown in Table A.2 under the column titled C3. By removing the 3rd and the 6th rods, and by judiciously adjusting the 1st, 4th and 5th rods, the resultant boundary layer profile matched much better.
(a) Mathematically explaining the iterative process for calculating the height of the second rod.

<table>
<thead>
<tr>
<th>Rod Count</th>
<th>( z_g ) (in)</th>
<th>( l ) (in)</th>
<th>( \frac{l}{2} ) (in)</th>
<th>( z'_g ) (in)</th>
<th>h (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Rod</td>
<td>0</td>
<td>0.5</td>
<td>0.25</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2nd Rod</td>
<td>0.5</td>
<td>1.0413</td>
<td>0.5207</td>
<td>0.7707</td>
<td>0.25</td>
</tr>
</tbody>
</table>

First approximation is the 2nd rod is \( \frac{l}{2} + h \).

Iterative process stops once \( z_g = z'_g \), hence h is calculated for the 2nd rod.

(b) Convergence history between the values of \( z_g \) and \( z'_g \).

Figure A.3. An example of the iterative process and its convergence for calculating the height of the second rod location of the Cowdrey grid.

A.5 Cowdrey Grid Combinations for the LSWT

Table A.1 shows the parameters used to calculate the Cowdrey rod positions for the LSWT. For the LSWT, which has a contraction section before the test section, it was found that two sets of Cowdrey rods were needed to produce the needed velocity.
Table A.1. Cowdrey grid parameters for both the BLWT and second grid for the LSWT.

<table>
<thead>
<tr>
<th>Wind Tunnel</th>
<th>d (in)</th>
<th>δ (in)</th>
<th>$K_1$</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLWT</td>
<td>0.5</td>
<td>24</td>
<td>0.2</td>
<td>7</td>
</tr>
<tr>
<td>LSWT</td>
<td>1.05</td>
<td>48</td>
<td>0.2</td>
<td>7</td>
</tr>
</tbody>
</table>

Table A.2. Height of the rods $h$ for the C1 and C3 combinations as tested in the BLWT.

<table>
<thead>
<tr>
<th>Rod Number</th>
<th>C1 case $h$ (in)</th>
<th>C3 case $h$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Floor</td>
<td>Floor</td>
<td>Floor</td>
</tr>
<tr>
<td>R2</td>
<td>1.38</td>
<td>1.53</td>
</tr>
<tr>
<td>R3</td>
<td>2.80</td>
<td>removed</td>
</tr>
<tr>
<td>R4</td>
<td>4.53</td>
<td>4.8</td>
</tr>
<tr>
<td>R5</td>
<td>6.70</td>
<td>7.03</td>
</tr>
<tr>
<td>R6</td>
<td>9.60</td>
<td>removed</td>
</tr>
</tbody>
</table>

Figure A.4. Comparison of the 1/7-th power law profile with the velocity profiles obtained using the C1 and C3 Cowdrey grids in the BLWT.
gradients and turbulence to form a representative ABL at the test section. The first set of Cowdrey rods was installed in the settling chamber to create an initial velocity gradients and turbulence in the low-speed flow.

The first grid consisted of five rods stacked together near the floor with a separation of 0.05 m (2 in), each rod being 4.39 m (14.4 ft) long and 0.11 m (4.5 in) in diameter, which was used to produce the initial velocity gradient, especially near the tunnel floor. The second grid consisted of seven rods, each rod being 1.52 m (5 ft) long and 0.03 m (1.05 in) in diameter, which were placed close to the exit of the contraction section. The initial rod placements for both the grids were also calculated using the same iterative procedure mentioned above. However, a larger rod diameter was not used because this will reduce the number of rods and this will not be enough to simulate a smooth ABL profile in the wind tunnel that matches the 1/7-th power law.

Table A.3 shows the initial height (C1 case) of the rods calculated using the iterative process as described previously. The corresponding boundary layer profile generated by C1 case is shown in Fig. A.5. It can be seen that the profile generated by the C1 grid arrangement did not match well with the 1/7-th power law profile. As such, several other grid arrangements were conducted. The grid arrangement that matched the best with the 1/7-th power law is shown in Table A.3 under the column C17. As shown in this table, the 3rd, 5th and 6th rods were moved closer to the floor to reduce the velocities there, and this approach gave a resultant boundary layer profile that matched better with a 1/7-th power law.
Table A.3.

