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**Assessing the Transient Gust Response of a Representative Ship Airwake using Proper
Orthogonal Decomposition**

by

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UNITED STATES NAVAL ACADEMY
ANNAPOLIS, MARYLAND

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**ASSESSING THE TRANSIENT GUST RESPONSE OF A REPRESENTATIVE SHIP
AIRWAKE USING PROPER ORTHOGONAL DECOMPOSITION**

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Abstract

In an effort to better understand at-sea helicopter operations and improve flight envelope definition, this project analyzed the effects of transient wind gusts on a representative ship airwake. Existing meteorological data were combined with a Simple Frigate Shape 2 model undergoing translational oscillations in order to simulate full scale, sweeping gusts in a closed-circuit wind tunnel. The experiment modeled a spectrum of full-scale gust durations and wind direction oscillations ranging from 4 to 14 degrees. When scaled to testing conditions for a 1:120 scale model, the test matrix included six separate data points at gust-frequency referenced Strouhal numbers ranging from 0.430 to 1.474. A 725-Hertz time-resolved Particle Image Velocimetry system was then used to acquire flow field data across a series of three horizontal planes spanning from 0.25 to 1.5 times the ship hangar height. All testing was conducted at a steady-state, ship hangar height-referenced Reynolds number of 26,000 which correlated to a tunnel velocity of approximately 25 feet per second. Dynamic results were compared with static results, and the differences in turbulent structures and wake velocities were quantified. For the transient gust cases, the most notable difference included an extended lee attached to the windward hangar edge. Upon further analysis this separation bubble was determined to be the result of a transient gust-induced dynamic stall causing a measurable change in turbulence over the flight deck.

Keywords: ship, airwake, gust, PIV, POD, transient

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1 Introduction

1.1 Background

In September of 2014, a US Marine Corps CH-53 Super Stallion helicopter was lost overboard of the USS Mesa Verde (LPD 19) while attempting to land. Fortunately, all 25 Marines and Sailors aboard were rescued, but several personnel sustained minor injuries and the helicopter sank to the bottom of the Gulf of Aden [1]. While significant mishaps like this are fortunately rare in today's Naval Air Forces, shipboard flight operations remain challenging and dangerous. As a consequence, the Navy has invested extensive time and resources towards improving aviation safety. A particular point of interest in recent years has been the interaction between the wind and a ship's hull and superstructure.

Warship superstructures are generally designed with the purpose of maximizing the effectiveness of onboard radar and fire control systems. In order to accomplish this, tall superstructures are used to mount radar arrays and position communication antennas. An unintended consequence of this above-the-waterline design is a non-aerodynamic shape which generates highly unsteady, turbulent airflow, normally denoted the ship's airwake. Once again in accordance with maximizing onboard weapon utility and operational efficiency, flight decks are placed on the stern of most warships, right in the midst of this airwake. As is shown in the markup of Figure 1, the general arrangement of situating the flight deck aft of the primary and secondary superstructures is true of all small Navy ships that service helicopters. From the pilot's perspective, this type of ship configuration creates an expansive unpredictable wake zone of dangerous air turbulence and unsteadiness behind a ship underway. This is seen in Figure 2, where the two most critical phases of flight, launch and recovery, occur in the midst of this airwake astern of these vessels.

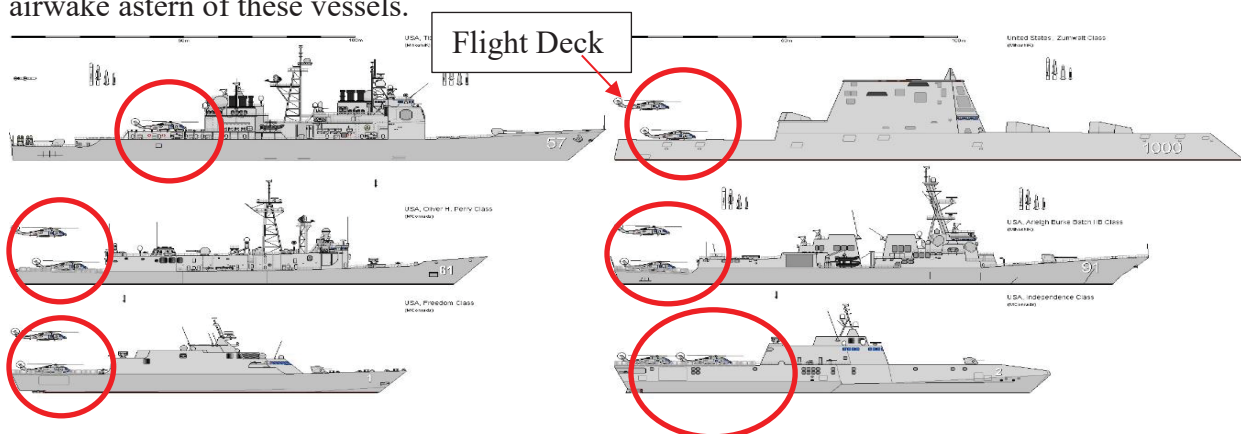


Figure 1. Small ships of the Navy. Clockwise from upper left: Ticonderoga-class guided-missile cruiser, Zumwalt-class destroyer, Arleigh Burke-class guided-missile destroyer, Independence-class littoral combat ship (LCS), Freedom-class LCS, Oliver Perry-class frigate [2].



Figure 2. A starboard approach to a San Antonio-class amphibious transport dock ship [3].

The unsteady airwake created as the ship passes through the air is the least controllable hazard for landing helicopters. In order to mitigate this hazard, a combination of wind tunnel scale model testing and full-size data gathering are used to develop flight envelope requirements for helicopter operation. However, the vast majority of the data must be gathered through shipboard testing. The created envelopes are specific to individual helicopter and ship pairs and are refined through both experience and continued research. The process of developing these flight envelopes is extremely intensive. In a report titled “Investigation to Study the Aerodynamic Ship Wake Generated by a DD963 Destroyer,” Theodore S. Garnett outlines the process used by the Boeing Vertol Company to contribute data toward the creation of flight envelopes for the Spruance Class Destroyer [4]. A scale model of DD963 was tested across a variety of yaw, roll, and pitch angles in order to determine the characteristics of the airwake in the full spectrum of possible conditions. In reality, aerodynamics do not fully scale with model size, but this was accounted for in the testing conditions selected through a process known as Reynolds number matching.

The flight envelopes created with this data are used in tandem by both pilots and shipboard conning officers in order to execute safe landings at sea. The ship is held on a course to place the relative wind, the ship roll, and the ship pitch within prescribed tolerances. The pilot then trusts that the ship will be held to these conditions and executes a standard approach. Due to ship asymmetry, both starboard and port approaches have individual flight envelopes. Figure 3 shows the envelope for an H-60 helicopter conducting a starboard approach to an Arleigh Burke Class Destroyer (DDG 51).

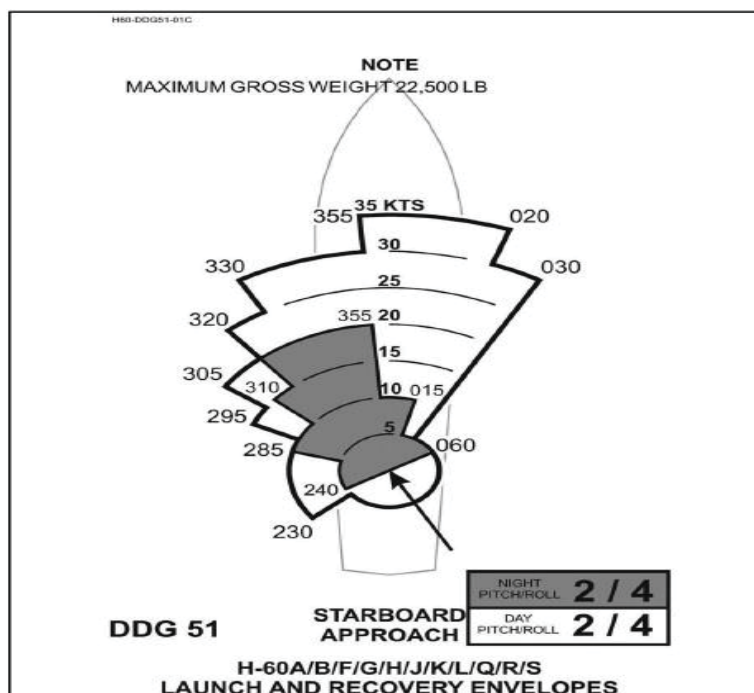


Figure 3. Starboard approach envelope for an H-60 approaching an Arleigh Burke Class Destroyer

Typically, this flight envelope is placed on a computer screen visible on both the bridge and in the flight control tower. A single dot floats on the display, showing the relative wind direction and speed. The arrow in Figure 3 represents the direction of approach for the helicopter. The center (the tip of the arrow) represents zero relative wind. As wind speed increases, the dot moves away from the center in the direction of the relative wind. The knot increment arcs are segments of circles of equal velocity. When the relative wind dot falls within the white or the grey during daylight hours, the helicopter is clear to land. However, the dot must fall within the more-restrictive gray zone during night operations. Additionally, the numbers in the bottom right shows the pitch and roll requirements for flight operations, which relate directly to the sea state. For this combination, the ship cannot pitch more than two degrees or roll more than four degrees during flight operations or the helicopter will not be clear to land under the stated conditions.

It is worth noting the narrow margins required by this envelope. Firstly, it is only applicable for the specific combination of an H-60 and a DDG 51. Secondly, it is only applicable up to a maximum gross aircraft weight of 22,500 lbs. Thirdly, the margin for pitch and roll is extremely small, topping out at two and four degrees, respectively. Finally, the relative wind velocity and direction must be held in a very narrow range, especially at night.

The difficulty in operating a helicopter at sea is apparent from these requirements, but the existence of these flight envelopes has led to extremely safe operation in recent years. Across

fiscal years 2015 and 2016, there were no Class A mishaps resulting from helicopters landing at sea [5]. A Class A mishap is an incident resulting in death, permanent disability, or greater than \$1,000,000 of damage. To put this number in perspective, there were 42 total Class A mishaps over the same time period, many of which involved helicopters in normal shore-based operation [5]. It would therefore appear that operation at sea is safer than normal shore-based operation.

Unfortunately, such an assertion is misleading. The narrow margins required by at-sea flight envelopes are equivalent to extreme weather restrictions on shore based aircraft. In general, rotor-craft are not launched or recovered in conditions that would be easily permissible in shore based operation. In more turbulent waters, such as the North Sea, this can lead to the grounding of rotorcraft up to 90% of the time [6]. This has a negative albeit necessary effect on operational readiness, as embarked rotor craft are critical components to the fleet's anti-surface and anti-submarine warfare capabilities. Additionally, the cost for developing the individualized flight envelopes was \$75,000 to \$150,000 per combination in 1987 [7]. While such outdated figures may seem irrelevant, the technology has not progressed past the need for experimental testing. As such, costs today may be as high as \$500,000 per aircraft-ship-approach combination when considering inflation and increasing Navy operating costs [8].

The purpose of this research was to analyze the effects of directional wind shifts on flow around a 1:120 scale representative ship geometry. This simplified geometry was engineered to model the most relevant structures including the bow, superstructure, flight deck, and mast while allowing comparison with prior research. An oscillating actuator swayed the model to produce a sweeping relative wind vector. This allowed for analysis of the fundamental principles governing the separated, unsteady flow in the ship airwake using stereoscopic Particle Image Velocimetry (PIV). The primary goal was to increase the understanding of ship airwakes so that shipboard helicopter operations can be made smarter, safer, and more efficient.

1.2 Flow Scaling Parameters

In aerodynamic experimentation, there are non-dimensional ratios which are used to ensure that experimentally obtained scale results match with full-scale observations. The relevant ratios to this experiment were Reynolds number and Strouhal number. Reynolds number is the ratio of inertial effects to viscous effects. Eqn. (1) shows the generic form of Reynolds number.

$$Re_l = \frac{\rho V_\infty l}{\mu} \quad (1)$$

In Eqn. (1), ρ is the fluid density, V_∞ is the fluid velocity, l is the characteristic length, and μ is the fluid viscosity. Reynolds number is used to compare steady flows and ensure that aerodynamic forces and moments appropriately scale. Strouhal number, in contrast, is used to compare unsteady flows and ensures that oscillation frequencies match between experimental

and full scale flows. Strouhal number is written as the ratio of oscillatory velocity to a reference velocity and is given in its general form by Eqn. (2).

$$St = \frac{fl}{V_{\infty}} \quad (2)$$

In Eqn. (2), f is the frequency of oscillation, L is the characteristic length, and V_{∞} is the freestream velocity. Matching these two ratios ensured that experimental conditions were an accurate representation of the full scale ship airwake.

1.3 Flow over a Backwards-Facing Step

The backwards facing step represents the most fundamental form of the ship airwake problem. If the mast, weapons, and communications equipment were removed, the back of the ship superstructure and the flight deck would form what is simply a very large backwards-facing step. Previous research has shown this interaction to be one of the more dominant structures present in the airwake. Fortunately, the backwards-facing step provides one of the simplest geometries for studying separated flow.

In general, separated flow is a complicated, unsteady phenomenon. It occurs when a flow originally traveling along a surface is suddenly separated from the surface. This commonly occurs at sharp corners, where the frictional forces attaching the flow to the surface and attempting to change its direction cannot overcome the air's own momentum. It has historically been difficult to predict the effects of separated flows, but recent advances in Computational Fluid Dynamics (CFD) have greatly improved the ability to analytically model the phenomenon. These methods, however, tend to be computationally intensive as they must solve for six degrees of freedom on a very small scale in order to provide reasonable accuracy. Additionally, the results obtained must be confirmed using experimental data in a tedious and difficult process known as validation. As a result, standard wind tunnel testing has often provided a cheaper and less time-intensive alternative to in-depth CFD modeling. When combined with technology such as Particle Imaged Velocimetry (PIV), data collected from wind tunnel testing of separated flow has been shown to be exceptionally precise.

With regards to the backwards facing step, there is a variety of specific terminology which describes the flow. Figure 4 shows a diagram labeling the important characteristics.

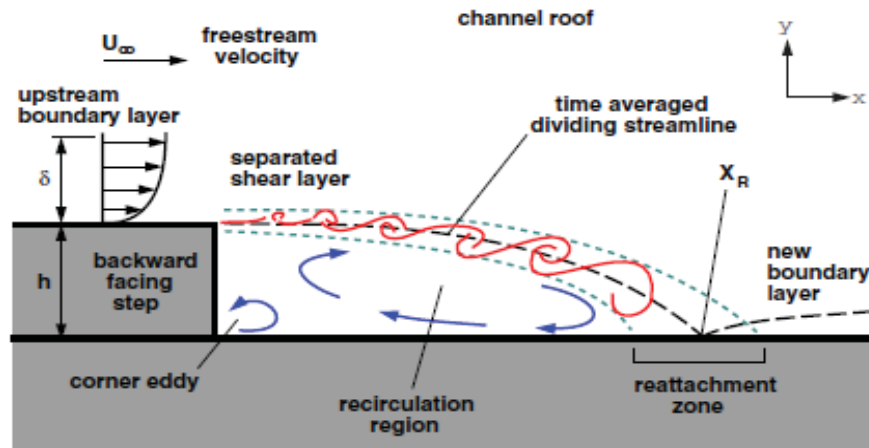


Figure 4. Important terminology describing flow around a backwards facing step [9].

1.3.1 Characteristics Affecting the Flow

A characteristic often used to compare backwards facing step flows is the reattachment length, or the distance between the base of the step and the reattachment zone. This value varies with the size and type of boundary layer (δ) before the flow separates. In general, the characteristics of the boundary layer are principally dependent on Reynolds number. There are two relevant forms of Reynolds number: momentum thickness Reynolds number and step-height referenced Reynolds number. The former is a function of the mass flow rate within the boundary layer and the latter is a function of the step-height. The two are proportional, but do not scale 1:1. In the case of a ship, both Reynolds numbers are very high and the boundary layer is almost certainly turbulent. This is a critical assumption, as the characteristics of the separated flow change drastically depending on whether the boundary layer is turbulent or laminar upon separation [10]. Figure 5 shows the difference in reattachment length depending on the momentum thickness Reynolds number at separation.

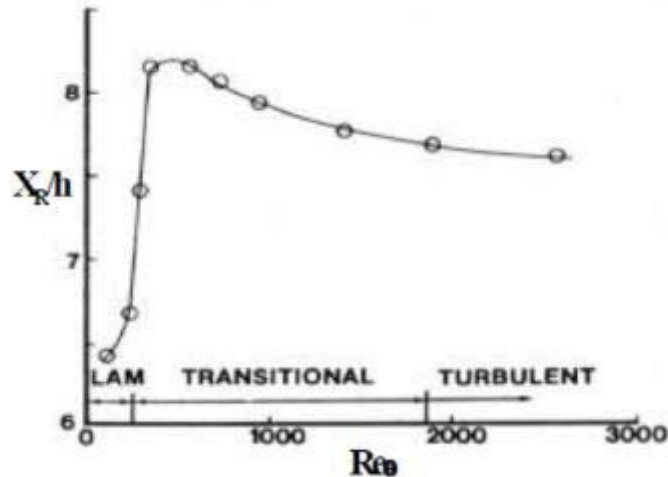


Figure 5. Reattachment length as a function of height versus momentum thickness Reynolds number at separation for flow over a backwards facing step [11].

Notably, Figure 5 is in terms of momentum thickness Reynolds number and can be converted to step-height referenced Reynolds number for analysis. Assuming that the boundary layer forms proportionally to a power law fit and that the flow is turbulent, a momentum thickness Reynolds number of 2,000 is equivalent to a model step-height referenced Reynolds number of 74,000. As demonstrated in the above plot, the reattachment length as a ratio of height approaches a limit of approximately 7.5 above this value. For a ship, this length can be on the order of hundreds of feet resulting in a step-height referenced Reynolds number on the order of 10^7 . Testing was conducted at a step-height referenced Reynolds number of 26,000 and momentum thickness Reynolds number of 700, which was below the desired threshold. The model, however, was oscillated at relatively high speeds during testing. Since laminar boundary layer require very low turbulence levels to form, this almost certainly resulted in the formation of a turbulent boundary layer for all data points. Additionally, the difference in reattachment length between the experimental testing and a hypothetical Reynolds number independent test would be a maximum of 4%. While an ideal test would have been run at a momentum-thickness Reynolds number greater than 26,000, a larger model could not have fit in the tunnel and more powerful equipment would have been needed to generate the required gust profiles at a higher test-section velocity. Considering that this work was intended to compare distinct profiles being run at approximately the same step-height referenced Reynolds number, this 4% error was accepted.

Additional research has also shown that aerodynamic characteristic of bluff bodies (to include a backwards facing step) can be considered Reynolds number independent for step-height referenced Reynolds numbers in excess of the range 10,000 to 20,000 [12, 13, 14]. Since testing occurred at a step-height referenced Reynolds number of 26,000, the flow was assumed Reynolds number independent. Therefore, the primary controllable factor affecting the flow

characteristics was the step geometry: the height of the step and the aspect ratio (the ratio of the step width to the step height).

There, however, are three other non-controllable test section factors which likely affect the flow around a step. These are boundary layer thickness (δ), free stream turbulence, and expansion ratio (the ratio of test section height downstream of the step to that upstream of the step) [15]. The middle factor, turbulence, can be neglected given the highly uniform flow generated in the CCWT.

According to Bradshaw and Wong, the ratio of boundary layer size to step height determines the degree of perturbation for the flow, which is inversely proportional to the dependence of the reattachment length on boundary layer height [16]. For $\delta/h \ll 1$ (the case of a ship airwake where the boundary layer height is very small in comparison to the step height), the degree of perturbation is said to be overwhelmingly large and the dependence of reattachment length on boundary layer height is said to be negligible. Figure 6 demonstrates this assertion.

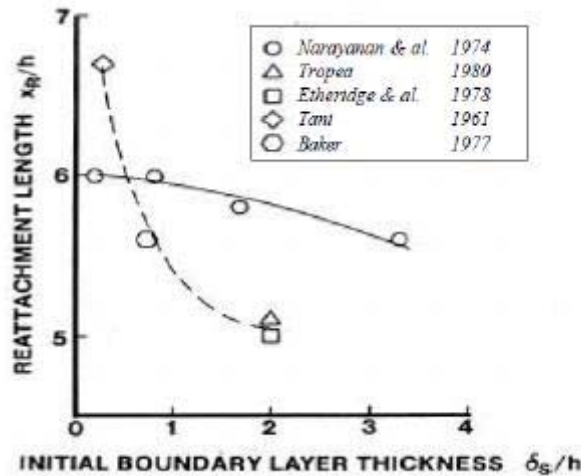


Figure 6. Reattachment length as a function of boundary layer thickness [11].

While much of the data shows a dependence between reattachment length and boundary layer thickness, the data collected by Narayanan was gathered at much lower turbulence levels. Considering the low levels of turbulence in the closed circuit wind tunnel, Narayanan's data is more applicable to this research.

The final factor, expansion ratio, is unavoidable but should be minimized for any experiment. Figure 7 shows the compiled body of research demonstrating the relationship of expansion ratio to reattachment length.

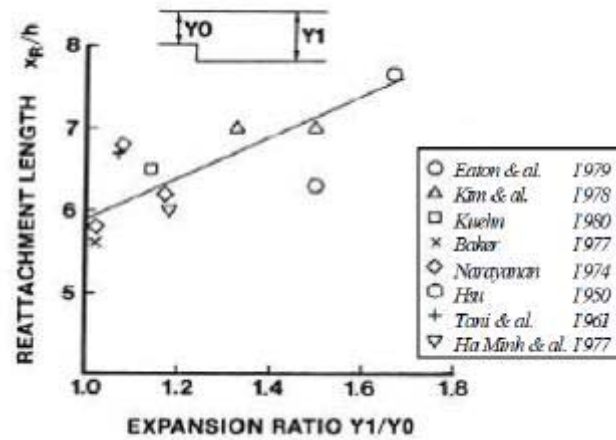


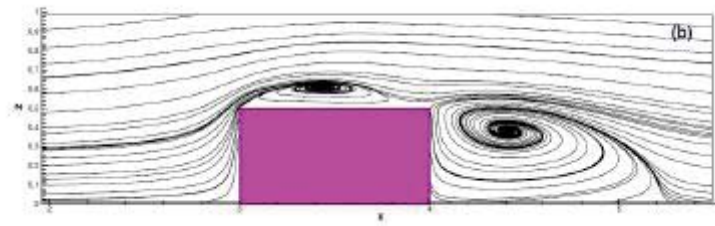
Figure 7. Reattachment length as a function of expansion ratio [11].

As shown, there is a linear relationship between the reattachment length and the degree of blockage quantified as the expansion ratio. The ideal testing condition involves an expansion ratio close to one, where the expansion ratio effects can effectively be neglected. In this experiment, the expansion ratio was 1.1 indicating an approximately 3% effect on the reattachment length.