Height of the rods $h$ for the C1 and C17 Cowdrey grids as tested in the LSWT.

<table>
<thead>
<tr>
<th>Rod Number</th>
<th>C1 case $h$ (in)</th>
<th>C17 case $h$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Floor</td>
<td>2.93</td>
<td>3</td>
</tr>
<tr>
<td>R2</td>
<td>5.96</td>
<td>4.5</td>
</tr>
<tr>
<td>R3</td>
<td>9.70</td>
<td>9</td>
</tr>
<tr>
<td>R4</td>
<td>14.46</td>
<td>12.8</td>
</tr>
<tr>
<td>R5</td>
<td>21.18</td>
<td>17.5</td>
</tr>
<tr>
<td>R6</td>
<td>22.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Figure A.5. Comparison of the 1/7-th power law profile with the velocity profiles obtained using the C1 and C17 grid combinations in the LSWT.
B. Hot-Wire Calibration

This appendix discusses the specifics of the calibration device used for the hot-wire sensors. Figure B.1 shows a general schematic of the calibration jet. Two different calibration jets were used, depending on the velocity range needed to be measured using the hot wire anemometry (HWA) system. The calibration jet used in the LSWT had a diameter of 114 mm (4.5 in) and the jet exit nozzle diameter is 5.05 mm (0.2 in). Honeycomb and a series of screens in the settling chamber were used to ensure the turbulence intensity was as low as possible. The calibration jet used in the BLWT has a diameter of 80 mm (3.14 in) and jet exit nozzle diameter of 6.4 mm (0.25 in). In each case, the jet was obtained using pressurized air and the exit velocity was controlled using a manual valve.

Figure B.1. Schematic of the calibration jet used for the hot-wire sensors.

The jet exit velocity was calculated using the continuity equation, i.e.,

\[ A_1 V_1 = A_2 V_2 \]  

(B.1)
and Bernoulli’s equation, i.e.,

\[ p_1 + \frac{1}{2} \rho V_1^2 = p_2 + \frac{1}{2} \rho V_2^2 \]  

(B.2)

where \( A \) is the cross-section area, \( V \) is the flow velocity, \( p \) is static pressure, and \( \rho \) is the flow density. The subscripts 1 and 2 represent before and after the nozzle contraction, respectively. Using Eqs. B.1 and B.2, the velocity at the jet is exit can be determined using

\[ V_2 = A_1 \sqrt{\frac{2(p_1 - p_2)}{\rho (A_1^2 - A_2^2)}} \]  

(B.3)

where \( p_1 - p_2 \) is the static pressure difference between before and after the nozzle contraction. This static pressure difference is measured using a precision pressure transducer, after which the nozzle exit velocity can then be calculated using Eq. B.3. By placing the hot-wire in the nozzle exit, the output voltage from the hot-wire and the nozzle exit velocity can be related, which becomes the calibration curve.

### B.1 Details of Hot-wire Calibration Procedure

Following procedures was followed to obtain the hot-wire calibration curve:

1. The probe was mounted on the traverse with the prongs parallel to the nozzle exit flow. The probe in the calibration rig was mounted with the same wire-prong orientation as was used during the actual experiment.

2. Ambient conditions: Temperature and atmospheric pressure were recorded using a thermocouple and pressure transducer, respectively to calculate density.

3. Overheat adjustments were bridged before calibration.
4. Minimum and maximum calibration velocities were selected, and 20 calibration points were selected within this range such that there was more resolution at higher velocities.