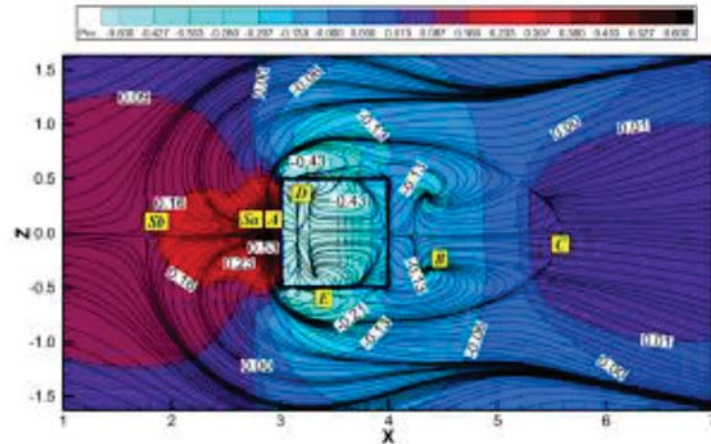
1.3.2 Three Dimensional Effects

In determining the effects of three dimensional geometry, it is prudent to examine the flow around a 3D parallelepiped (or more simply, a cube) placed flat against the test section and with the front face orthogonal to the flow. While this setup does not provide a perfect analog to a ship due to its short effective length, the effects at the corner edges are certainly applicable. A full representative ship geometry will be discussed in Section 1.4.

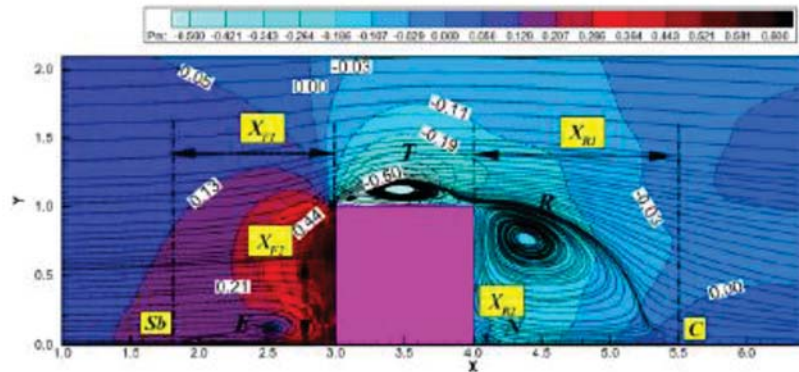
For the purpose of visualization, a CFD model developed by Yakhov et. al. demonstrates the streamline and pressure distribution about a cube in a uniform flow field (Figure 8). These results were later validated by PIV testing resolved by Wang and Zhou [17].



a) Time averaged distribution of streamlines, horizontal view, mid-cube height and width



b) Time averaged distribution of pressure and streamlines, top view



c) Time averaged distribution of pressure and streamlines, horizontal view, bottom height

Figure 8. Time average streamline and pressure distributions for a three dimensional cube using CFD modeling [18].

As shown in Figure 8.a, excluding the front face from analysis yields a flow very similar to that of a 2D backwards facing step (Figure 4). However, the effects of corner eddies (labeled “B” in Figure 8.b) clearly change the reattachment length (labeled X_{R2} in Figure 8.c). This

phenomenon of corner eddies is very similar to wing tip vortices around the edges of a finite wing and is similarly dependent on the aspect ratio of the cube. Far from the corners (point C in Figure 8.b), the flow is nearly analogous to that of the 2D step. Moving toward the edges, the reattachment length decreases exponentially as the corner eddies have stronger and stronger effects. Concurrently, the size of the recirculation region reduces proportionally with the reattachment length. It is worth noting that the overall reattachment length for a cube is significantly lower than that of a 2D step, as an amount of flow energy is lost interacting with the front face of the cube.

In summary, Figure 9 shows a schematic representation of vortices around a surface-mounted cube [19]. The structures labeled C and D are largely generated by the effects of the corner eddies, while A and B are generated by flow separation on the leading face. All of the labeled structures are relevant to the ship airwake problem, as the flow downstream of the cube is affected by the vortices at the cube.

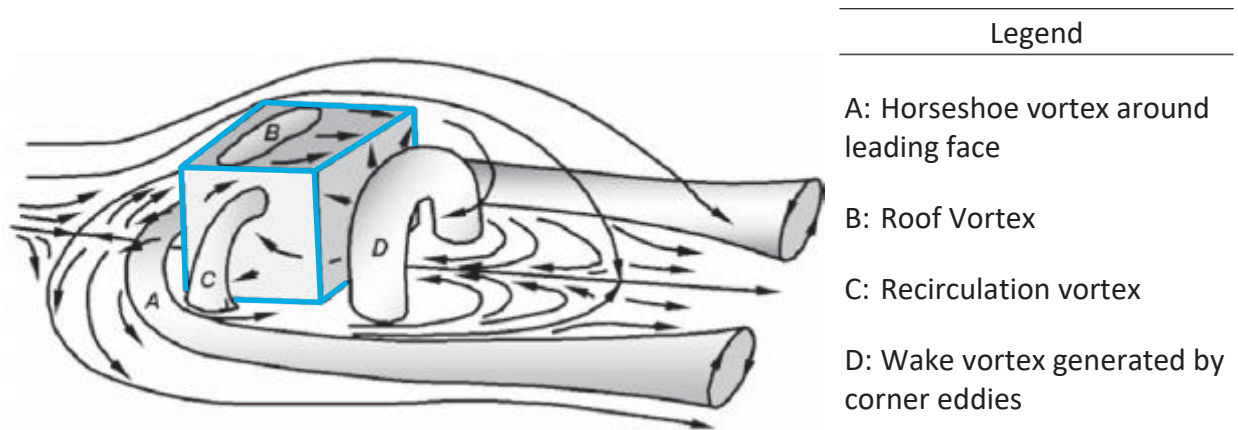


Figure 9. Schematic representation of vortices around a surface-mounted cube [19].

1.4 Ship Airwakes

Ship airwake research is critically important to navies around the world due to its operational relevance. As a result, a great deal of research exists on the topic and the field is well funded. In addition to airwake analysis for individual classes of ships, yaw, pitch, and roll response have been well researched on a more general scale. However, there is yet to be a comprehensive study on transient gust response. As a result, this experiment used assumptions based on relevant prior experiments conducted on similar topics. One example is the use of a representative ship geometry, which is elaborated upon in the following sections.

1.4.1 The Simplified Models

There are several simplified models commonly used to simulate ship airwakes, with the most common shown in Figure 11. The SFS2 model shown below is one of many “Simple Frigate Shapes”. While this research targets United States Navy ships (specifically, cruisers and destroyers), Figure 10 shows that the SFS2 geometry is still very similar to the Ticonderoga Class Cruiser profile.

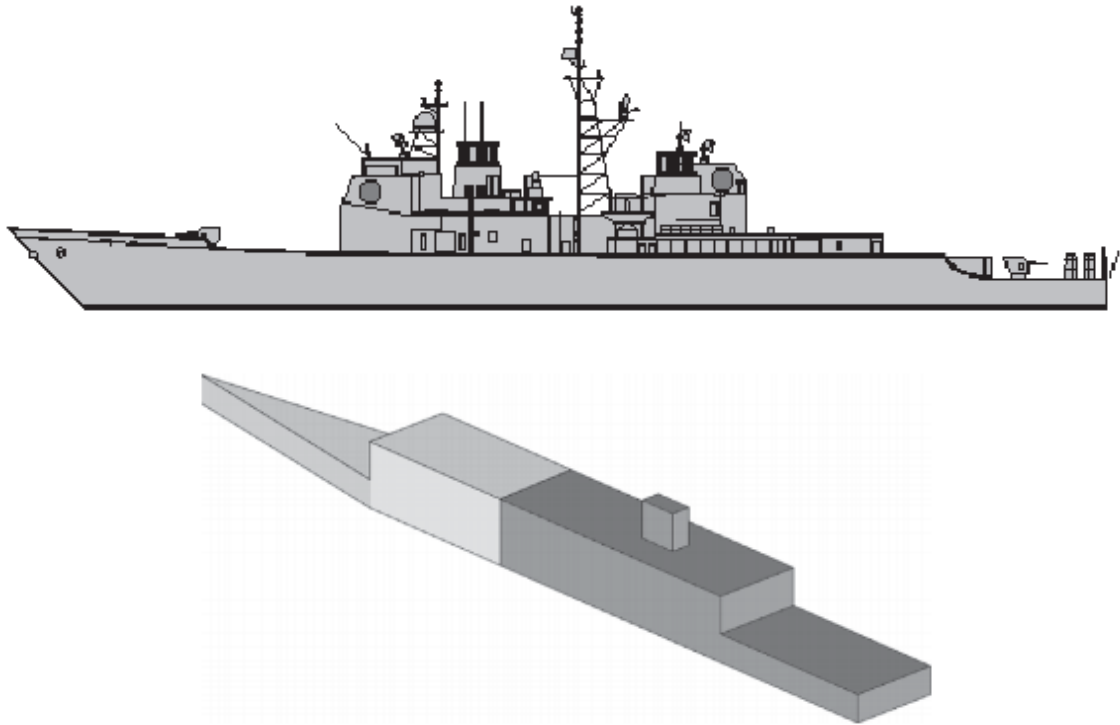
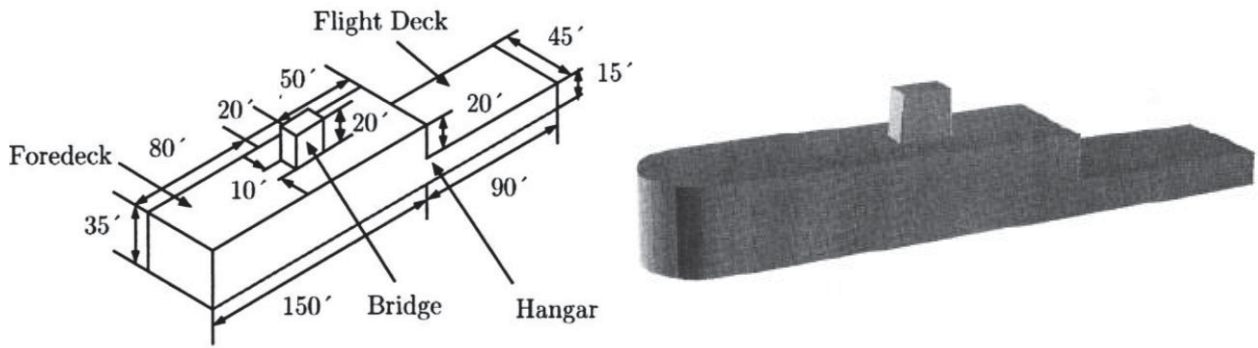
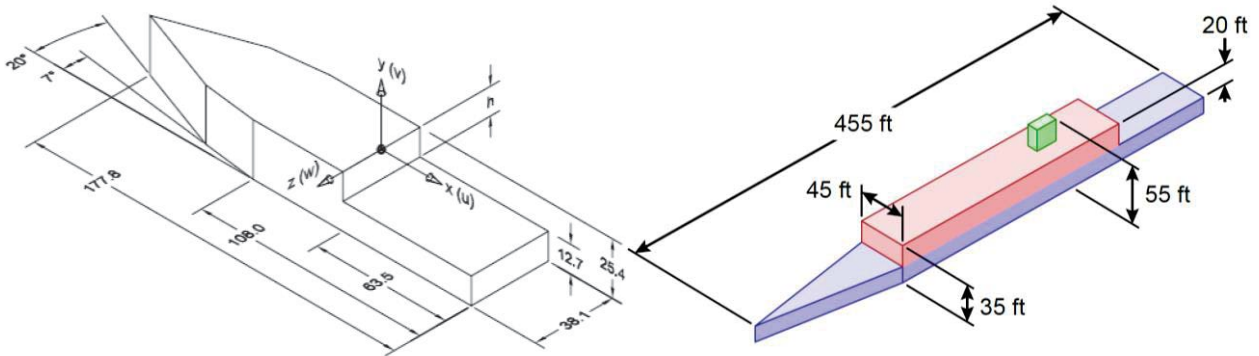


Figure 10. Frigate geometries. Ticonderoga Class Cruiser profile (top) and the SFS2 geometry (bottom). In the lower diagram, the lighter region denotes an addition to the base geometry.



a) Simple Frigate Shape One (SFS1) [20]

b) Simple Frigate Shape "C" (SFSC) [21]



c) Simple Frigate Shape "T" (SFST) [22]

d) Simple Frigate Shape Two (SFS2) [23]

Figure 11. Simplified ship geometries in full-scale dimensions.

1.4.2 Comparison with Scale Geometry

Forest and Owen, in their paper "An investigation of ship airwakes using Detached-Eddy Simulation", compared flow around a simple frigate shape geometry (SFS2) with that around an actual Royal Navy Type 23 Frigate (T23) [24]. Their analysis combined methodologies using, Detached-Eddy Simulation (DES) on an unstructured grid, high quality wind tunnel data provided by the National Research Council of Canada, and full scale data gathered at sea aboard a Type 23 Frigate. The wind tunnel experiment was conducted in a 2 m x 3 m low speed wind tunnel and hot-film anemometry was used to map mean velocities and turbulence intensities within the flow. The at sea data was gathered using 3-axis propeller anemometers. Their results show that there are differences between the SFS2 and T23 airwakes. Specifically, the T23 airwake contains smaller turbulent structures that are similar in strength to the SFS2 structures.

Additionally, there are larger differences in the local flow patterns around prominent features of the super structure, such as a hangar ‘notch’. Forest and Owen conclude that while it is certainly more accurate to account for the actual structure, the use of a simplified ship geometry “may be adequate for many purposes [24].”

Figure 12 shows a comparison between the CFD modeling of the simplified geometry and that of an actual T23 geometry. The purpose of this figure is not to show an exact resemblance, but to show a general resemblance of trends which demonstrates the validity of the simplified model. In their paper, Forest and Owens confirm the validity of their CFD model for describing real flow around both the simplified geometry and the full scale T23.

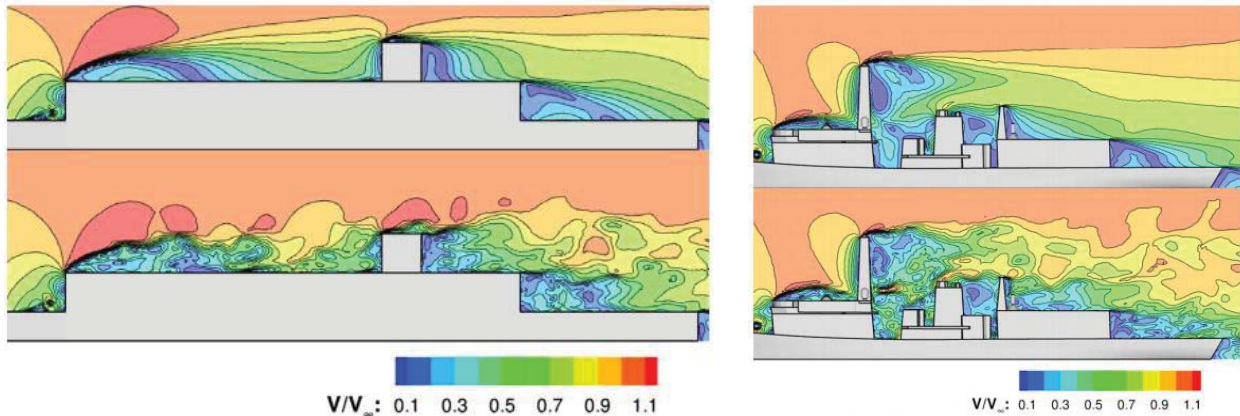


Figure 12. CFD modeling of airwake velocity over SFS2 (left) and T23 (right) geometry [24].

Given that the nature of this research was determining the effects of directional gusts, a simplified ship geometry was acceptable. The core analysis was the difference between uniform flow and flow that directionally shifts. As such, it was not required that conditions exactly model that of a real ship. The differences between the static (control) and dynamic (transient) runs provided sufficient basis for comparison and determination of actual effects on a full scale ship geometry.

1.5 Gust Modeling

Even today, the physics behind sudden wind direction changes is poorly understood. Historically referred to as “headers” and “lifts” by sailors, these directional changes are above the threshold considered turbulence, yet are always present [25]. Contributions to the phenomenon are believed to include steepening gravity waves, density currents, pulses of drainage flow, and a variety of other complex factors [26]. Statistical analysis of directional gusts conducted by Mahrt in 2010 provided the necessary data to accurately simulate real world conditions and to determine effects on a representative ship airwake.

1.5.1 Standard Analysis

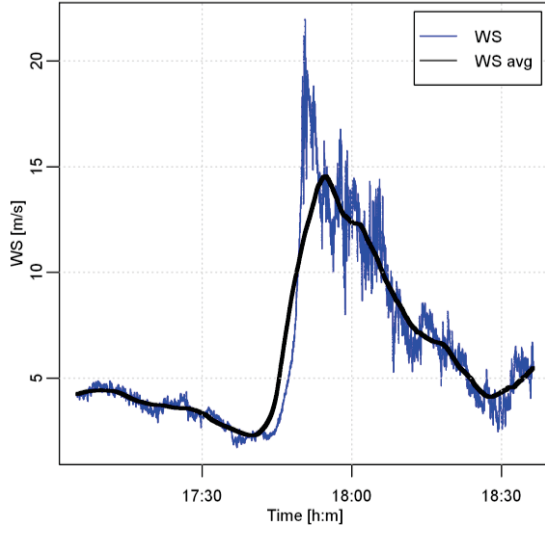
To adequately model a gust, accepted definitions will be used that are found in standards and reference literature. In general, a gust is defined by Bradlard as “*a short-term wind speed variation within a turbulent wind field* [27].” While the delineation between turbulence and gusts can be murky at best, it is generally accepted that timescales of 1 second to 10 minutes encompass the domain. At the upper end of this range, one can consider the wind transients to be long-duration, turbulent wind patterns rather than gusts. Figure 13 shows two measurement examples of these types of transient wind profiles. In Figure 13.a, the wind magnitude changes by a factor of three, but the duration is approximately 45 minutes. Thus, this is actually more like a large-scale weather front moving past the measurement location. Even in Figure 13.b, the timescale of about 5 minutes is still too long to be considered a transient gust.

A more representative example of a wind gust that is relevant to the present research is shown in Figure 14. Branlard considers transients of 5-10 second duration to be germane to larger-scale structures such as wind turbines, buildings, and ships [27]. Figure 14.a shows a moderate wind transient that increases about 30% in magnitude over 5 seconds, for a total gust duration of about 10 seconds. Manwell defined this profile analytically using the sombrero-shaped curve shown in Figure 14.b [28]. This type of profile is a perturbation to a steady wind at the mean freestream speed, V_∞ , that suddenly rises to a maximum of Δv_g above the mean over the rise time, t_r , then decreases again to the mean speed. The peak-to-peak magnitude is given by $\Delta v_{\max}$, and the maximum flow deceleration time is t_d . The overall duration, or period, of the gust is given by T .

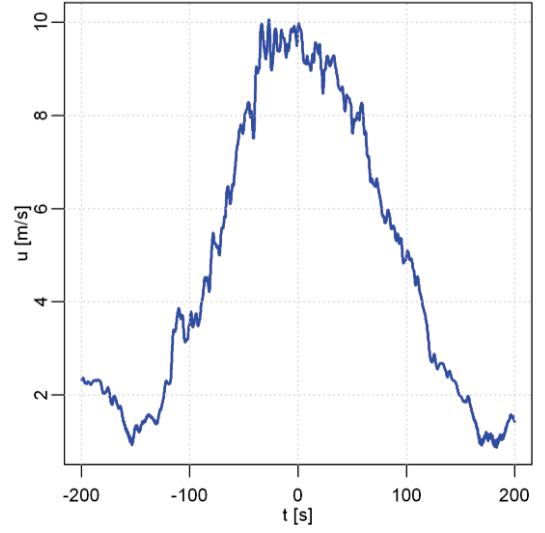
The Manwell profile was idealized to model the so-called extreme operating gust (EOG) used for wind turbine design, and is shown in Figure 15.a. The analytic expression is given by Eqn.(3), and assumes a symmetric profile. The given example shows $V_\infty = 25$ m/sec, $\Delta v_{\max} = 11$ m/sec, and $T = 10$ sec. However, this gust profile was more complicated than necessary for the purpose of this experiment. Specifically, the brief decreases in wind velocity prior to the main body of the gust would be difficult to replicate in a wind tunnel, and it is unlikely that these small decreases would have more of an effect on the ship airwake than the main body of the gust. As a result, the expression of Eqn. (4) will be used. This profile assumes, in addition to Manwell’s formula, that $\Delta v_{\max} = \Delta v_g$ and $t_d = t_r = T/2$, and is a common simplified representation of a gust. Because this research modelled a lateral gust that changes the local flow angle momentarily, it was also assumed that $V_\infty = 0$ even as the axial freestream velocity, U_∞ , was nonzero. Therefore, the only two variables required to model the gust experimentally were Δv_g and T .

$$v(t) = \begin{cases} V_{\infty} - 0.37\Delta v_g \sin\left(\frac{3\pi t}{T}\right) \left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] & \text{for } 0 \leq t \leq T \\ V_{\infty} & \text{otherwise} \end{cases} \quad (3)$$

$$v(t) = \begin{cases} V_{\infty} + \Delta v_g \left[\frac{1 - \cos(2\pi t/T)}{2} \right]^n & \text{for } 0 \leq t \leq T \\ V_{\infty} & \text{otherwise} \end{cases} \quad (4)$$

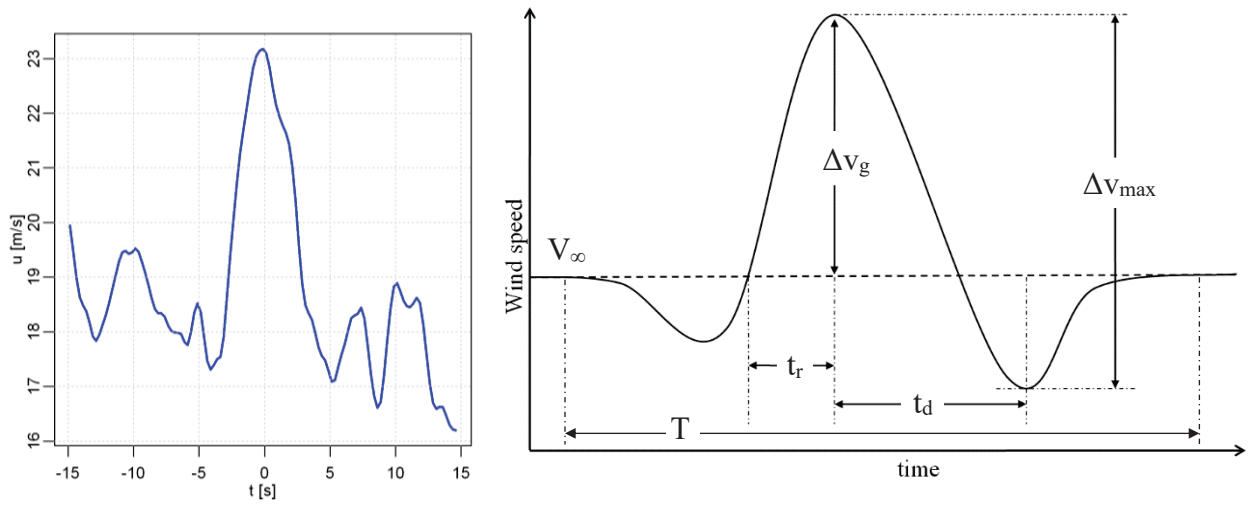


a) A long-duration wind front



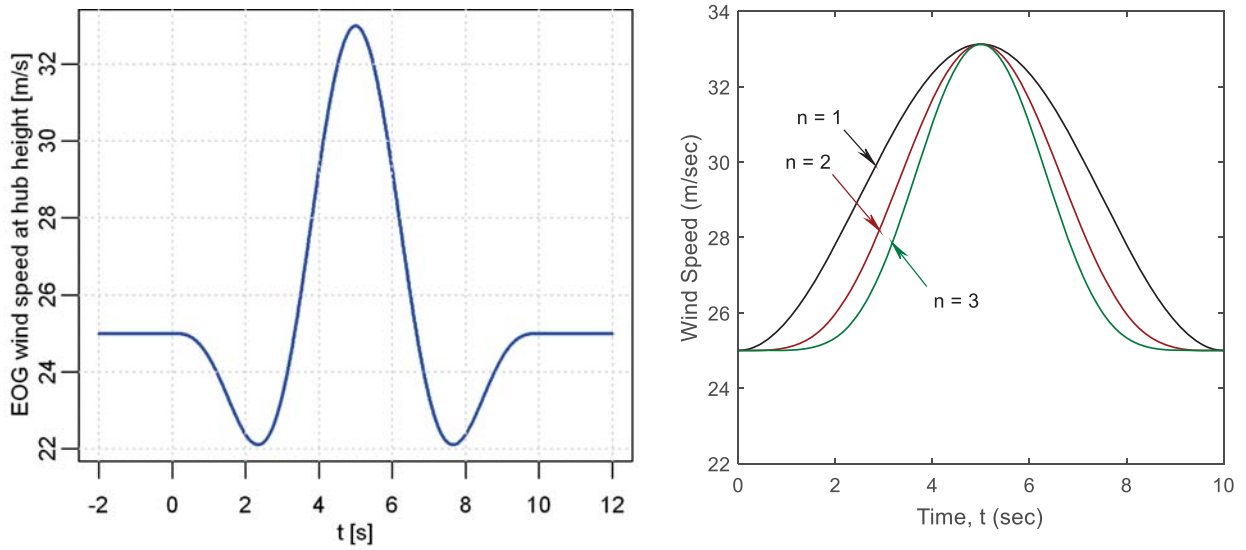
b) A moderately long-duration squall

Figure 13. Wind speed variations not considered to be gusts [27].



a) Typical short-term wind transient b) Generalized gust model [28]

Figure 14. Transient wind pattern considered for present gust modeling [27].



a) Idealized gust model [2]

b) Lateral gust models for present study

Figure 15. Modeling an extreme operating gust.

1.5.2 Statistical Distribution of Wind Direction

Mahrt gathered his data from a variety of test sites in a spectrum of climates with varying surrounding surfaces. The emphasized data in Mahrt's report comes from a 34 meter tower denoted "Fluxes over Snow Surfaces II" (FLOSSII) [26]. Mahrt chose to emphasize this data because it represented an "intermediate site", displaying a mix of topography between relatively homogeneous sites and those with complex terrain [26]. As a result, the bulk of figures contained in his report analyze the results from FLOSSII. Considering that these data points were specifically chosen to represent a generic wind flow, the trends can be assumed to hold accurate even in a maritime environment. The report does contain data acquired from the ASIT sea-based sampling location, but this data is limited to a single location and season. For the purpose of discussion, it was sufficient to use the figures and analysis of FLOSSII provided by Mahrt.

Upon analysis, it is immediately obvious that wind direction variability is inversely proportional to wind speed. Figure 16 clearly demonstrates this relationship using data gathered from FLOSSII.

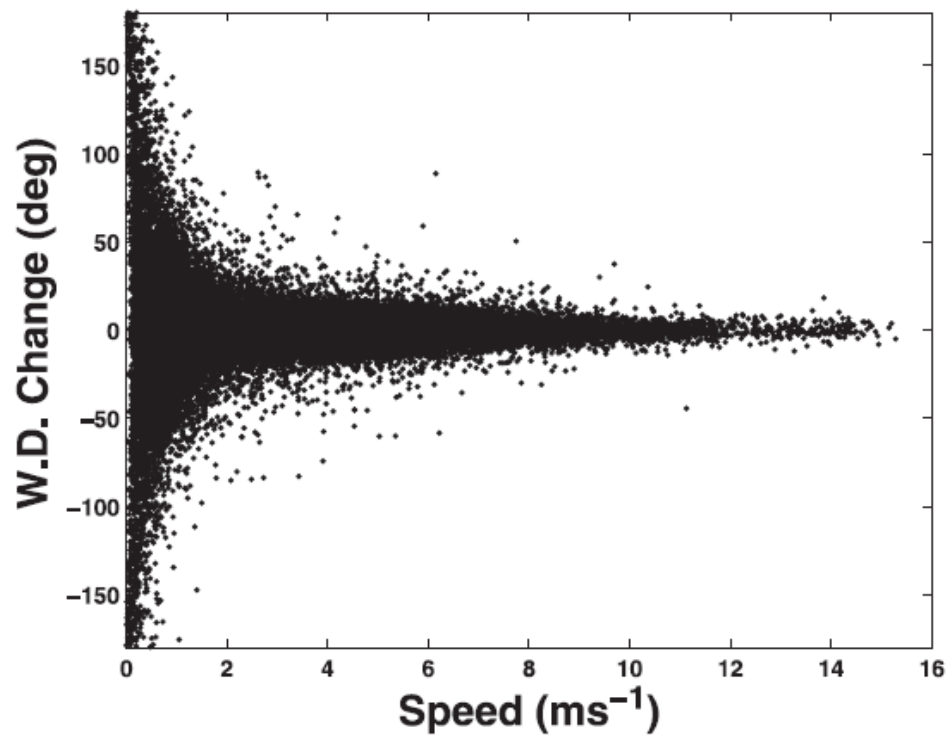


Figure 16. The change in 1-min wind direction as a function of wind speed. Gathered from nocturnal FLOSSII data [26].

While the scatter is enormous at low wind speeds, this has little effect on shipboard operation. Cruising speed for most Navy ships is generally around 5 m/s (10 knots). This speed would generate a 5 m/s relative headwind, meaning that a drastic change in true wind speed at 1

m/s would have a marginal effect on the relative wind experienced by an approaching helicopter. Additionally, winds at less than 5 m/s would have little effect on aircraft performance in any flight conditions. As such, this discussion will focus on wind speeds in excess of 5 m/s.

In order to model the shifting wind, the standard deviation of the wind direction with respect to wind speed must be known. Additionally, the relative stability of this data must be determined. Mahrt approached this latter problem by comparing the standard deviations of the wind direction based on the time interval in which they were based. Figure 17 shows the results of this comparison.

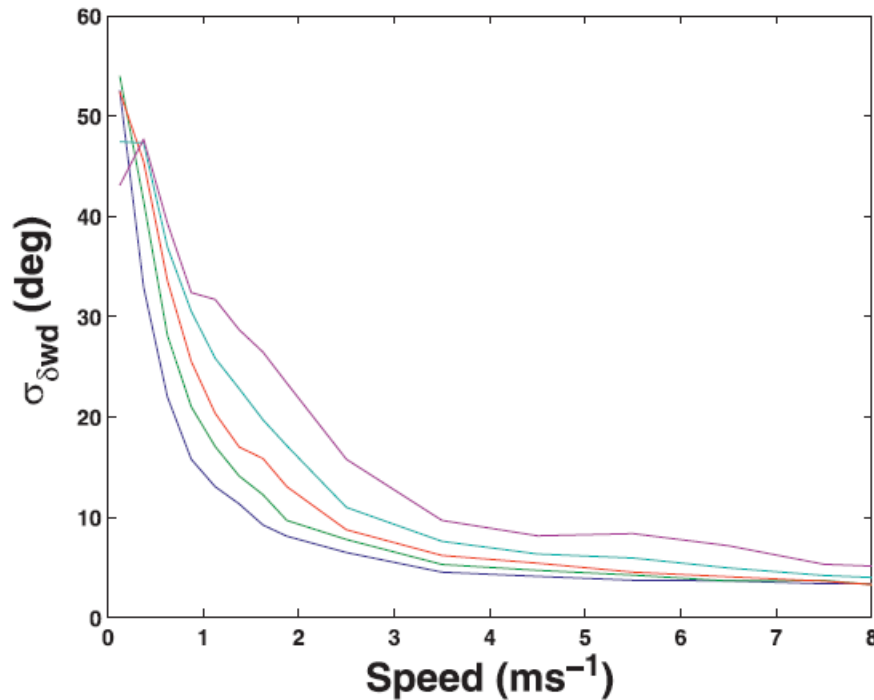


Figure 17. The dependence of standard deviation on averaging time as a function of wind speed with intervals of 1-blue, 2-green, 4-red, 8-cyan, and 16-magenta minutes [26].

As shown, the spread converged as wind speed increased, indicating increasing stability in measurement. While there was still a margin of uncertainty caused by this difference, it appears to be more acceptable at wind speeds greater than 4 m/s. Since this research focuses on flow effects for the worst case scenario, it is permissible to take the 16 minute standard deviation as an upper boundary on flow effect.

Figure 18 shows the standard deviation of the wind direction (one minute interval) as a function of wind speed for all tested sites. ASIT, the sea-based sampling location, is modeled by black crosses which are somewhat muddled by the more vibrant colors. For more easy reading, close inspection reveals that the black crosses correlate almost exactly to the more easily discernible solid red squares at wind speeds greater than 2 m/s.

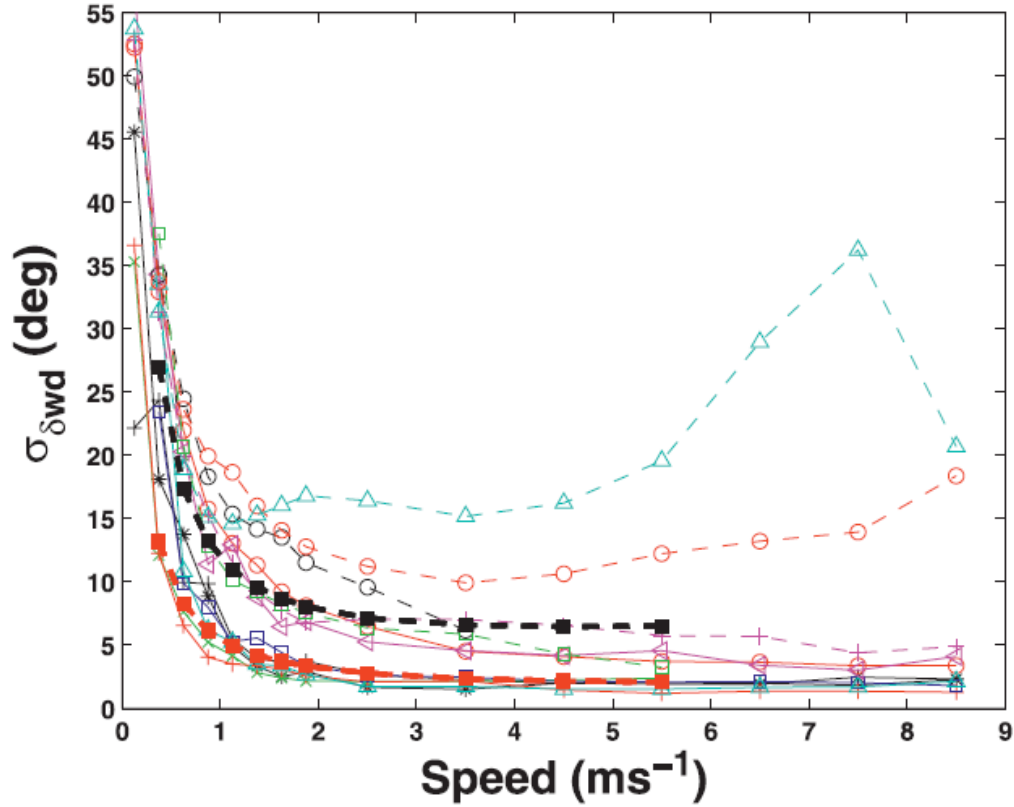


Figure 18. Near-surface nocturnal 1-min wind-direction variability as a function of wind speed [26].

From visual analysis, the standard deviation of wind direction at sea seem seems to be significantly less than that for FLOSSII. However, this data was taken over a limited period of time (3 months) and may not be valid for all oceans across the globe. Therefore, it is prudent to take a conservative yet realistic upper limit, which for this research will be the FLOSSII data.

1.6 Particle Image Velocimetry

Particle Image Velocimetry (PIV) systems use pulsed lasers and light framing optics in combination with high resolution high speed cameras to effectively “film” a flow field. There are several types of PIV systems and they are usually referred to by a XDYC designation, where X stands for the dimensionality of the area scanned by the camera and Y stands for the number of velocity components returned for individual particles. In a basic form, a single camera is used to generate the two dimensional velocity in a single planar frame of reference in a system denoted as 2D2C. This is demonstrated in Figure 19, which shows the basic setup for a PIV system. In general, 2D setups are referred to as stereoscopic PIV and 3D setups are referred to as tomographic PIV.

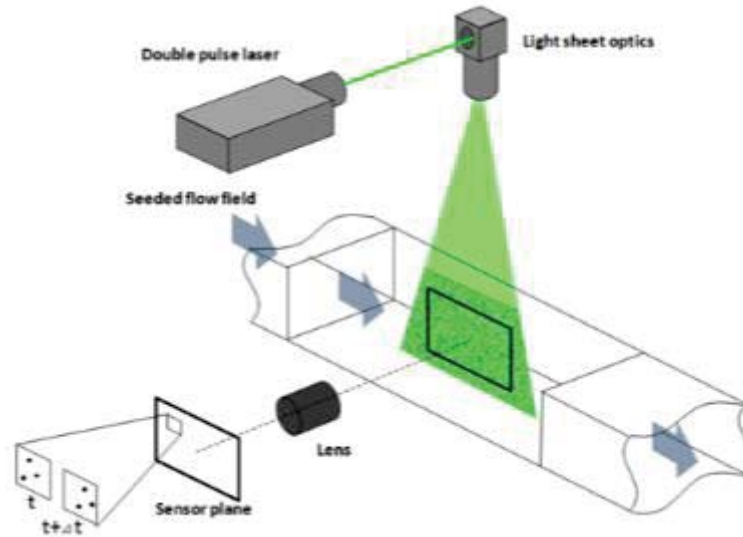


Figure 19. A typical 2D2C PIV setup [29].

At set time intervals, the position of individual particles within the flow field are captured. Software is then used to compare subsequent images and to generate velocity vectors for each individual particle. When calibrated using a true coordinate system based on the test section, the true velocities of each particle can be determined. Ideally, the time interval is small enough and the sampling area is large enough to ensure that the vast majority of particles remain visible in subsequent images. Figure 20 shows this process.

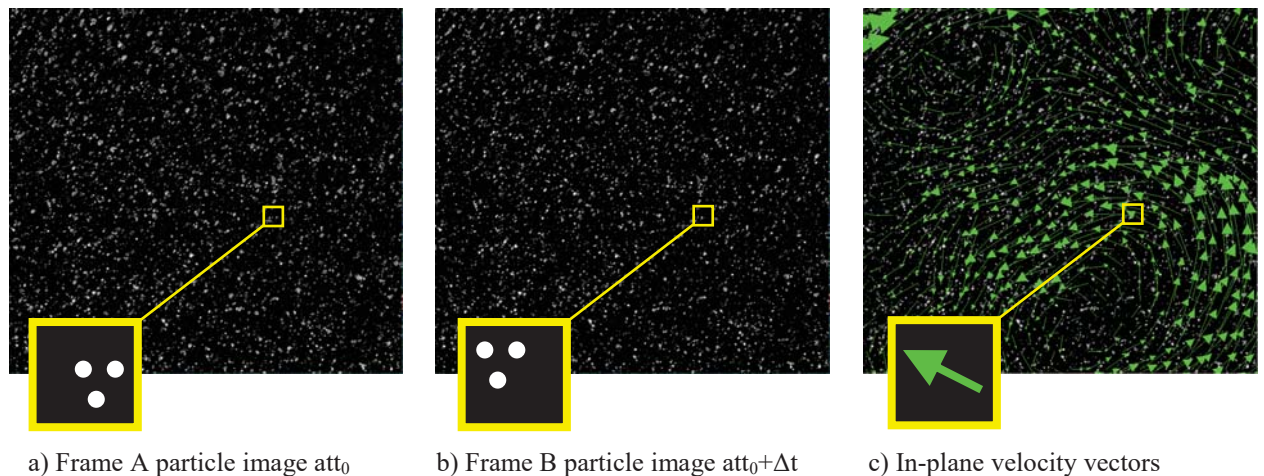


Figure 20. Particle images and resulting 2D2C vector map generated by PIV [30].

The current facilities in the CCWT allow for the use of two cameras when scanning a planar area. The differences between each camera (in a process analogous to triangulation) can

be resolved to give three dimensional velocity components for particles in a planar field. Additionally, the facilities are capable of supporting high-speed, time-resolved PIV (TRPIV) systems. This allows for high frequency sequencing of images of rapidly changing flow fields. This experiment used the two camera, 2D2C time-resolved PIV capability.

1.6.1 PIV Data Processing

A bilateral approach was taken when processing the PIV data. One component was referred to as statistical analysis and involved analysis of the PIV generated velocity fields. The second component used a dynamic post-processing technique known as Proper Orthogonal Decomposition to quantify changes in turbulent structures as a result of directional variation in the relative wind. Figure 21 visually demonstrates this approach.



Figure 21. A block diagram showing the proposed steps for data analysis.

1.6.1.1 Statistical Analysis

Statistical analyses was applied to the velocity fields generated by PIV software. Common statistical analyses include mean velocity and vorticity determination for an analyzed data field. This allows visualization of the flow in a manner similar to Figure 12. Additionally, standard deviations are used to determine initial indications of data quality

The primary use for this statistical data is comparison over varying gust periods and magnitudes. These comparisons were combined with the control (non-oscillatory) data and provided insight into how the airwake changes with these transient gusts.

1.6.1.2 Proper Orthogonal Decomposition

Proper Orthogonal Decomposition (POD) is a dynamic post-processing technique which can be implemented with time-accurate PIV data. It can be used to determine dynamic length and time scales, flow structures, modes, and decay times for a flow field. In regards to ship airwake research, it can be used to identity coherent flow structures within a flowfield.

POD works through applying an orthogonal transformation (or filter) to the principal velocity component and effectively reducing the order of the dynamic system. Spatial functions and temporal coefficients are then found through POD eigenmodes and integration, respectively.

The results allow for the estimation of length and time scales for the coherent structures within the flow [29]. The principle results of this research will be the analysis of the coherent structures within directionally varying flow determined by this POD analysis. This would allow for quantification of observations made using the TRPIV system, something that has yet to be done for transient gust response.

Figure 22 shows sample results of POD analysis for backwards facing step flow. The purpose of this figure is simply to demonstrate what POD results look like and what they mean. Each sequential mode indicates a decreasing effect on the overall flow structure. The 1st mode contains larger and stronger structures while the 10th mode contains smaller and weaker structures. This is somewhat intuitive, as the bigger and stronger structures should have a bigger overall effect than smaller structures.

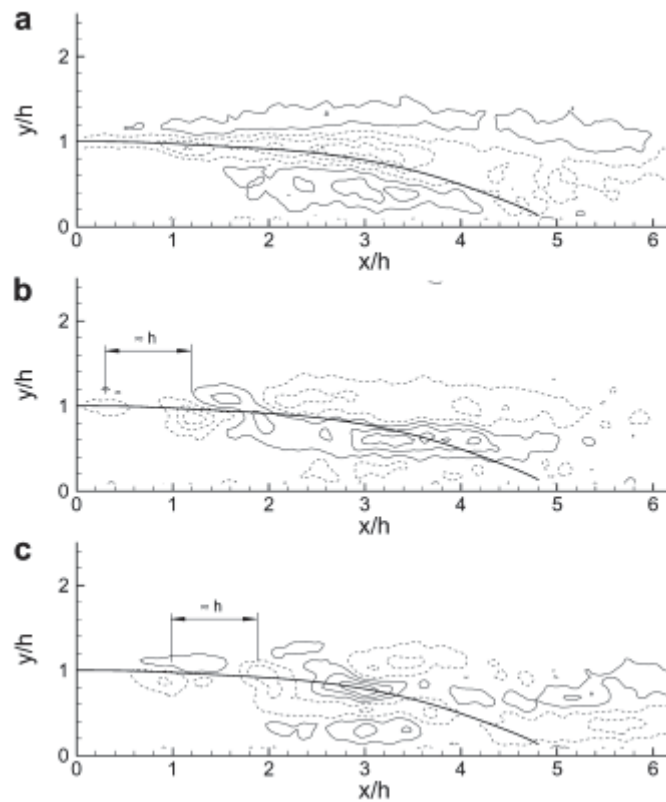


Figure 22. The 1st, 4th, and 10th mode (top to bottom) of a backwards facing step flow [31].

Computationally, POD relies on approximating functions as finite sums. For a general case $z(x, t)$, the following approximation applies [32]:

$$z(x, t) \approx \sum_{k=1}^M a_k(t) \phi_k(x) \quad (5)$$

It is reasonably assumed that this approximation becomes exact as M approaches infinity. However, there exist a variety of series approximations which could satisfy Eqn. (5). In the method of POD, orthonormal basis functions are chosen for $a_k(t)$ and $\varphi_k(x)$. By definition, orthonormal basis functions satisfy the relationship in Eqn. (6). Given Eqn. (6), then Eqn. (7) is the result.

$$\int_{x_1}^{x_2} \varphi_{k_1}(x) \varphi_{k_2}(x) dx = \begin{cases} 1, & \text{if } k_1 = k_2 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$a_k(t) = \int_{x_1}^{x_2} z(x, t) \varphi_k(x) dx \quad (7)$$

The importance of this relationship is that each coefficient, $a_k(t)$, is based only on $\varphi_k(x)$ and not on any other value of φ . In addition to being orthonormal, the basis functions should be selected so that the Eqn. (7) is as accurate as possible for any possible value of M . In simpler terms, the functions should be selected such that the first two terms give the most accurate possible two-term approximation and the first seven terms give the most accurate seven-term approximation and so forth [32]. These special functions ($\varphi_k(x)$) are referred to as the *proper orthogonal nodes* for the function $z(x, t)$. When these function are substituted for their appropriate variable, Eqn. (7) is referred to as the POD of $z(x, t)$.