5. The exit nozzle velocity of the jet and output voltages from the hot-wire were acquired at the prescribed 20 points.

6. A third-order polynomial curve fit was performed as given by

\[
\bar{u} = C_0 + C_1 E + C_2 E^2 + C_3 E^3
\]  

(B.4)

where \(C_0\)–\(C_3\) are the calibration constants and \(E\) are the output voltages obtained from the hot-wire. The polynomial curve fit is normally recommended, because makes very good fits with regression errors less than 1%. Figure B.2 shows an example of the hot-wire calibration curve in which the third-order polynomial through the points \((E, \bar{u})\). This curve then provides the formal relationship that is used for converting the data records from voltages into flow velocities.
Figure B.2. An example of the hot-wire calibration curve. The symbols are the measured calibration velocity and the curve represents the corresponding third-order polynomial fit.
C. Simulated ABL Profiles

This appendix discusses the comparison of simulated ABL generated in both the BLWT and LSWT in terms of mean velocity profile and turbulence intensity profiles relative to the other wind tunnel measurements in the form of log scale, as shown in Figures C.1 and C.2. It is evident that the mean velocity profiles simulated in the BLWT and LSWT follow the logarithmic law in the overlap region, which is the fully turbulent region. However, there were no measurements made in the viscous sub-layer because of the limitation of the HWA setup.

For both the mean velocity and turbulence intensity profiles, it can be seen that they deviated from the trends shown by Peterka & Cermak (Case 2). This was because Peterka & Cermak (Case 2) used spires with the addition of extra roughness elements on the tunnel floor that led to severe effects on both velocity and turbulence profiles (Peterka and Cermak, 1974).
Figure C.1. Measured mean velocity profile relative to the other wind tunnel measurements presented in the form of log scale.
Figure C.2. Turbulence intensity profiles of the simulated ABL relative to the other wind tunnel measurements presented in the form of log scale.
D. Effects of Reynolds Number

This appendix discusses the two-dimensional mean velocity and turbulence intensity profiles were extracted from the TR-PIV measurements in the LSWT at four locations (A–D) near the center of the flight deck at $x/SH = 1.84$, and four locations (E–H) near the trailing edge of the deck at $x/SH = 2.53$ at a $Re$ of 6.2 million. It should be noted the measurements were made using a single-component hot-wire in the BLWT and, therefore, no comparisons to the $Re$ of 0.6 million case have been shown here.

Figures D.1 and D.2 compare the normalized mean velocity $w/\bar{U}_\infty$ and turbulence intensity profiles $w'_{rms}/\bar{U}_\infty$ at locations A–D and E–H for a $Re$ of 6.2 million obtained from TR-PIV measurements. It was observed that the mean velocity in the wall-normal direction were found to be lower as compared to the mean velocity in the streamwise direction. In addition, below $z/SH = 0.6$, the largest deviations in the mean velocity and turbulence intensity profiles were observed for the mid-deck locations A–D because of their closer proximity to the recirculation region.

Figures D.3 and D.4 compare the normalized velocity magnitude $U/\bar{U}_\infty$ and overall turbulence intensity profiles $U'_{rms}$ at locations A–D and E–H for a $Re$ of 6.2 million obtained from TR-PIV measurements. The velocity magnitudes profiles showed symmetry among the profiles away from the centerline on both port and starboard sides. However, overall asymmetry was observed among the turbulence intensities profiles. In addition, higher turbulence intensities were observed in the profiles A–D when compared to other locations. This behavior can be observed because of their closer proximity to the recirculation region.
Figure D.1. Comparison of normalized wall-normal mean velocity profiles ($\overline{w}/U_\infty$) at the prescribed flight deck locations for a $Re$ of 6.2 million.
Figure D.2. Comparison of normalized wall-normal turbulence intensity profiles ($w'_{	ext{rms}}/U_{\infty}$) at the prescribed flight deck locations for a $Re$ of 6.2 million.
Figure D.3. Comparison of normalized mean velocity magnitude profiles $(\bar{U}/U_\infty)$ at the prescribed flight deck locations for a $Re$ of 6.2 million.
Figure D.4. Comparison of normalized turbulence intensity profiles \( \frac{U'_{\text{rms}}}{U_\infty} \) at the prescribed flight deck locations for a Re of 6.2 million.
E. List of Publications

E.1 Journal Papers


E.2 Conference Papers