1.6.1.3 The Discrete Case

For experimental data, it is necessary to use the above theory in the discrete (matrix) form. The conversion between the simple and discrete assumes m data points taken at N sets of time. From this data, matrix A is arranged so that element A_{ij} is the measurement at the j th probe taken at the i th time. The final result is the $N \times m$ matrix A . At this point, the singular value decomposition (SVD) must be computed. The SVD is governed by Eqn. (8).

$$A = U \Sigma V^T \quad (8)$$

In Eqn. (8), U is an $N \times N$ orthogonal matrix, V is an $m \times m$ orthogonal matrix, the superscript T indicates the matrix transpose, and Σ is an $N \times m$ matrix with all elements zero except along the diagonal [32]. The components of Σ are defined by the matrix operation $r = \min(N, m)$ and are arranged in decreasing order, including only nonnegative numbers. These are normally denoted σ and are called the singular values of A . At this point, it is prudent to make the substitution $U \Sigma = Q$, where Q is a $N \times m$ matrix. Additionally, let q_k represent the k th

column of Q and v_k be the k th column of V . When substituted into Eqn. (8), the discrete form of the POD of $z(x, t)$ is described as shown in Eqn. (9), from reference [32].

$$A = QV^T = \sum_{k=1}^m q_k v_k^T \quad (9)$$

1.6.1.4 Computational Application

The goal in POD is to determine $\varphi_k(x)$, or the matrix V in the discrete form. This can be done directly using SVD in most commercial computational software, such as MATLAB. In fact, MATLAB contains a built in function, *svd*, which returns the U , Σ , and V matrices for a given matrix A . Each column of the V matrix represents a proper orthogonal mode. Due to the decreasing order of the Σ matrix, the columns will be ordered in degree of influence from left to right. In this manner it is possible to determine the small number of dominant modes which govern the observed data, thereby reducing the dimensionality. Generally, the degree of influence will drop off significantly across each column. This can be quantified by analysis of the singular values of A , which can be thought of as coefficients for each mode. This assumption does not hold numerically true, but is qualitatively accurate. Figure 23 shows the singular values for the equation $z(x, t) = e^{-|(x-0.5)(t-1)|} + \sin(xt)$, $0 \leq x \leq 1$, $0 \leq t \leq 2$. As described above, Figure 23 demonstrates that the first three modes have far more significance than any of the other nodes.

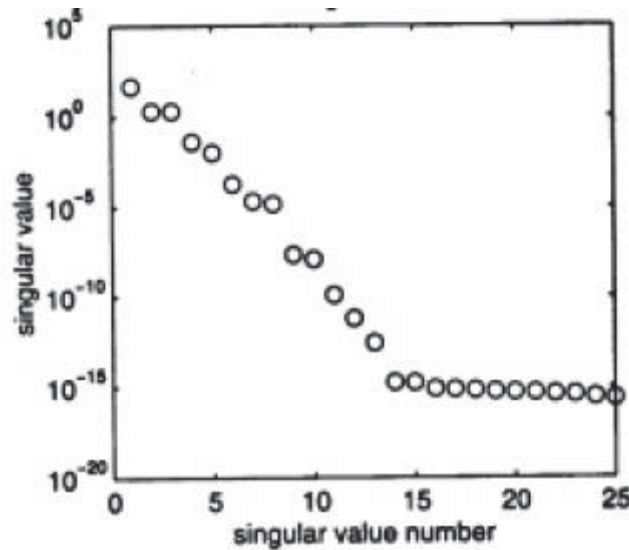


Figure 23. Singular values for the equation $z(x, t) = e^{-|(x-0.5)(t-1)|} + \sin(xt)$ [32].

2 Methodology

2.1 Test Facility and Equipment

2.1.1 Wind Tunnel

Testing was conducted in the United States Naval Academy Subsonic Closed Circuit Wind Tunnel (CCWT). This facility is located in Rickover Hall on the campus of the United States Naval Academy (USNA) in Annapolis, Maryland. This system was designed and built by Aero Systems Engineering (ASE). Figure 24 shows a schematic diagram of the wind tunnel.

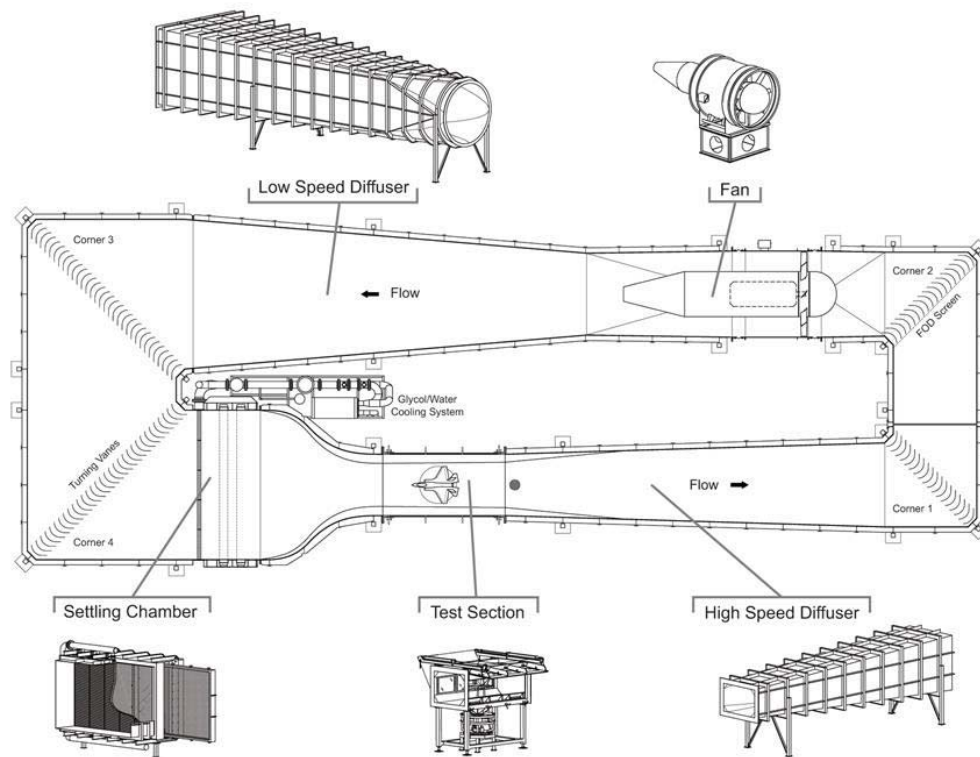


Figure 24. Schematic diagram of the USNA Subsonic Closed Circuit Wind Tunnel

In contrast to an open-circuit wind tunnel, the closed circuit wind tunnel continuously circulated air within the enclosed test section allowing particle seeding of the entire test section volume. The fan was used to create a pressure difference which forced the air to circulate around the tunnel. Downstream of the fan, the flow encountered a low speed diffuser which slowed the flow in order to be effectively turned by the turning vanes at corners 3 and 4. After corner 4, the flow encountered the settling chamber which reduced the turbulence present. The flow was then accelerated to the desired test speed through the contraction cone and entered the test section.

Following the test section the flow encountered a high speed diffuser and was slowed in order to round corners 1 and 2. The cycle then repeated. Performance specifications were provided by the manufacturer and are included in Table 1.

Table 1. Performance Specifications for the CCWT

Test section dimensions	42×60×120 in.
Contraction ratio.....	6.5
Maximum speed.....	300 ft/sec
Reynolds number	1.9×10^6 per ft. (maximum)
Fan output	295,000 CFM at 1,200 RPM and 400 HP
Test pressure	Atmospheric (nominally)
Test temperature.....	50–120 deg. F

The tunnel was run between 10% and 20% of its maximum operating speed for the entirety of testing. Test section dynamic pressure was observed using a micromanometer filled with liquid water. The dynamic pressure was set to match flow conditions on what was found to be an average Annapolis day. This corresponded to a test section velocity of 25 fps with a temperature of 65 °F and an ambient pressure of 30.10 inches Hg. The results were ship-length referenced Reynolds numbers routinely on the order of 10^4 . Table 2 provides flow quality specifications for the CCWT.

Table 2. Flow Quality Specifications for the CCWT

Turbulence intensity.....	< 0.15%
Flow angularity	< 0.2 deg. (mean flow angle)
Velocity uniformity (spatial)	0.5% (mean flow velocity)
Temperature uniformity (spatial)	1 deg. F (with active cooling)
Horizontal buoyancy	0 (adjustable)

2.1.2 Representative Ship Model

As shown in Figure 11, there are four widely used models for simplified ship airwake modeling. When deciding which model to use, the Ticonderoga Class Missile Cruiser profile (Figure 10) was primarily considered. From simple visual comparison, the SFS2 (Figure 11.d) and SFST (Figure 11.c) were the closest geometries, with the principle difference between the two the inclusion of a forward facing step and a block on top of the superstructure on the SFS2 model.

From visual flow field analysis, the similarities between flow around the SFS2 and the scale T23 Frigate model shown in Figure 12 were extensive. While the SFST geometry was simpler and isolated the effects of the backwards facing step, the purpose of this research was representative ship airwake modeling, not backwards facing step modeling. As such, the more representative geometry was chosen: the SFS2 model.

2.1.2.1 Relative Dimensions

The dimensions of the model were based on the dimensions used in previous tests and provided by Naval Air Systems Command (NAVAIR). These dimensions were $l/H = 4.50$ and $w/H = 2.25$. Figure 25 shows the wind tunnel model geometry for the baseline configuration.

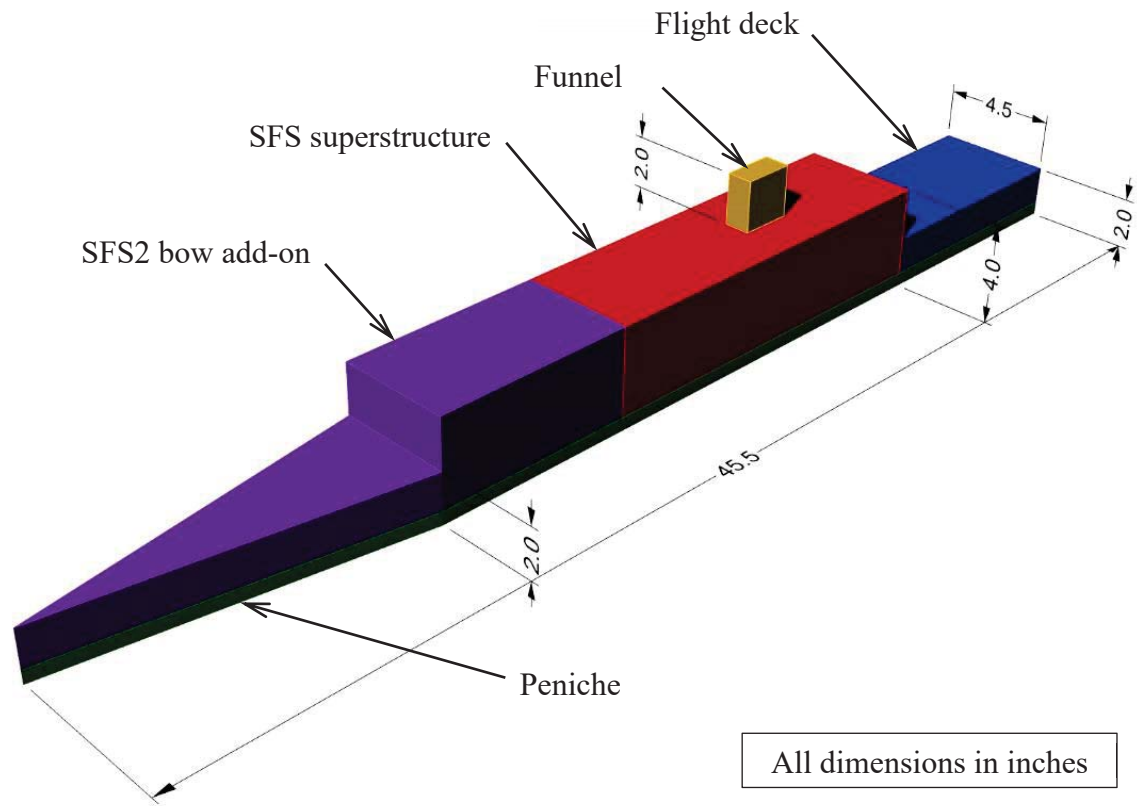


Figure 25. Dimensions of the 1:120 scale SFS2 model

2.1.2.2 Scale

The model length was 45.5 inches, the width was 4.5 inches, and the overall height was 4 inches. The resulting scale was 1:120. This scale was determined by the size of the test section at the upper limit and by the desired Reynolds number at the lower limit. A secondary concern was limiting blockage effects. As shown in Table 1, the size of the test section is 42 inches tall by 60 inches wide by 120 inches long. Figure 7 demonstrated that the relationship between test section height and step height had a significant effect on reattachment length. Unfortunately, this effect could not be fully negated while running at the desired Reynolds and Strouhal numbers. While shortening the model length would reduce the model height and the blockage effects, this would

also lower the Reynolds number. In order to then run at the same Reynolds number, the test section velocity would then need to be increased. This would in turn limit the Strouhal numbers attainable.

2.1.3 Ship Motion Actuator

A Tolomatic B3W10 belt-driven actuator was used to move the ship transversely within the test section in order to induce a transient, non-axial flow vector. Figure 26 demonstrates the simplified physics of inducing a gust using an oscillation orthogonal to the freestream velocity.

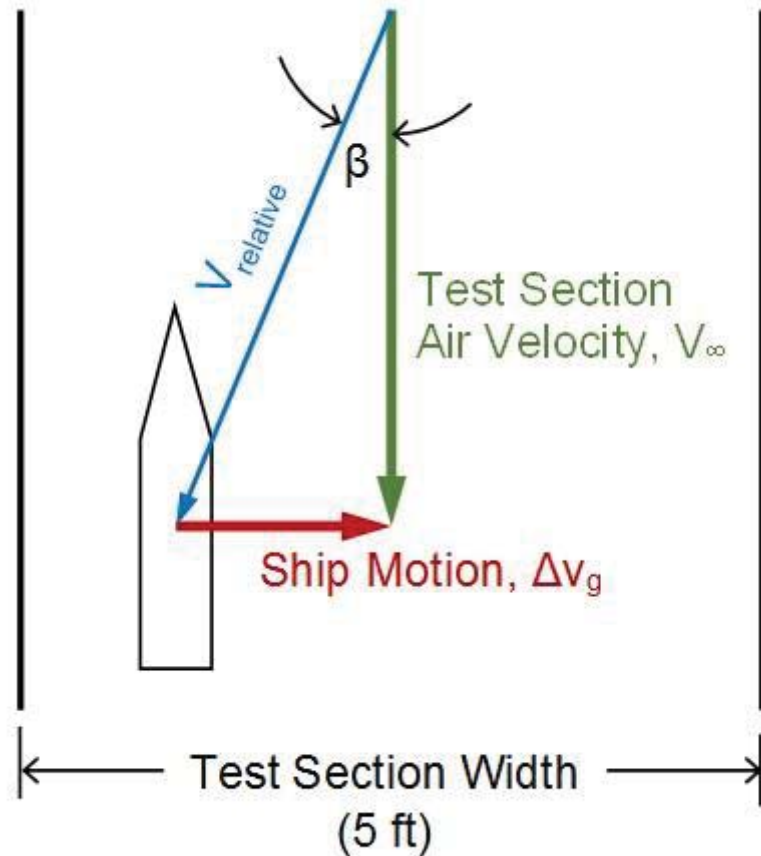


Figure 26. A representation of model oscillation.

The actuator was controlled using a Controllogix controller, a Kinetic 5500 drive, and Studio 5000 software all purchased through Rockwell Automation. User-entered motion profiles were correlated using closed-loop position feedback, allowing for the variation of oscillation frequency and lateral gust speed. Testing required lateral speeds of up to 6.8 ft/sec, accelerations

of up to 8.3 ft/sec^2 and stroke lengths of up to 9 inches. The components used are shown in Figure 27.



Figure 27. Experimental hardware. Top: Tolomatic belt-driven actuator. Left: Controllogix chassis setup. Right: Kinetix 5500 drive.

2.1.4 Particle Image Velocimetry Setup

2.1.4.1 PIV Hardware and Software

The current PIV system in the CCWT was installed between 2014 and 2016. This state-of-the-art system contains two 4-MP time-resolved imagers (12.3 KHz capture rate), a 380 mJ/pulse, 10 kHz high-speed laser, and a variety of planar light sheet optics and beam delivery systems. The particular optics employed were a beam focusing lens, an adjustable spherical lens, and a cylindrical lens ($f = -10 \text{ m}$). A 2.8 meter light arm was used to direct the light sheet into the tunnel. All data was gathered and processed using *DaVis* software purchased from the company LaVision Inc.

2.1.4.2 PIV Planes

Data was collected at three separate planes oriented parallel to the test section floor. These planes were denoted “waterplanes” as they would be parallel to the surface of the water.

Water planes are in the x-y plane as defined within the test section. The water planes were placed at $\frac{z}{H} = 0.25, 0.75, 1.5$, where H is the height of from the flight deck to the top of the step. Figure 28 shows a graphical representation of these planes.

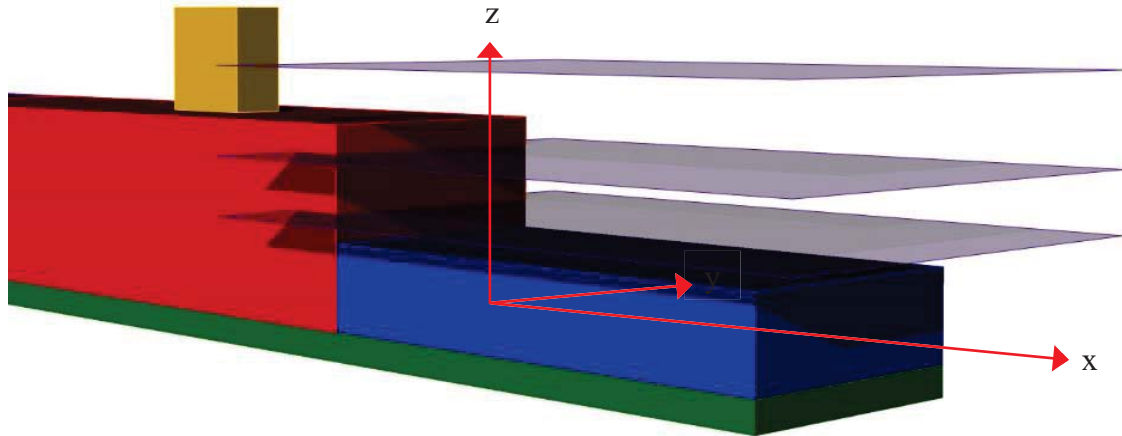


Figure 28. TRPIV waterplane fields of view to be tested

These planes were placed to create a somewhat holistic representation of the flow field. The top plane ($z/H = 1.5$) was primarily affected by the mast on top of the superstructure. The middle plane ($z/H = 0.75$) represented the part of the wake where an approaching helicopter would spend most of its time. The bottom plane ($z/H = 0.25$) represented the most dangerous point of the approach path for a helicopter. This region is where the helicopter is closest to the ship, and even a small amount of turbulence can force a blade strike.

2.2 Test Conditions

2.2.1 Determining the Test Matrix

The testing matrix was comprised of the two testing variables for this experimentation: gust duration and magnitude of directional oscillation. Duration was measured in seconds and directional change was measured via the trigonometric ratio of lateral model velocity to test section free stream velocity. As demonstrated below, the number of required data points increased exponentially as the range of both variables increased. The majority of these data points, however, were not critical for analysis.

2.2.2 Strouhal Number

The basis for test matrix determination was the wind gust frequency analysis conducted by Shaw, Ward, and Aylor [33]. Their findings demonstrated that the greater in deviation from the norm, the shorter period and rarer occurrence of the gust. In more simple terms, the stronger the gust, the less time it lasted. These findings were in agreement with the research conducted by Mahrt as discussed in Section 1.5. The period (or length) of the gust was used to determine the full scale frequency, as shown in Table 3. A stated objective of this research was to determine the individual relationships between oscillation frequency and resultant flow structures. As such, the Strouhal number (St) needs to be matched for the model and real world conditions.

Strouhal number is a dimensionless number (analogous to Reynolds number) used to describe oscillating flow mechanisms. In order to ensure scaling with model size, the Strouhal number for the model and the full scale ship needed to match. This was to ensure that the vortices present in the experimental flow were equivalent to those found in the full scale flow. For a lateral gust application, the Strouhal number takes the form of Eqn. (10).

$$St = \frac{fl}{\Delta v_g} = \frac{1}{T \Delta v_g} \quad (10)$$

In the case of this experiment, l represented the characteristic length, T represented the gust period, and Δv_g was the lateral velocity. Table 3 shows a matrix of full-scale conditions likely to be experienced by a ship conducting flight operations. The gust period values were converted to Strouhal numbers using a step height of 20 feet (approximately the height of the Type 23 Frigate analyzed in the Forrest and Owen study [24]) and a free stream velocity of 30 knots (50.6 fps, near the limit of conditions permissible for flight operations [Figure 3]).

2.2.3 Velocity Determination

The required translational velocity was determined through simple trigonometry. It was calculated from Eqn. (11), where x was the required translational velocity (ft/s), V_∞ was the freestream velocity (ft/s), and β was the sideslip angle (degrees), which was the desired wind shift in degrees off the starboard bow.

$$x = V_\infty \tan \beta \quad (11)$$

2.2.4 Conversion from Full Scale to Experimental Scale

As discussed above, Table 3 contains full-scale gust conditions likely to be encountered by a ship conducting flight operations. This was a total of 14 separate flow conditions (the purple-shaded cells in the lower right corner are not entirely relevant, as high-magnitude, long-duration gusts do not occur very often in nature). It was worth noting that the Strouhal numbers along the diagonals fell into bands of approximately the same value. These diagonals are color-coded.

Table 3. Full-scale gust Strouhal numbers for a ship conducting flight operations.

Gust Period (sec)	Maximum Change in Flow Direction (deg)				
	0	5	10	20	35
5	—	$St = 0.903$	0.448	0.217	0.113
10	—	0.452	0.224	0.109	0.056
20	—	0.226	0.112	0.054	0.028
30	—	0.151	0.075	0.036	0.019
∞	0 (control)	—	—	—	—

These bands of Strouhal numbers were averaged so that model-scale values could be tested. Table 4 used these averages to determine the model-scale gust periods to be tested in the wind tunnel. Note that these calculations assumed a 2-inch step height and 25 fps freestream velocity. When converting these Strouhal numbers, it became clear that the proposed setup could not accommodate some of the required conditions. The red shading in the upper right corner of Table 4 indicates accelerations too high for use with the proposed actuator (in excess of 100 ft/sec²) and the purple shading near the bottom indicates actuator stroke lengths too long for the actuator (i.e., greater than 1.5 ft); this also corresponds to the unlikely gust profiles shaded in Table 3. When discarding these values, 6 run conditions remained for testing. These were colored green for easy reference.

Table 4. Intermediate test matrix for experimental gust periods (T_m , sec)

Strouhal number	Maximum Change in Flow Direction (deg)				
	0	5	10	20	35
0.903	—	$T_m = 0.08 \text{ sec}$	0.04	0.02	0.01
0.450	—	0.17	0.08	0.04	0.02
0.222	—	0.34	0.17	0.08	0.04
0.111	—	0.69	0.34	0.17	0.08
0.062	—	1.23	0.61	0.30	0.15
0.032	—	2.38	1.18	0.57	0.30
0.019	—	4.01	1.99	0.96	0.50
0	∞	—	—	—	—

In an effort to increase the overall range of data points analyzed, a 7th data point was added for a change in flow of 15 degrees at a Strouhal number of 0.111. This individual point represented the maximum possible change in wind direction using the experimental apparatus. Table 5 shows the final test matrix, where green indicates a recorded data point.

Table 5. Target Test Matrix

Strouhal number	0°	5°	10°	15°
0.450	—		—	—
0.222	—			—
0.111	—			
0		—	—	—

At each of these run conditions, PIV data was acquired for the three waterplanes identified in Figure 26 yielding a total matrix size of 21 overall data points. It can be seen that a range of Strouhal number and gust magnitudes were observed to provide a broad spectrum of conditions.

2.2.5 Physical Motion Profiles

The simplified Manwell gust profile was used to simulate a transient gust with a linear actuator. The full gust profile was separated into three segments which analyzed the beginning of the gust (Segment C), the point of maximum lateral velocity (Segment B), and the end of a gust and switch from a clockwise to a counterclockwise gust (Segment A). All three segments are

shown in Figure 29. A convention was defined so that Profile 1A would refer to Profile 1, Segment A. The motion profiles used in data reduction are included in Appendix A.

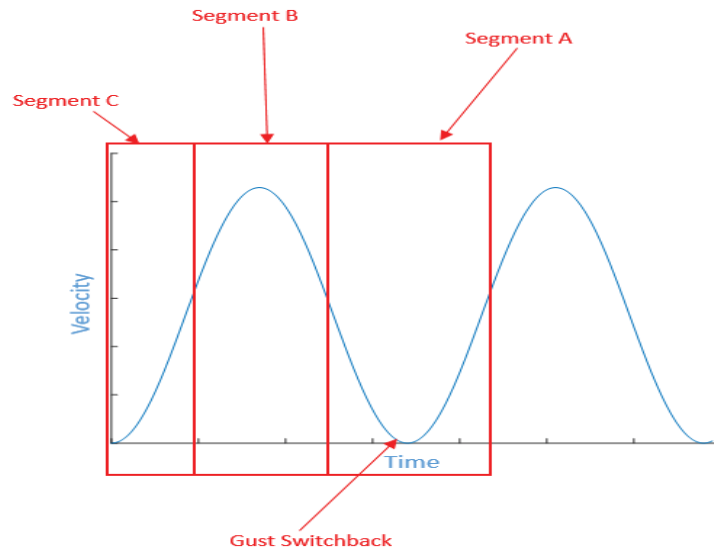


Figure 29. Motion profile segments.

2.3 Experimental Procedure

The ambient conditions of the day were used to set the indicated dynamic pressure for testing. As discussed previously, these conditions matched a 25 fps test section flow on an average Annapolis day. After flow had steadied within the test section, boiled olive oil was added as seed particles. The amount of total seed added was somewhat arbitrary, but in general enough seed was added to maximize correlation values in the data while not reducing the ability of the software to distinguish individual particles.

Motion profiles were preloaded and calculated based on the average Annapolis day. As a result, they did not change throughout testing. A physical trigger was wired to engage both the ship motion and the PIV recording at the same time. Upon receiving the trigger signal, the PIV software recorded for a preset length depending on the motion profile. For a Segment A run, the PIV recorded for the time period of the profile multiplied by a factor of 1.2. For a Segment B run, the PIV recorded for the period length. For a Segment C run, the PIV recorded for the time period of the profile multiplied by a factor of 1.5. The longer recording time for Segment C intended to capture the full transition from the transient gust to normal, steady flow.

The pulsed laser was run at maximum power (37 Amps) and employed a spacing (Δt) of 90 μs . The cameras recorded at 725 Hz, the maximum frequency possible for a full sized field of view. Three trials were recorded for each motion profile in each waterplane. Additionally for the three longest stroke lengths, Segment A was run a second time from a separate starting point in

order to capture the point of maximum model velocity in the PIV field of view. Static (control) runs included the stationary ship recorded for a duration of 2 seconds, the standard freestream (ship moved well outside the field of view) recorded for 0.25 seconds, and the freestream at 50 fps recorded for 0.25 seconds. For the faster freestream, the laser spacing (Δt) was changed to 45 μs in order to maintain a constant pixel shift. The freestream data points were taken to analyze data uncertainty and the quality of the test section flow. Collectively, this totaled 54 recorded data sets per waterplane.

2.3.1 Particle Image Velocimetry Settings

DaVis, produced by LaVision, Inc., was the PIV software used in the experiment. Processing settings were determined through a series of trade studies, to be detailed later in this report, which compared both results quality and processing time. During final testing, successive frames were taken with a separation time (Δt) of 90 μs , and the overall frequency was set at the camera maximum of 725 Hz. During processing, multi-pass cross correlation was used with a 64x64 pixel square as the first interrogation area. The final pass was a 32x32 pixel ellipse with 75% overlap. Post-processing removed vectors varying by more than 1.5 standard deviations from vectors in the nearest 8x8 pixel grid. Proper Orthogonal Decomposition operations were conducted over a select number of frames which calculated sufficient eigenmodes to isolate the most dominant flow structure.

3 Results and Discussion

3.1 PIV Trade Studies

3.1.1 Determining PIV Timing

In time-resolved PIV systems, there are two separate timing parameters which are controlled by the user. They are frequency and the spacing between each pair of images. Since the system is “time-resolved”, pairs of images are taken at speeds far faster than the overall frequency. This results in the overall frequency representing the number of separate vectors (not images) observed per second. The spacing between subsequent frames is referred to as “ Δt ” and the overall frequency is simply referred to as the frequency. Take a hypothetical setup with a Δt of 100 μs and a frequency of 1000 Hz. Every millisecond, two subsequent images spaced apart by 100 μs would be triggered. The timeline would be as follows: first image triggered, 100 μs delay, second image triggered, 900 μs delay, process repeated.

In this experiment, the maximum possible frequency was desired to increase the time resolution of the data. This value of 725 Hz was physically determined by the cameras and represented a vector every 1.4 ms. Figure 30 shows two subsequent vector images from the static ship (control) data taken in Waterplane 1. The red spot at the top of both images should be neglected as it represent an error induced by laser reflection off the hangar face.

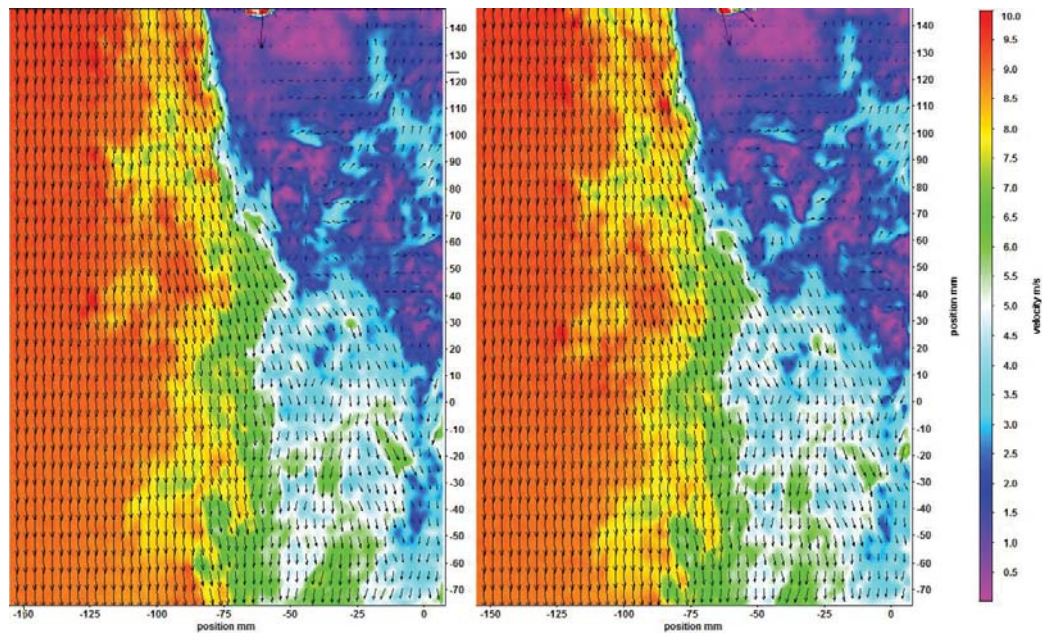


Figure 30. Two subsequent vector images at 725 Hz.

The above figure is intended to demonstrate the time resolution at 725 Hz. The black arrows represent the velocity of the flow and are scaled with increasing velocity magnitude. Additionally, the velocity magnitude can be observed by correlating the background color to the scale on the right. While the changes in vectors between frames were small, they were noticeable to the naked eye when zoomed all the way out. The ideal setup would have had a smaller difference in vectors to the point where all evolving flow features are visible in consecutive frames. This was simply not possible with the existing hardware, but a frequency value of 725 Hz is competitive with most university level research programs.

In contrast to the frequency, changing Δt does not change the time resolution of the data. Instead, it affects the quality of the vectors produced. The two primary gauges of vector quality are correlation and uncertainty. Correlation is a measurement of how well the sum of the particles in an interrogation area agree with the determined vector. If every particle in an interrogation area was measured to travel the same displacement in the same direction, the correlation would be 1.0. If no particles were detected or there was no agreement in particle motion, the correlation would be 0. Typical PIV data has average correlation values in the 0.7 to 0.9 range. Uncertainty is a measurement of the accuracy to which the computer could determine the physical displacement of individual particles. In general, larger displacements result in small uncertainty as small errors in measurement represent a lower overall percentage of the total displacement vector.

The goal in experimental setup was to maximize correlation and to minimize uncertainty. Specific goals were an average correlation value greater than 0.7 for the field of view and uncertainty below 2% on average and below 5% for the vast majority of the field of view. In order to test for this, static data was gathered for a large range of Δt 's from 10 μs to 500 μs . Several frames were evaluated for each Δt , and the results were compared qualitatively. Figure 31 shows the correlations and uncertainties of data gathered at the bottom half of the model flight deck using Δt 's of 10 μs , 100 μs , and 200 μs .

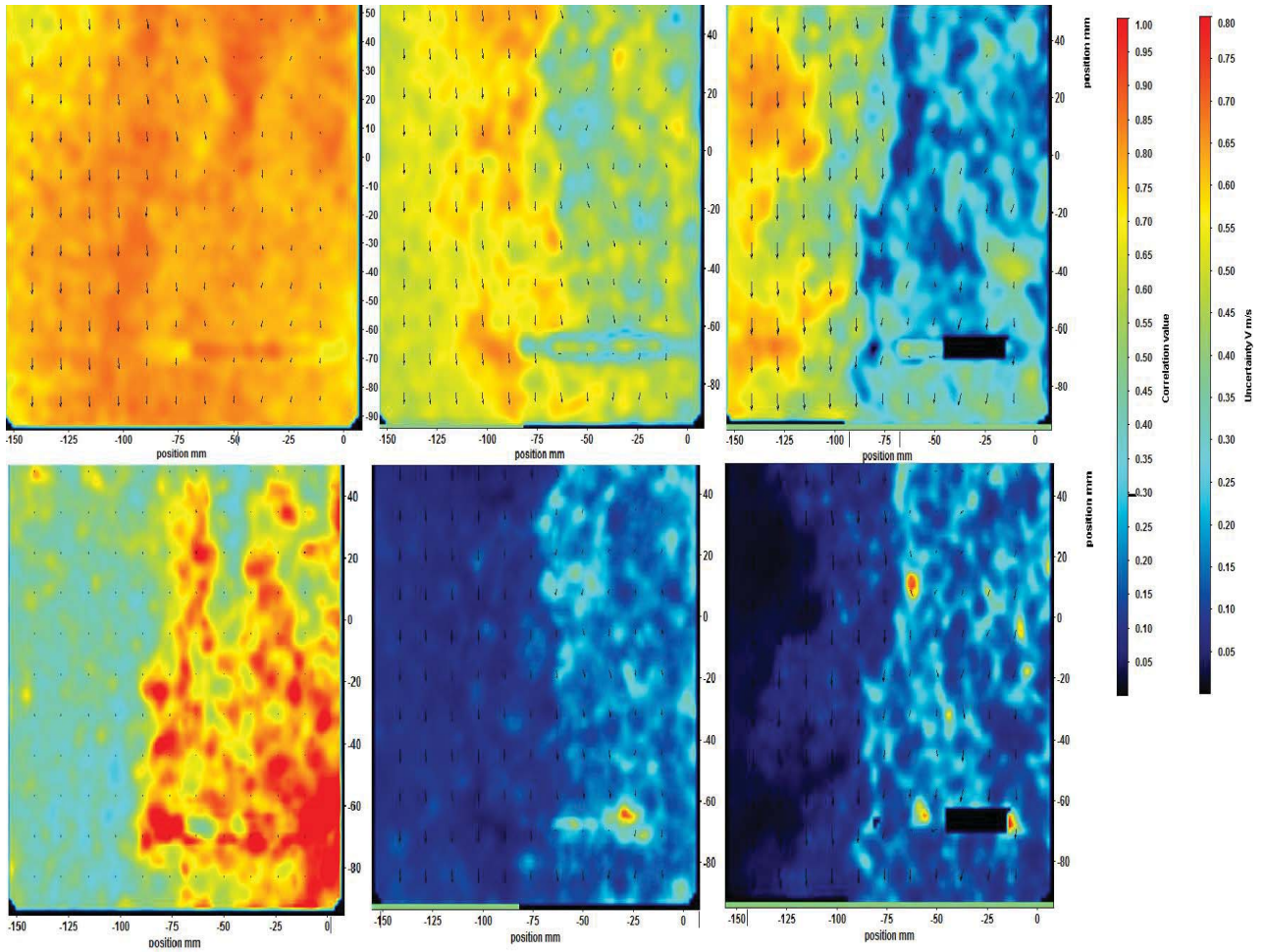


Figure 31. Correlations (top) and uncertainties (bottom) for static data gathered using a Δt of 10 μs (left), 100 μs (middle), and 200 μs (right).

Unfortunately, the results of the Δt sweep showed that correlation and uncertainty were competing requirements. As shown above, decreasing Δt resulted in an increase in both correlation and uncertainty. The solution was to qualitatively optimize Δt in order to achieve the best correlation values while keeping the uncertainty within the stated goal of a 2% average. This optimization resulted in the selection of 90 μs as the Δt for testing. Figure 32 shows the correlation and uncertainty values at this Δt . The inconsistent vectors at the top and bottom of the flight deck should be neglected as errors caused by laser reflection.

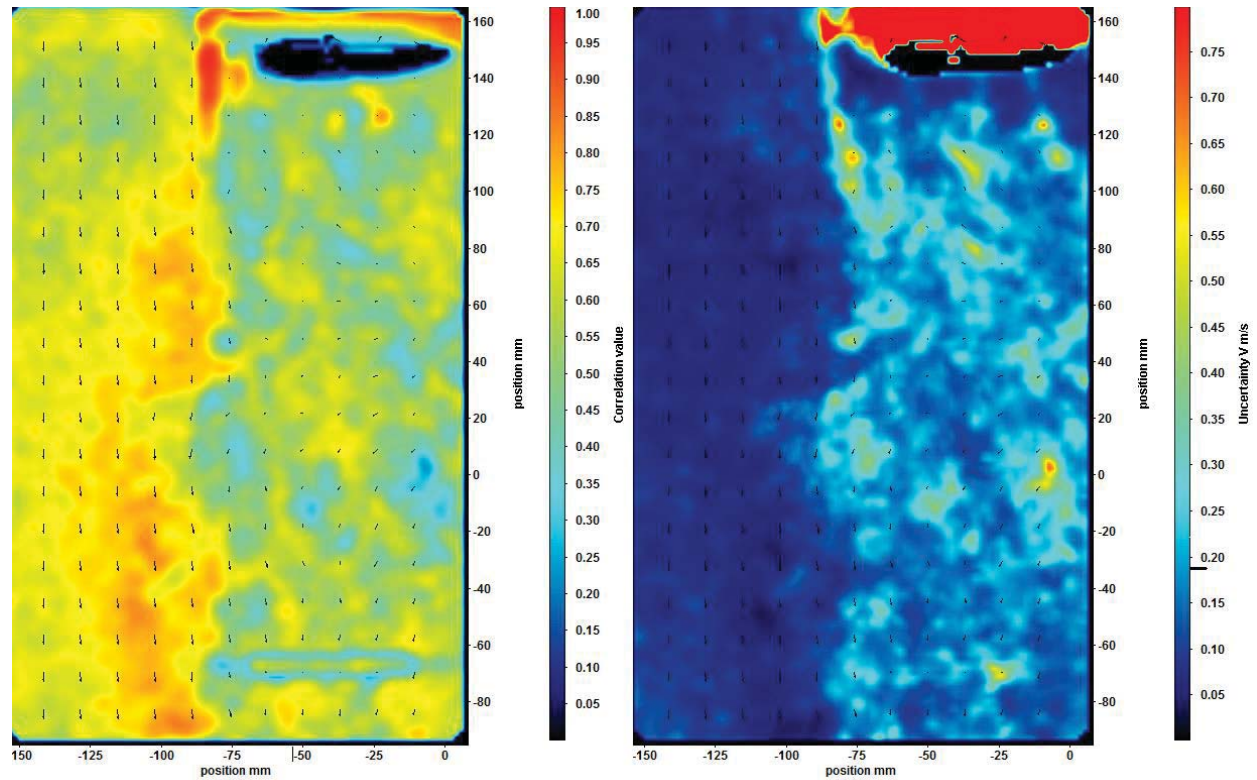


Figure 32. Correlation and uncertainty values for static data at $\Delta t = 90 \mu s$.

For the Δt of $90 \mu s$, the correlation values averaged approximately 0.65 across the field of view and the uncertainty values averaged 1.6% based on a freestream velocity of 9 m/s. While the wake correlation was not greater than the desired value of 0.65, most of the correlation values in the freestream were in excess of 0.75. From the image, it appears that correlations were highest along the wake-freestream boundary. This was a region of high vorticity where seed particles were more likely to congregate. A likely reason that values in the wake were much lower is that the seed particles did not propagate evenly in the lee of the hangar. This is a common pitfall in ship airwake PIV work, and the usual solution is to inject seed particles into the flow directly from the hangar face. Since the model was moving in the testing for this project, such a solution was not practical as the ship's motion would be imparted on the seed particle when entering the flow. Additionally, the movement of the ship effectively entrained seed particles into the hangar lee and improved wake correlation dramatically in the dynamic data points. Figure 33 shows an example of this for a Strouhal number of 0.111 and a gust magnitude of 5 degrees. The inconsistent vectors at the bottom of the flight deck should once again be neglected as errors caused by laser reflection.

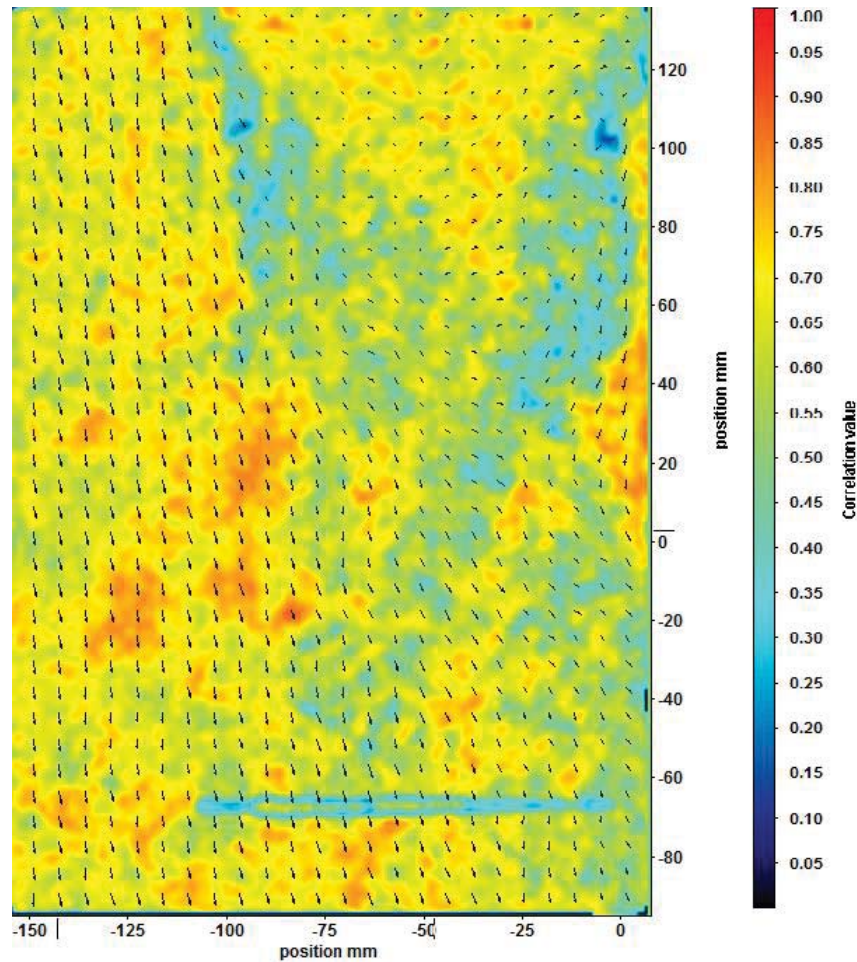


Figure 33. Correlation values for a moving frame at a Strouhal number of 0.111 and a gust magnitude of 5 degrees.

There were still points of relatively low correlation values, but the overall data quality in the wake improved significantly. The average correlation value across the field of view was approximately 0.70. While the processing settings were slightly different for this particular frame, this trend held true across all processed data. This was deemed an acceptable and repeatable data quality for testing.

3.1.2 Determining Processing Settings

The time required to process PIV data is significant and often forces a compromise between the quality of results and the timeliness in which the results are provided. There is always a more refined processing technique which can be applied to the data set, but it is pragmatic to pick the technique which provides a solution viable for the intended post-processing in enough time for the project to remain funded.

In the case of this project, the intended post processing involved time-intensive proper orthogonal decomposition (POD) and the project needed to be completed over the span of one calendar year. With these factors in mind, a processing technique trade study was conducted to determine the most effective method for the gathered data. Many of the decisions were made using observations from prior research tweaked for the intricacies of this experiment. These included the settings for the algorithmic mask, using multi-pass cross correlation, and using a non-linear sliding minimum subtraction. Processing settings that were unique to this experiment were the use of a geometric mask to eliminate laser reflections and the particular mesh used in the multi-pass cross correlation calculations.

A geometric mask is used to exclude portions of the field of view from being processed in order to save processing time and prevent erroneous calculations. For the lower waterplanes (one and two), this was used to exclude the regions of data corrupted by laser reflection. Areas effected included the areas around the hangar face and the back edge of the flight deck. A geometric mask was placed over the top 30 mm in the field as the turbulence near the hangar face is not exceptionally relevant to a helicopter approaching from astern. The back lip of the flight deck, however, is very relevant and was left to be smoothed out in post-processing. Figure 34 shows processed static data with a geometric mask.

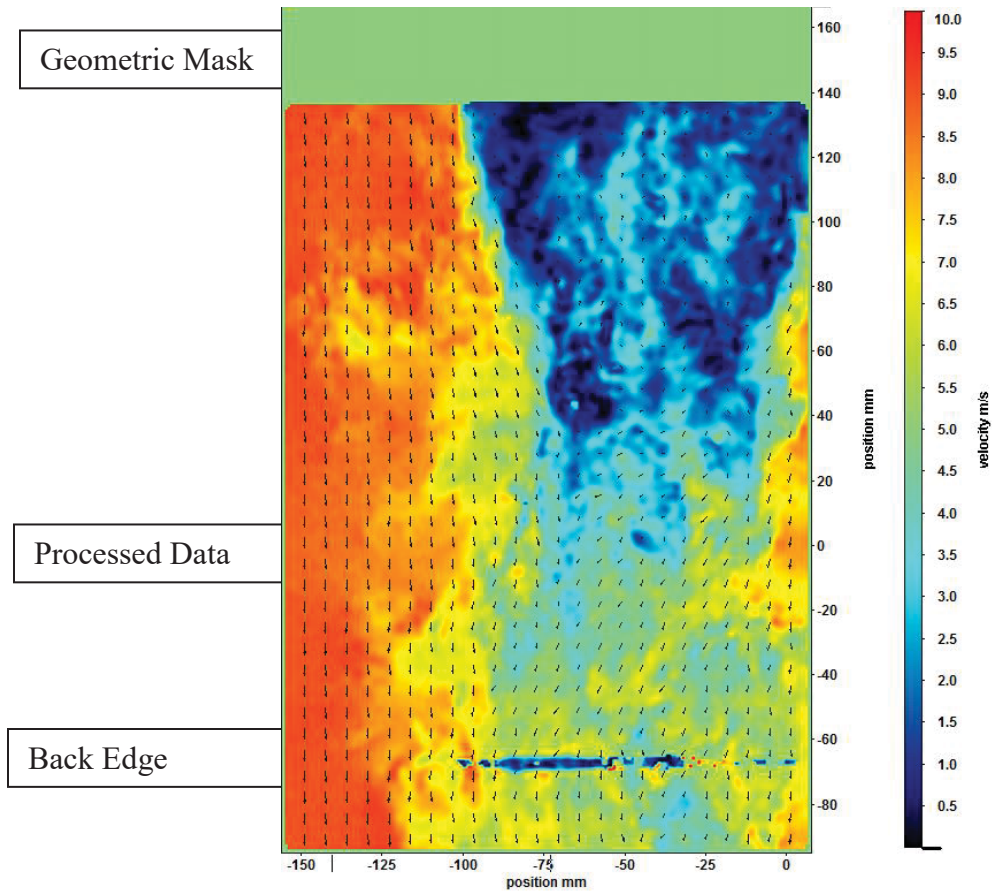


Figure 34. Processed static data employing a geometric mask to eliminate laser reflection.

The geometric mask eliminated the erroneous observations visible in many of the previous figures. Unfortunately, some valuable data was lost at the upper corners of the flight deck with the elimination of such a large area, but the loss was unavoidable. Additionally, the errors caused by laser reflection on the back edge were visible at approximate y-axis coordinates of -65 mm (un-shifted coordinated).

Determining the proper mesh for the multi-pass cross correlation was a much more involved process as this particular step represented the majority of total processing time. The trade study analyzed six different setups which varied the size, percent overlap, and shape of the second (final) interrogation area. The first interrogation area was held constant as a 64x64 pixel square, as this has historically worked well for most PIV applications. Table 6 shows the details of these tests and the time that it took with each setup to process 100 frames. It is worth noting that some of the larger data points were composed of more than 2,000 total frames.

Table 6. Data processing trade study results.

<i>Name</i>	<i>Size (pixels)</i>	<i>Overlap (%)</i>	<i>Shape</i>	<i>Time (100 frames)</i>
<i>Trade 1</i>	32x32	75	Gaussian	58 min
<i>Trade 2</i>	16x16	50	Gaussian	40 min
<i>Trade 3</i>	16x16	75	Gaussian	94 min
<i>Trade 4</i>	32x32	75	Elliptical	54 min
<i>Trade 5</i>	16x16	50	Elliptical	34 min
<i>Trade 6</i>	16x16	75	Elliptical	69 min

In addition to comparing processing times, the data was qualitatively compared to determine whether the resolution was satisfactory. Trade 3 was expected to be the most accurate of the techniques, and the other five were evaluated against it. Visual analysis was conducted to see whether the flow structures visible in Trade 3 were visible and accurate in the less refined meshes. There were noticeable differences in Trade 2 and Trade 5, so these meshes were determined to be too rough. Trade 2, 4, and 6 were all determined to satisfactorily match the results from Trade 3. Since Trade 4 required the shortest processing time of the viable methods, it was selected to be used for data processing. Though there was only 4 minutes difference in processing between Trade 4 and Trade 1, this would have amounted to over three days throughout the processing of the full matrix. Figure 35 shows a side-by-side comparison of data processed using Trade 3 and Trade 4. Note that the data processed using Trade 3 took nearly twice as much time.

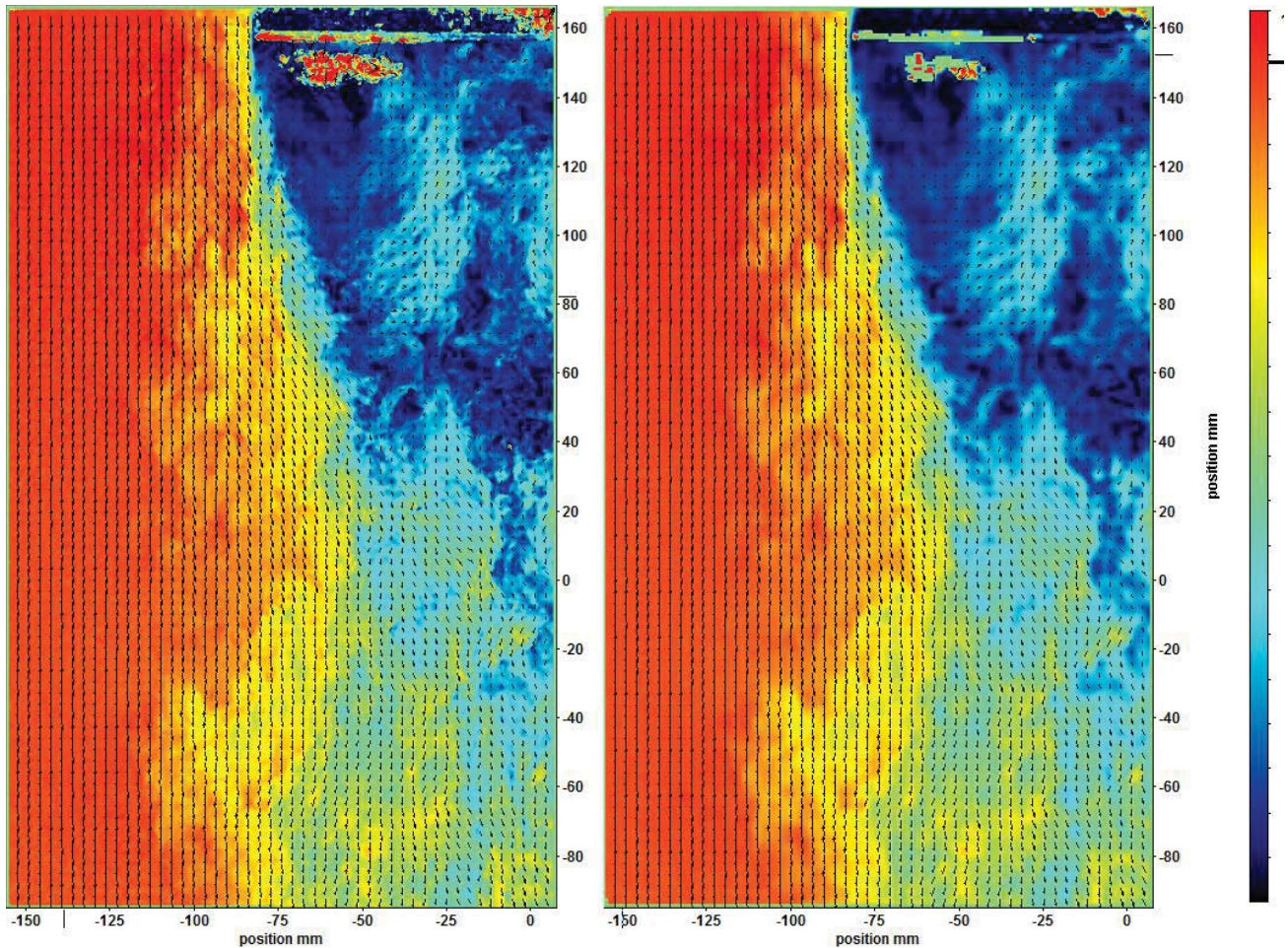


Figure 35. Comparison between Trade 3 (left) and Trade 4 (Trade 4) processed data.

The only difference between the two methods was the number of vectors per pixel. The Trade 3 processing produced four times as many vectors per pixel, but the comparison indicated that this resolution was not required to show the flow structure. There was no discernable difference in the magnitude or direction of the vectors between the two methods, so the pragmatic solution was to use the quickest method: Trade 4.

3.1.2.1 Post-Processing Settings

PIV processing generally tends to produce a number of erroneous vectors due to a coarse resolution during cross-correlation operations. Essentially, the processing algorithm takes the most probable velocity vector based on the total sum of particles within each interrogation window. As mentioned previously, the final pass in processing was 32 x 32 pixels (approximately 5% of the hangar height squared). While each window overlapped 75% of the

previous window in an effort to improve resolution, there were still some vectors that were much different in magnitude and direction than adjacent vectors.

Post-processing refers to the specific operations used to remove vectors which were likely improperly calculated. Various methods exist, but statistical methods were used in this project. Any vector which varied by 1.5 standard deviations from a local 8 x 8 pixel window was removed. Figure 36 shows a sample frame from Profile 1C in Waterplane 1 demonstrating the effects of post-processing.

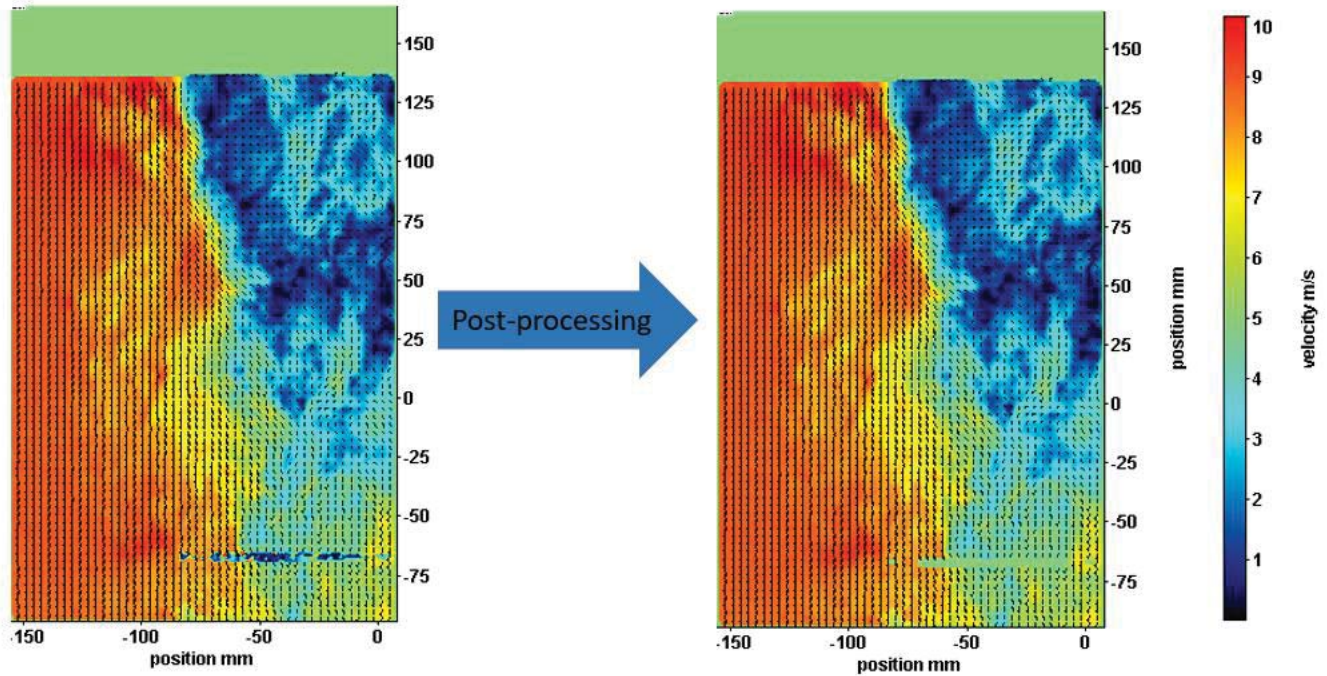


Figure 36. Flow field before and after post-processing.

If deemed erroneous by the algorithm, the vectors were not replaced by interpolation and were instead left as empty. When a large enough vector section was removed, the affected section appeared a lime green color which simulated a geometric mask. Waterplane 1 was particularly susceptible to this effect in areas of significant laser reflection, specifically the aft edge of the flight deck. Throughout the data set, the vast majority of calculated vectors were left untampered. Any post-processing effects which caused significant changes to data validity would have become apparent during POD operations later on during processing. Specifically, the POD algorithm would have been unable to calculate more than a handful of modes. Future sections will demonstrate that this was not a concern.

3.1.3 Scaling and Vector Merging

The built-in *Davis* “Merge vectors” function was used to merge the fields of view for the left and right cameras. Coordinates determined using a calibration plate stationed at a set reference point were used to ensure that the absolute coordinates matched between the two cameras. The calibration plate was placed flush with the back edge of the model flight deck and at a horizontal location where the center of the plate was 67.83 cm from the inboard test-section wall. Additionally, cameras were adjusted so that the two field of views overlapped at least 10% in accordance with manufacturer specifications. An identical process was followed for each waterplane to ensure that global coordinates were consistent across all data points.

3.1.4 Shifting and Cropping

Without data modification, the experimental apparatus filmed the ship model moving across a stationary field of view in a steady flow field. This represented a stationary tunnel, moving ship reference frame. In order to more closely model a natural transient gust, the reference frame was shifted to a stationary ship and moving tunnel. The new reference frame used the intersection of the ship centerline and the hangar face as the origin. Downstream (i.e. more aft) locations were increasingly negative along the y axis. Starboard locations were labeled positive and port locations were labeled negative along the x axis. Figure 37 shows this coordinate system as displayed on a non-processed image.

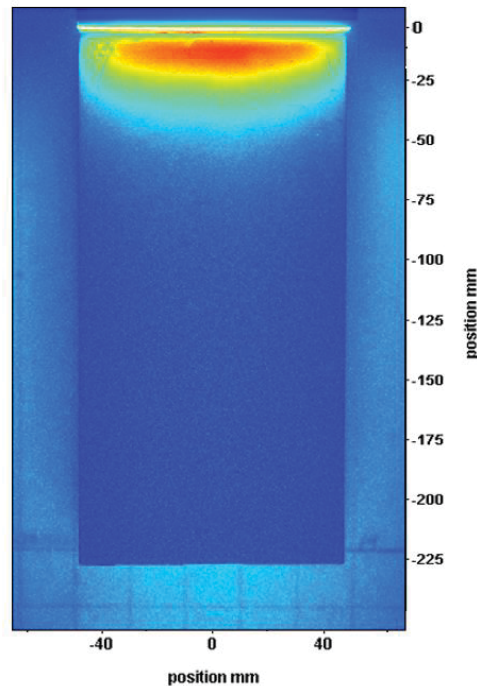


Figure 37. Standard coordinates in the ship-centered reference frame.

The standardized coordinate system was used to ensure that results could be easily compared across separate motion profiles and waterplanes. As the ship moved throughout the motion profiles, the specific coordinate shift was calculated from an interpolated lateral displacement of the model between subsequent frames. Interpolated motion profiles were calculated from tables of the ship's non-shifted coordinates taken at standardized intervals inversely proportional to gust magnitude. When setup for Waterplane 1, the port corner of the hangar face was constantly illuminated by laser sheet reflection. This specific point was tracked for each profile to generate the coordinate tables. Figure 38 shows the coordinate table and interpolated motion profile used to shift coordinates for Profile 1C.

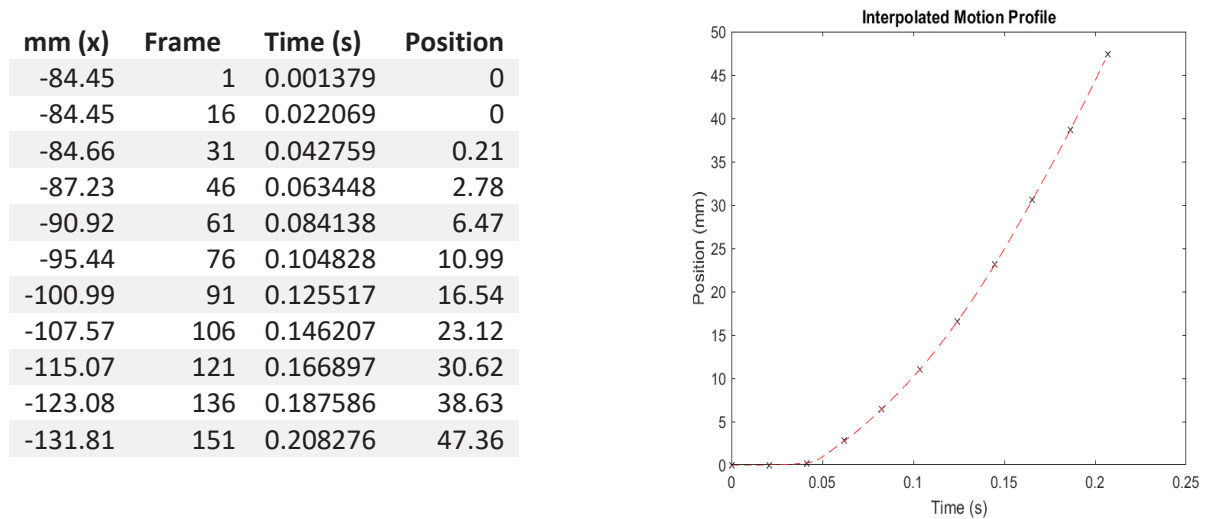


Figure 38. Reference coordinates and interpolated motion profile for Profile 1C.

In addition to shifting the coordinates, the x direction velocity of each frame was adjusted to account for the motion of the ship. The instantaneous ship velocity was determined via a computational central difference derivative method applied to the interpolated motion profile. In accordance with the defined global coordinate system, ship motion to port required a positive (right) x velocity shift in accordance with a counterclockwise rotation of the relative wind vector and motion to starboard required a negative (left) x velocity shift in accordance with a clockwise gust. Figure 39 demonstrates the counterintuitive mathematics involved in this operation.

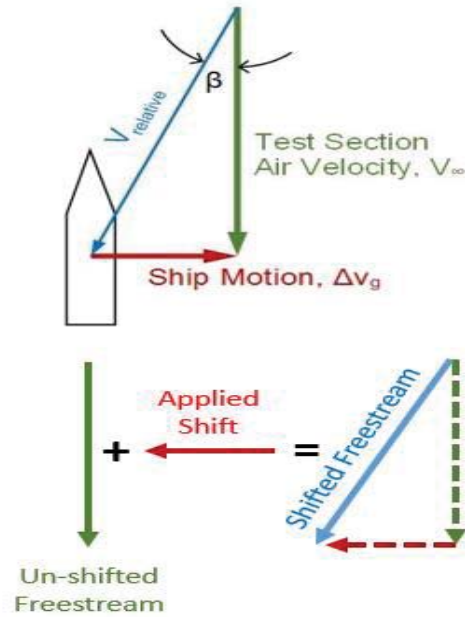


Figure 39. Illustrated velocity shift vector arithmetic.

The shifting of each frame resulted in a wind sweeping effect where the wind direction changed according to a specified motion profile. Unfortunately, the experimental equipment did not actually mirror the commanded motion profile. After data collection it was discovered that the controller gains were improperly tuned and that the apparatus was unable to accommodate the large commanded accelerations. As a result, the actuator was delayed in both ramping up to maximum velocity and then in slowing down on the backside of the profile. The result was a steeper and faster actual motion profile which resulted in different Strouhal numbers than originally predicted. Coordinate tables obtained via the previously described method were used to calculate these new Strouhal numbers. Table 7 shows the actual Strouhal numbers for the experiment.

Table 7. Experimental Strouhal numbers.

<i>Profile</i>	<i>Targeted Shift (Deg)</i>	<i>Targeted Strouhal number</i>	<i>Actual shift (deg)</i>	<i>Strouhal Number</i>
1	5	0.111	4.2	0.502
2	10	0.111	8.8	0.472
3	15	0.111	13.7	0.430
4	5	0.222	4.9	0.784
5	10	0.222	9.8	0.722
6	5	0.450	5.0	1.474

All experimental Strouhal numbers were higher than the commanded profiles. Because higher Strouhal numbers are representative of more common short duration transient gusts, it was determined that the actual outputs were still in the range of applicability to full scale ship airwakes.

With a ship centered reference frame, the field of view needed to be laterally (x-dimension) cropped to only include a small portion of the original viewing frame. Specifically, a range of 140 mm centered on the ship centerline allowed for 12.85 mm of additional flowfield outside the ship flight deck. A specific number of frames were selected to ensure that the entirety of the viewing window was always unobstructed. The y dimension was cropped at a different amount for each waterplane to ensure that laser reflection on the hangar face was not visible.

3.1.5 Proper Orthogonal Decomposition Operations

The built-in *Davis* “POD Spatial Eigenmodes” decomposition was used for the final stage of data reduction. As discussed in Section 1.6.1.2, the singular values decomposition techniques used in the POD implementation allowed for analysis of the dominant flow structures. A select number of frames for each run were analyzed in order to maximize the number of calculated eigenmodes and more accurately map the flow energy. Table 8 shows the approximate frames used in the POD calculations and the number of eigenmodes calculated for each run.

Table 8. POD frame ranges and calculated eigenmodes.

<i>Profile</i>	<i>A Frames</i>	<i>A Eigenmodes</i>	<i>B Frames</i>	<i>B Eigenmodes</i>	<i>C Frames</i>	<i>C Eigenmodes</i>
1	250-515; 516-770	58; 203	130-250	42	1-149	110
2	130-255; 256-380	112; 117	80-130	31	1-89	69
3	90-167; 168-250	64; 74	52-80	18	1-64	52
4	100-255; 256-410	138; 137			1-139	93
5	65-133; 134-210	53; 55			1-74	56
6	10-133; 134-280	80; 93			1-150	105

In general, the number of eigenmodes exceeded 50% of the frames used, which was the goal to ensure that the results were meaningful. The number of frames needed to be adjusted for each profile because the software algorithms had difficulty calculating a sufficient number of eigenmodes for “A” and “B” segments whenever the beginning and end of the profile were

included in the calculation. A potential explanation is that the computational difference method used to calculate the shifted velocities is less accurate for the end points than the middle of the profile. This was due to the lack of a point after or before the first or last point in the profile making the central difference method effectively a forward or backward difference. Errors resulting from the difference in method could make the entire data set appear non-continuous to the POD algorithm which would result in fewer calculated eigenmodes. While the cause of this cannot be completely confirmed, the data quality was not considered to be compromised provided the number of eigenmodes exceeded 50% of the frames used in the calculation. Profile 1A and all B segments failed to meet this criteria and were checked for conformity with other results throughout data analysis.

3.2 Validation of Control Data with Prior Research

The purpose of control runs was twofold: to compare against the transient case and to compare against previous wind tunnel and CFD testing. The specific source of data used for this validation were CFD data compiled in the previously referenced Forrest and Owens paper [24]. Forrest and Owens validated their work against their own wind tunnel data which makes their results ideal for validation in this experiment.

The SFS2 model used by Forrest and Owen in their work was designed to the same relative scale as the model used in this experiment and they used Detached Eddy Simulation for calculations. Their data was collected at a step-height referenced Reynolds number of 1.0×10^7 as opposed to 26,000. While the Forrest and Owen data was collected at a much higher Reynolds number, as discussed in Section 1.2, this should only result in a difference in reattachment length of up to 4% between the two data sets due to a low threshold for Reynolds number independence in backwards facing step flows. Figure 40 shows an overlay of each waterplane on the time averaged, steady-state CFD obtained along a y-z axis plane placed along the SFS2 centerline by Forrest and Owen.

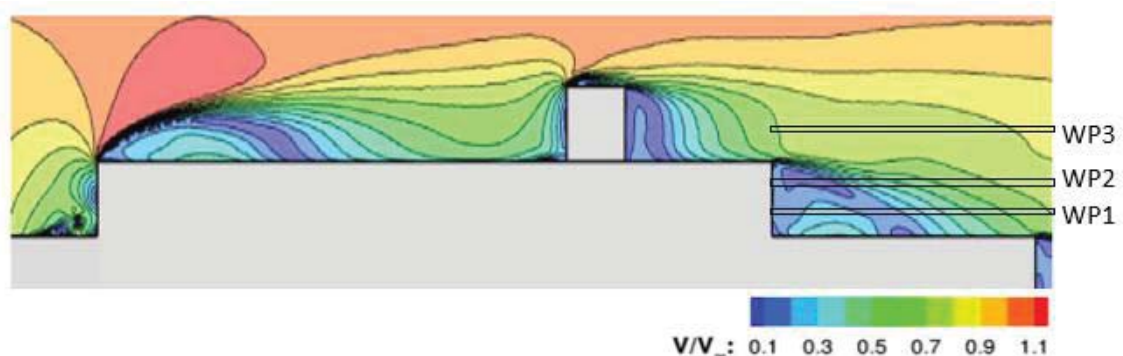


Figure 40. Forrest and Owen's results in each waterplane [24].

Each experimental waterplane was compared directly against Forrest and Owen's with an ideal velocity difference less than the combination of PIV uncertainty (approximately 2%) and the Reynolds number effects (approximately 4%). Figure 41 shows this comparison. The PIV results were displayed to match the velocity magnitude legend used in Figure 40, where the reference velocity was treated as 9 m/s, the average freestream velocity across all runs. While the PIV results calculated velocity to the third decimal place, the data resolution for the CFD was only 10% of the freestream velocity. This was not fine enough to compare on the order of 6%, but did allow for easy qualitative comparison.

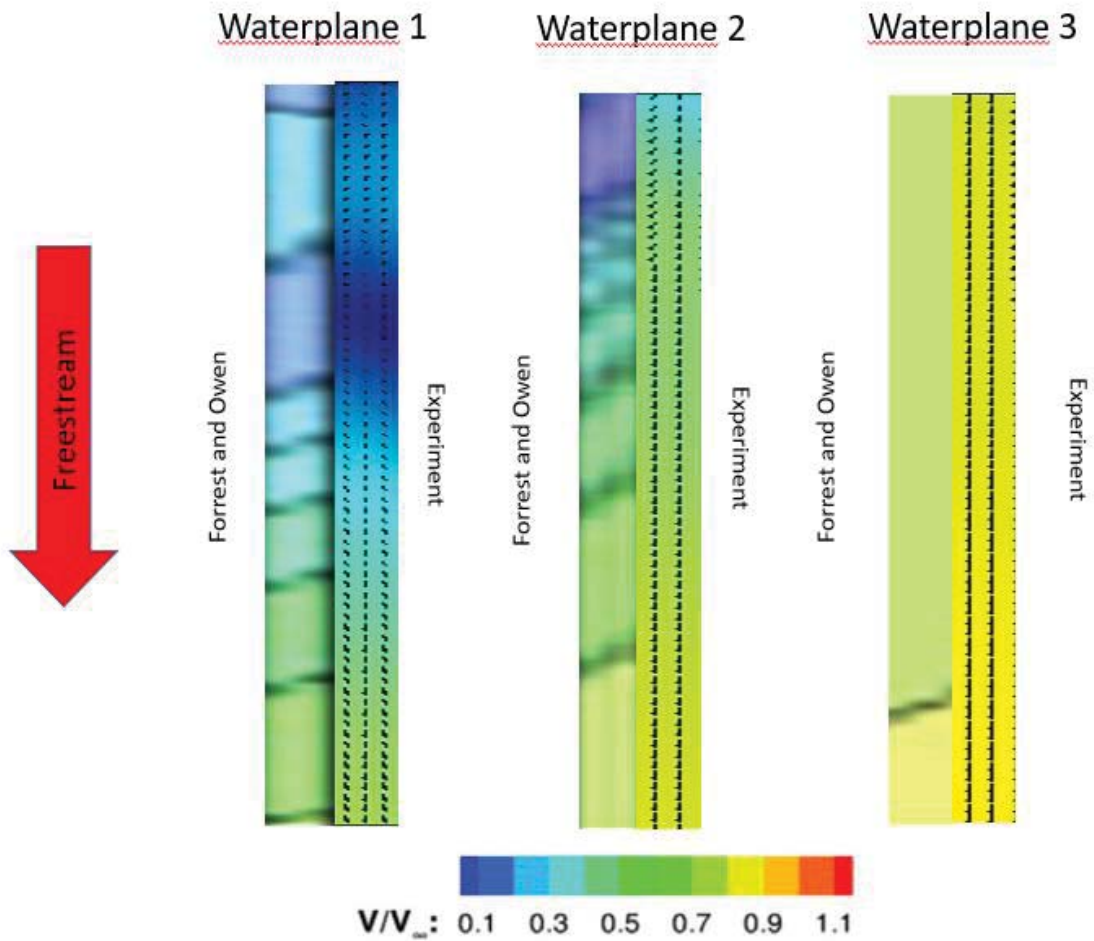


Figure 41. Direct comparison of experimental results against prior Forrest and Owen CFD results [24].

In Waterplane 1, the experimental and CFD results were nearly identical. Velocity magnitudes and gradients matched between the two data sets indicating strong agreement. While the velocity resolution in the CFD data only allowed comparison on the order of 10% of the

freestream velocity, this was sufficient to indicate data agreement. There was a slightly lower level of agreement in Waterplane 3, but the data still indicating a relatively close alignment. Differences were no more than 10% of the freestream velocity (one gradient of the CFD legend).

For Waterplane 2, however, there were significant disagreements between the two data sets over the upstream flight deck quarter. Forrest and Owen's CFD predicted a large, zero-velocity lee extending approximately one quarter of the flight deck length in Waterplane 2. The experimental data did not record the lee extending beyond the first 10% of the flight deck. Beyond the first quarter, the data matched well between the two sources. Both observed a gradual increase in velocity with increasing distance along the y axis, and the gradients were located in approximately the same location.

Data validation resulted in a full acceptance of data obtained in Waterplanes 1 and 3. The data in Waterplane 2 was cautiously accepted with specific attention directed towards results in the first quarter of the flight deck. In the following sections, most conclusions were taken from Waterplane 1, and data from Waterplane 2 was exclusively used to validate trends observed in other waterplanes.

3.3 Windward Edge Separation Bubble

A significant difference noted in the average flowfields for the transient gust profiles was the existence of a separation bubble on the windward hangar edge similar to that observed on an airfoil entering a dynamic stall. Sometimes referred to as leading-edge stalls, dynamic stalls are the result of a rapid change in angle of attack causing flow separation near the leading edge. Transient gusts result in a changing angle of attack experienced by the windward hangar edge. Gust magnitude was directly equivalent to the change in angle of attack and Strouhal number was proportional to the rate of change. Figure 42 shows this phenomenon observed in Waterplane 2 for Profile 2B. The image represented the average flowfield taken over frames 80-130.

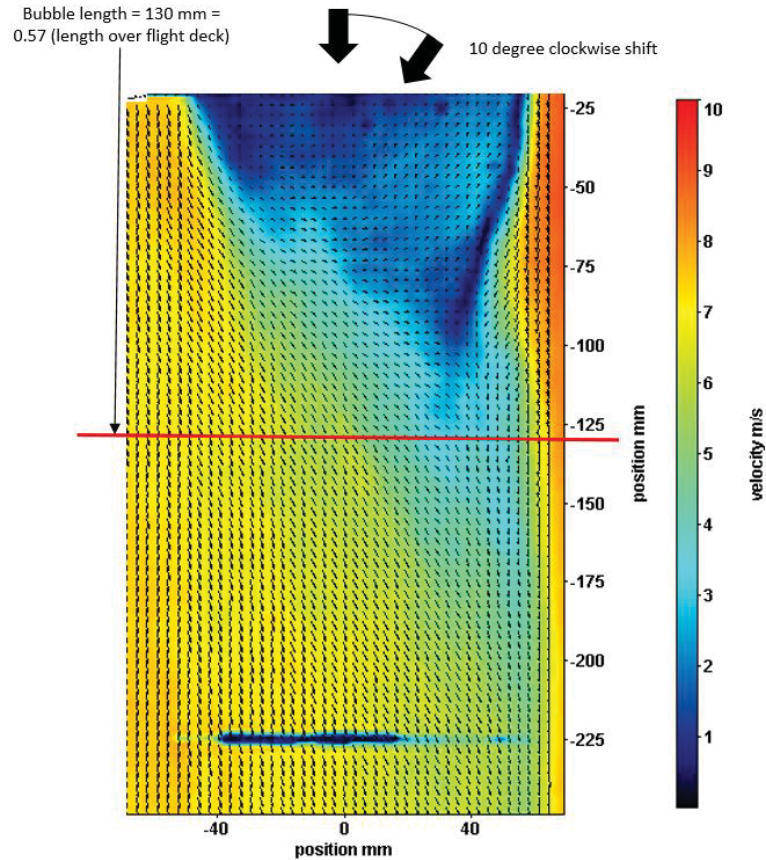


Figure 42. Windward edge separation bubble observed for Profile 2B in Waterplane 2.

In this particular instance, the bubble was nearly half the length of the flight deck and had an accordingly significant impact on the flowfield. The primary characteristic used to categorize the size of the bubble was the length along the y axis. Results were expressed as a non-dimensional ratio of bubble size to flight deck length. Uncertainty was calculated in terms of bubble size standard deviation and was expressed as a percentage. The separation bubbles were only visible in Waterplanes 1 and 2

3.3.1 Wake Phase

In addition to the separation bubbles visible in the transient gust cases, there was a similar phenomenon visible in the wake for static cases. These separation bubbles, however, oscillated from port to starboard between different static runs. While four out of the six runs were observed to have a bubble on the starboard hangar edge, there were too few data points to make any statistical claims regarding tendencies. Previous experimentation and aerodynamic theory predict that a non-streamlined shape, such as a backwards facing step, will shed an oscillating wake. The repeating pattern of swirling vortices in the wake of a blunt body is referred to as a Von Karman

Vortex Street. Figure 43 shows the vortex street for a cylinder taken using wind tunnel flow visualization techniques.

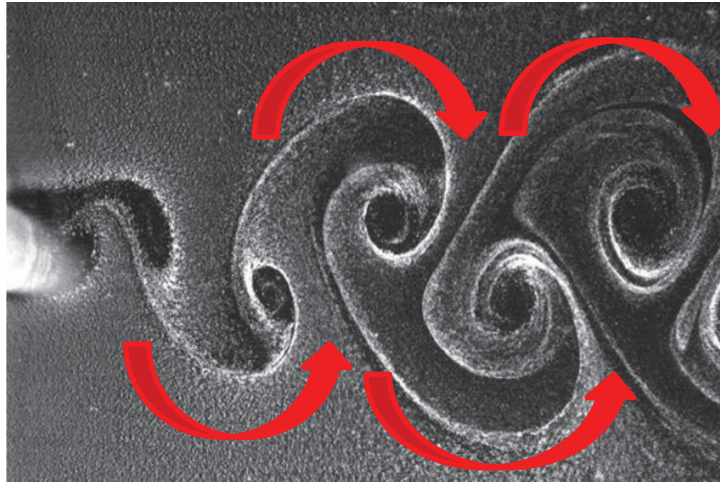


Figure 43. Von Karman Vortex Street for flow around a cylinder. [34]

Wake effects are similar for all blunt bodies, but a cylinder creates the cleanest and most-easily visible vortices. Strouhal numbers, used to describe transient gust profiles in this experiment, are normally used to describe the frequency of this vortex shedding for a blunt body. Vortices are typically shed above a threshold step-height Reynolds number on the order of 90. The frequency at which the vortices are shed is inversely proportional to the free stream velocity, which in the experimental test was purposely low. The static vortex shedding frequency was observed to be in excess of two seconds. In the average flowfield calculated over 1450 frames (2 seconds), there appeared a definitive phase (i.e. the location of a small bubble). Figure 44 shows the phase observed over all six static runs in Waterplanes 1 and 2.

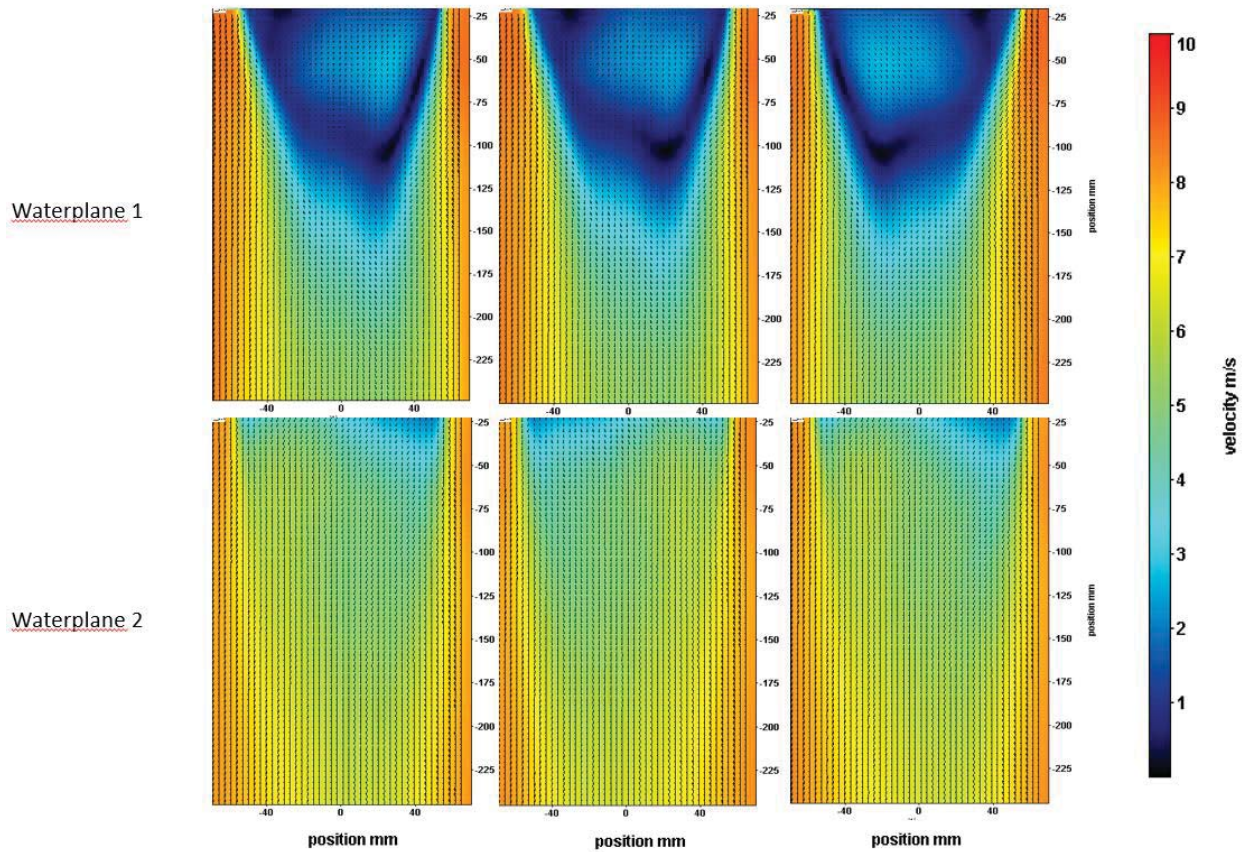


Figure 44. Separation bubble phase observed during control runs.

If the bubble had been alternating from side to side during the run, there would not have been a clearly visible asymmetry. The averaging function would have used frames with the bubble on the opposite side and effectively created a visual “smearing” effect. Not visible in any of the runs, there is no reason to suspect that this occurred. The wake phase accordingly was in excess of two seconds, so each run, including the transient gust profiles with periods much shorter than two seconds, was assumed to take place during one specific phase of the wake. Therefore, control runs were, in the context of this experiment, steady runs with the transient gusts representing an applied un-steady influence.

3.3.2 *Gust Magnitude Dependence*

The original test matrix was designed so that both gust magnitude and Strouhal number were varied independently. Six total motion profiles span three separate gust magnitudes and three separate Strouhal numbers. Since the actuator did not operate precisely as commanded, there were some variations in both the constant gust magnitude and constant Strouhal number runs. For Profiles 1 through 3 (the lowest Strouhal number), the standard deviation was

approximately 7.7% of the average Strouhal number. For Profiles 4 and 5, the standard deviation was approximately 5.9% of the average Strouhal number. Despite these errors, there were glaring trends in separation bubble size as a function of gust magnitude. Figure 45 shows the separation bubble size as a function of gust magnitude for all profiles in Waterplane 1.

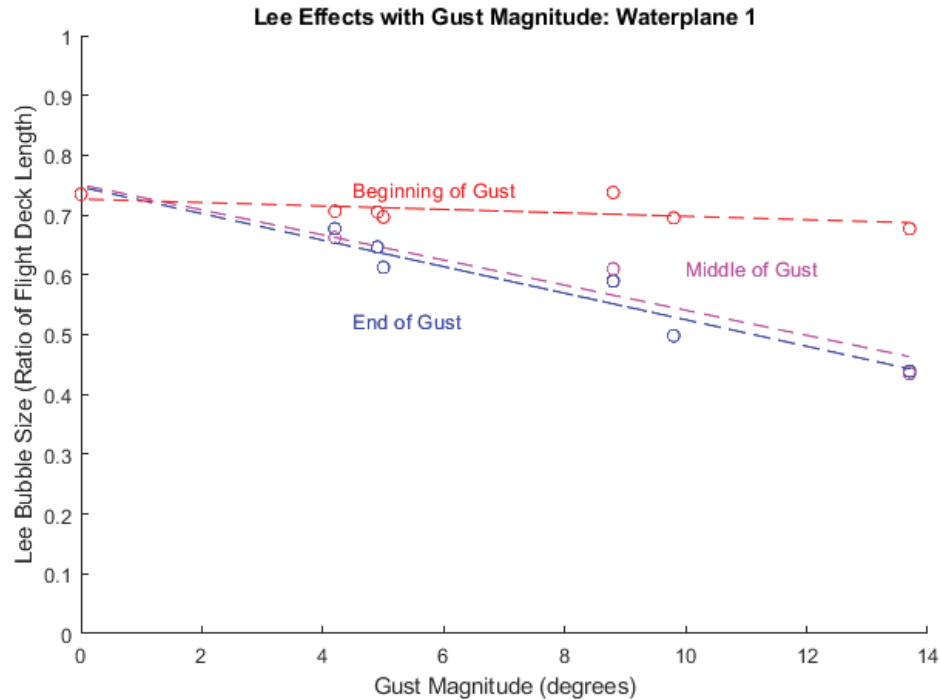


Figure 45. Separation bubble size as a function of gust magnitude.

The bubble size decreased over time for all but Profile 1. At the beginning of the gust (C segments), the ship was moving very slowly, and the separation bubble was nearly identical to the Von Karman vortices observed during the static runs. Additionally, two-thirds of the bubbles were observed on the lee hangar edge indicating that the bubble was more dependent on wake phase than gust characteristics. As the ship reached maximum velocity during the middle and latter parts of the gust (Segments B and A), all of the bubbles became attached to the windward hangar edge. The bubble at maximum lateral velocity was an entirely different shape than at the start of the gust which implies a transition from a vortex generated by bluff body separation to one generated by a dynamic stall. As the ship slowed back down to rest (Profile C), the bubble began to resume the same shape as at the beginning of the gust. The size, however, was much smaller as the dynamic stall appeared to remain the dominant flow feature. Figure 46 shows the progression from bluff body separation to dynamic stall for the largest gust magnitude profile (13.7 degrees).

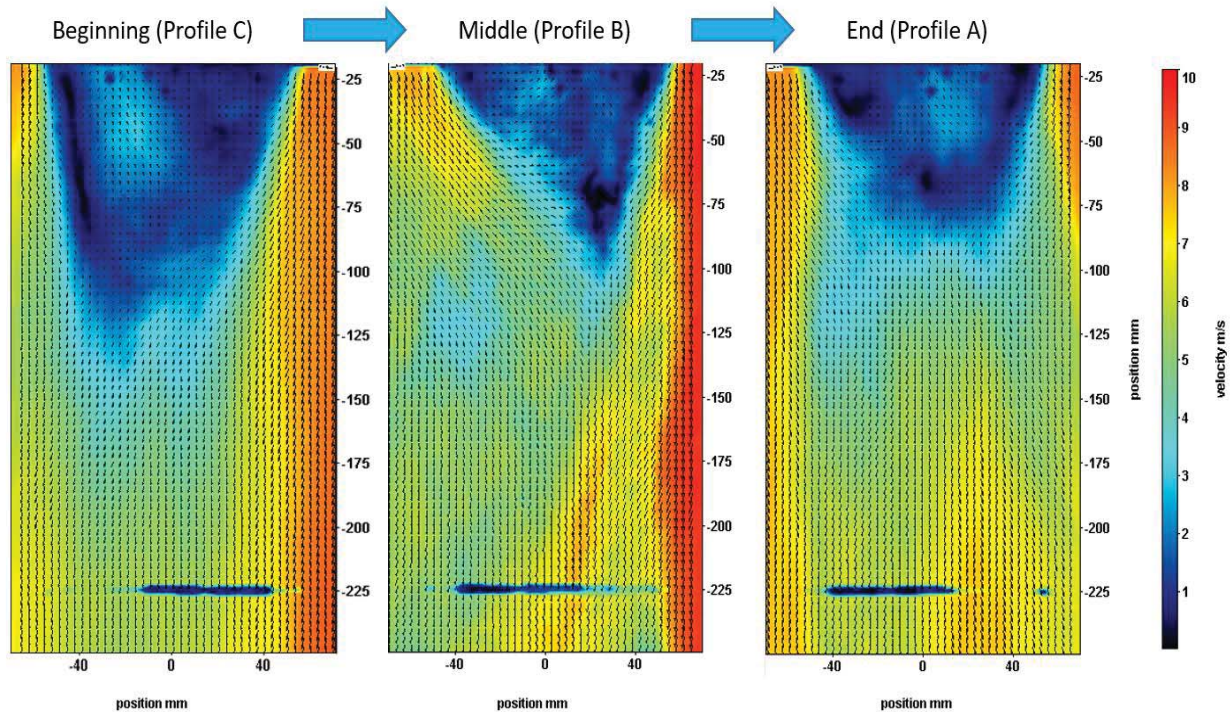


Figure 46. Progressions from bluff body separation to dynamic stall for Profile 3 (clockwise gust).

The difference between stages of the gust was apparent for all profiles. Though with increasing gust magnitude, the differences increased. Figure 45 demonstrated that the dynamic stall induced bubble decreased linearly in size with gust magnitude. The vortices from bluff body separation, as seen at the beginning of the gust, did not significantly change in size with gust magnitude. Since the changes in the wake were caused by stall, there was a direct linear relationship which caused an increase in wake energy with increasing transient gust magnitude. As the separation bubble shrunk, the velocity in the wake increased close to the hangar face. A helicopter landing on a flight deck placed close to the hangar would experience a noticeable increase in wind velocity if subjected to a transient gust. Since this effect is most pronounced in Waterplane 1, the helicopter would be in its most critical phase of flight as it neared touchdown. Measureable changes in wind velocity could result in uncontrolled movement with rotor blades in near proximity to the ship.

3.3.3 Strouhal Number Dependence

The test matrix allowed for two constant gust magnitude comparisons: Profiles 1, 4, and 6 which were 5 degree shifts and Profiles 2 and 5 which were 10 degree shifts. Variations induced by the non-commanded profile for the constant gust magnitude profiles were on the same order

as for the constant Strouhal number grouping. The standard deviation for Profiles 1, 4, and 6 was 9% of the average gust magnitude, and the standard deviation for Profiles 2 and 5 was 7.5% of the average gust magnitude. Figure 47 shows the separation bubble size as a function of Strouhal number for the relevant profiles in Waterplane 1. Differences in gust magnitude in Table 7 were corrected for using the trendline slopes from Figure 45.

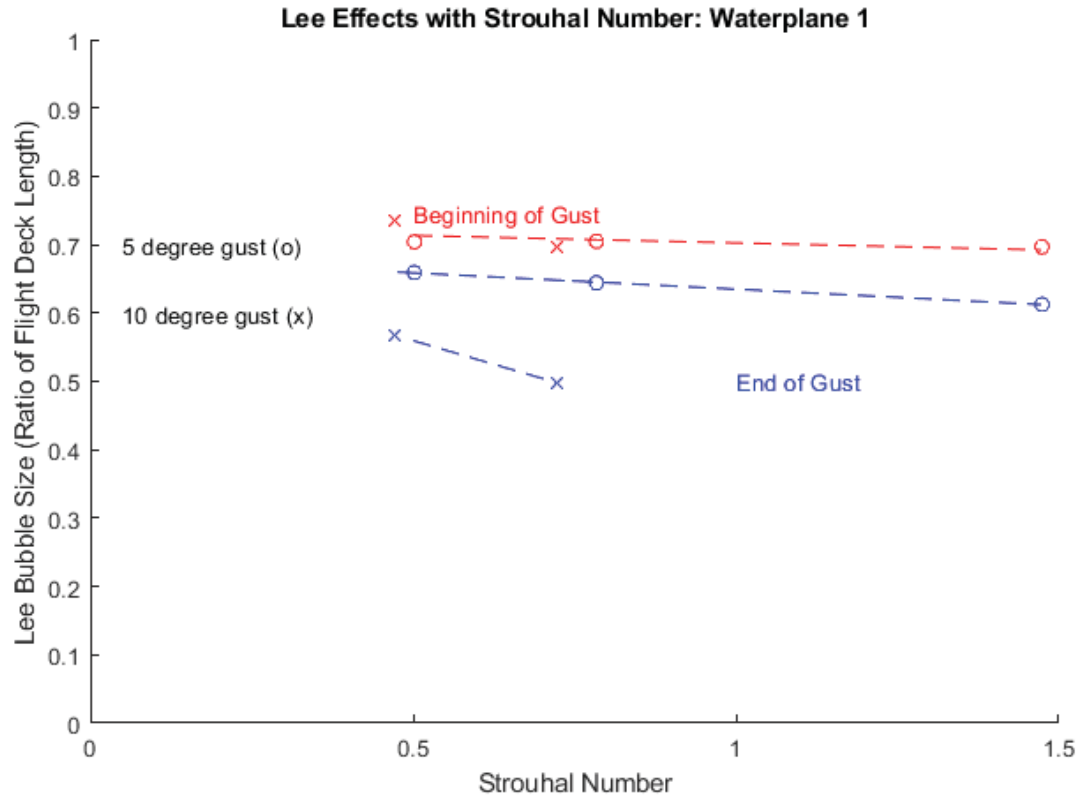


Figure 47. Separation bubble size as a function of Strouhal number.

The variation with Strouhal number was not obvious. For both 5 degree cases, the slope of the trendline was on the order of 10^{-2} indicating a very weak dependence. While the slope was negative in all cases, the difference between the largest and smallest Strouhal number was too small to make any substantive claims. The 10 degree gust featured a steeper gradient (on the order of 10^{-1}), but the difference in gust magnitude was still the dominant feature. Specifically, the difference in bubble size between the beginning and end of the gust nearly tripled transitioning from a 5 to 10 degree gust profile. Even for the 10 degree gust case, the Strouhal number, assuming a linear relationship with bubble size, would need to be increased by a factor of 2.3 to match this increase. There was not enough evidence to definitively establish a dependence on Strouhal number, but there was ample quantitative evidence to support that the bubble size was more dependent on gust magnitude.

3.3.4 POD Confirmation

For the middle of all profiles, the first POD mode was a near direct representation of the vortex generated by a dynamic stall. The first mode vortex for the middle of each gust profile was significantly different than those observed for the static runs and beginning. Most notably, the stall vortex rotated counter to the directional shift (i.e. the vortex rotated counterclockwise in a clockwise gust). Stall vortex size and intensity also directly increased with gust magnitude. Figure 48 shows the first mode stall vortices observed for Profiles 1B, 2B, and 3B.

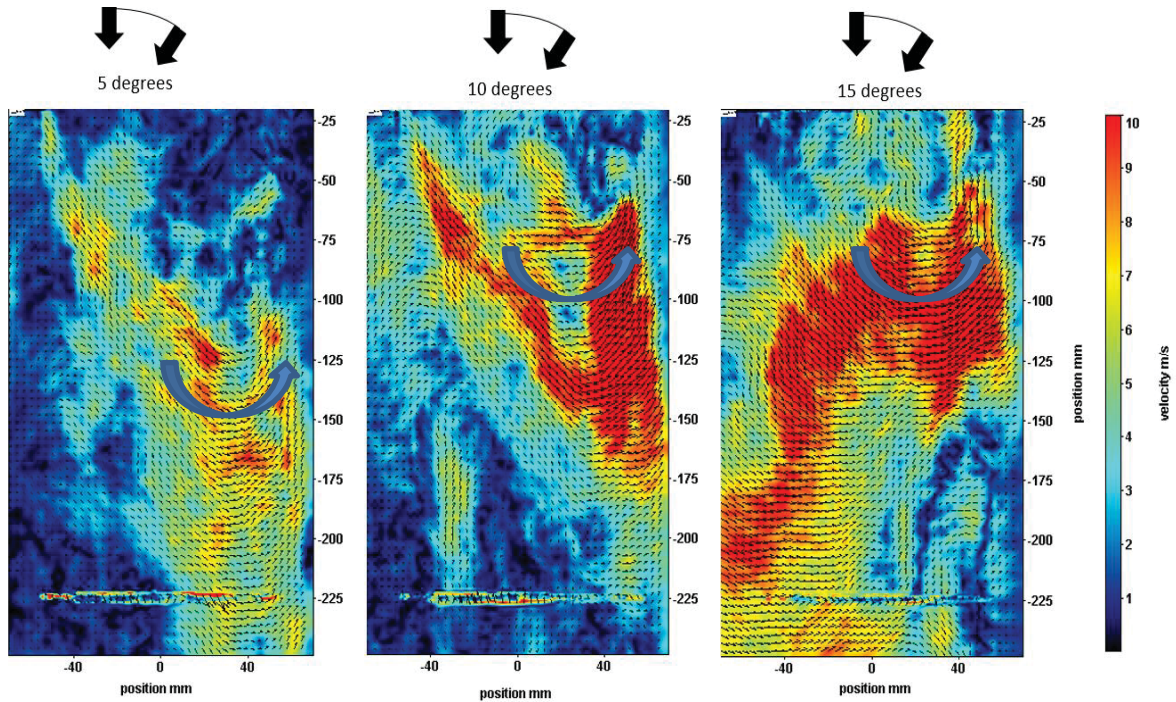


Figure 48. First mode stall vortices shown with increasing gust magnitude.

The structure was similarly shaped in each separate case. The center of the vortex was located on the windward edge of the flight deck, and the surrounding turbulence increased in energy with gust magnitude. Vortex rotation was the most indicative feature because Von Karman separation vortices, as shown in Figure 43, rotate inboard once formed. Therefore a vortex formed on the starboard flight deck would rotate clockwise having negative vorticity. Figure 49 is a side-by-side first mode vorticity comparison between the static run and 15 degree transient gust.

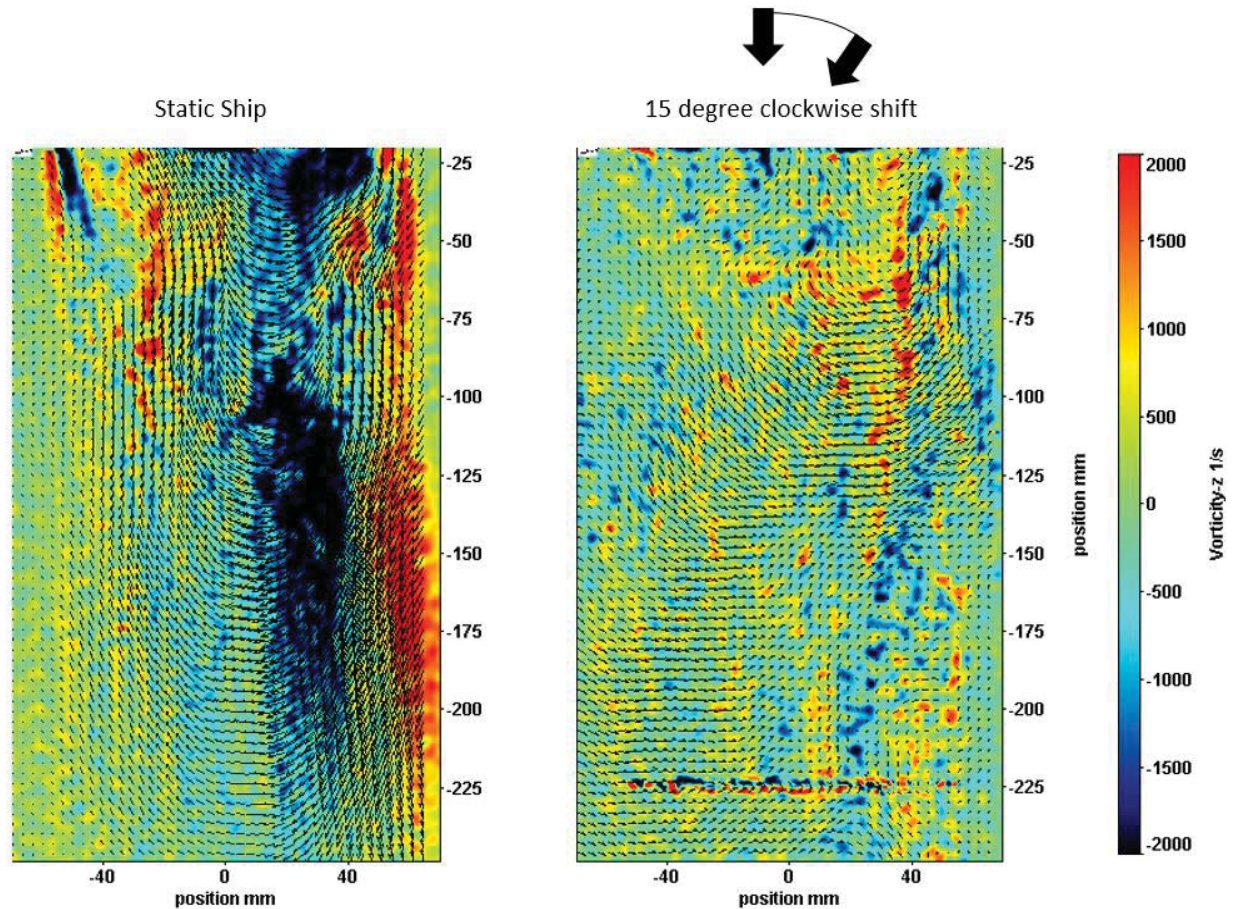


Figure 49. First mode vorticity for static ship and 15 degree transient gust.

The static ship, with a counterclockwise rotating vortex on the starboard flight deck, was defined by a layer of negative vorticity just inside the starboard edge of the flight deck. A positive vorticity shear layer was present to the right of the flight deck. When the 15 degree clockwise shift was applied, the vortex on the starboard flight deck was defined by a positive shear layer with a negative shear layer present to the right of the flight deck. Dynamic stall has been shown to produce eddies rotating counter to the freestream on airfoils due to interaction between outer shear layer vortices and the airfoil wall [35]. Interactions between the hangar wall and shear layer were much different for the ship airwake case, but there was likely a similar phenomenon which occurred to cause the counter-rotating eddies. At the middle of a given gust profile, the rapid changes in wind angle relative to the windward hangar edge likely caused a dynamic stall interaction. This stall decreased separation bubble size, increased the average flow velocity over the flight deck, and resulted in a more turbulent and less predictable airwake.

3.4 Turbulent Length Scales

Turbulent scales represent standardized metrics used to classify and compare unsteady flows such as a ship airwake. In this experiment, the turbulent length scale was defined as the diameter of the largest vortex in the first POD mode and was measured as a ratio of the hangar step height (2 inches). For asymmetrical vortices, the largest diameter was measured. All measurements were taken visually likely resulting in a bias error. This was not significant to the results since all measurements were taken by the same individual and only used for comparison within the same waterplane. Figure 50 shows a sample turbulent scale measurement taken from a Profile 2A run in Waterplane 2.

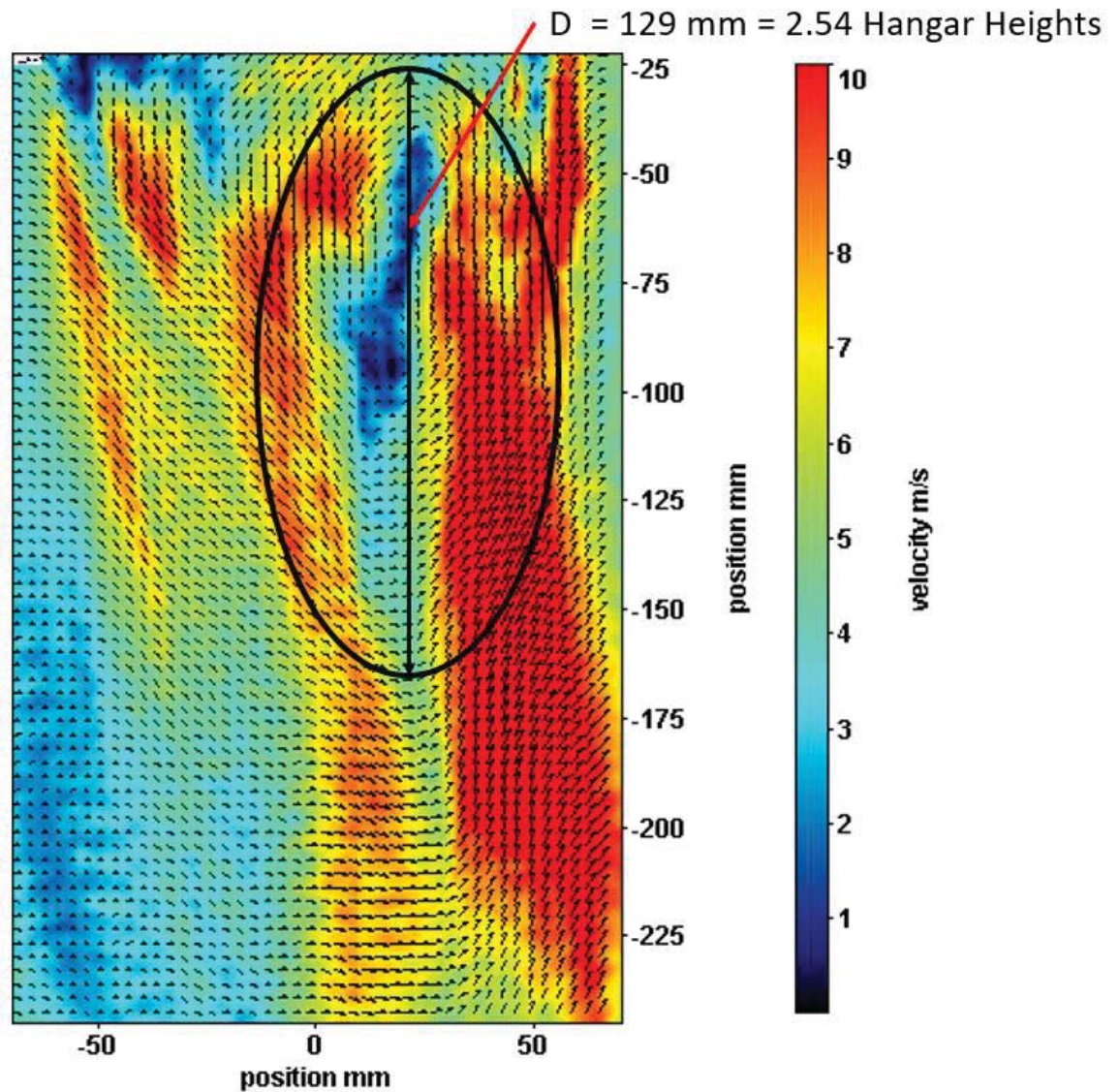


Figure 50. Turbulent scale measurement taken from the first POD mode in Profile 2A.

The structure shown, an elongated and imperfect vortex, was typical of the first mode for most C segments and for the second-half of each A profile. B segments, as discussed in Section 3.3.4 featured an entirely different flow structure. In aerodynamics, vortex characteristics generally include a near zero velocity at the center and a continuous clockwise or counterclockwise rotation with radially increasing velocity. A characteristics unique to the experiment included an asymmetric shape elongated in the y direction. Vortices for some runs were merged with other smaller flow structures resulting in difficulty measuring the size. The rule employed during measurement was to take the largest continuous velocity ring (i.e. where every velocity vector was indicating rotation in the same direction) and to consider that the vortex edge.

3.4.1 Gust Magnitude Dependence

Similarly to the separation bubble comparisons, the test matrix allowed for turbulent scale comparison as a function of gust magnitude between the second half of each A segment and every C segment. Throughout this section, the A segments were referred to as switchback profiles due to them recording the ship switching directions from starboard (clockwise gust) to port (counterclockwise gust) lateral motion. The C segments were referred to as the beginnings of each profile in a similar manner to all previous sections.

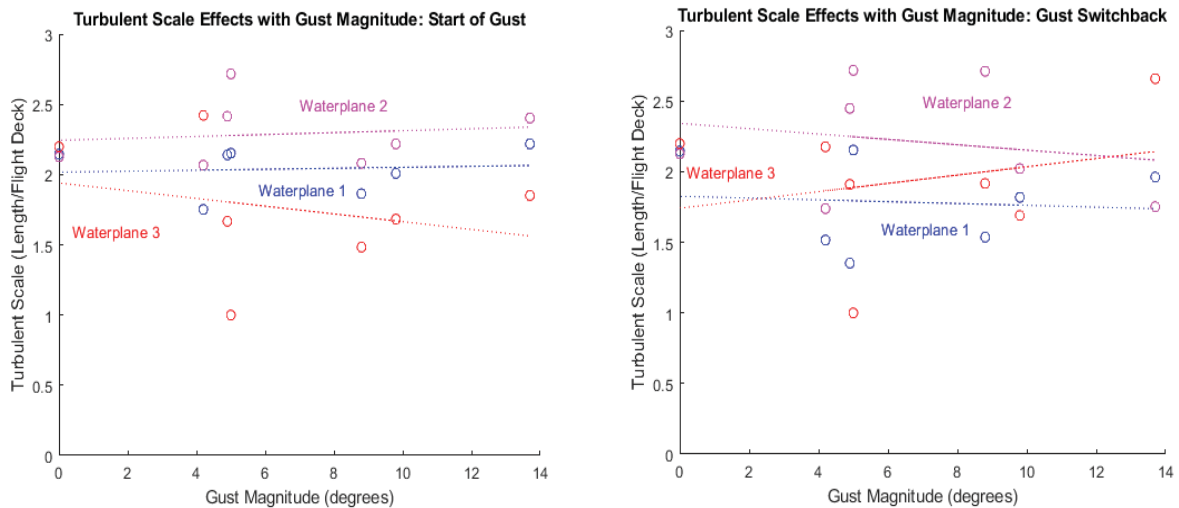


Figure 51. Turbulent length scales as a function of gust magnitude for C and A segments.

Unlike separation bubble size, there did not appear to be a direct relationship between gust magnitude and turbulent length scale for the beginning of the gust and the switchback. This was expected, as the dominant flow feature was likely due to bluff body vortex shedding. Dominant characteristics affection these vortices were likely the size of the bluff body (i.e. the hangar height) and the freestream velocity. The hangar height did not change during testing, and

freestream velocity, which is the combination of the constant wind tunnel flow and the ship's lateral motion, was not greatly affected by gust magnitude for Segments A and C. Between the slowest and fastest motion profiles, the freestream velocity only varied by 0.12 m/s (1.3 % of the test section velocity). Such a small change should have had no significant effect on the vortex shedding, and the experimental results supported this hypothesis.

3.4.2 Strouhal Number Dependence

Strouhal number dependence was evaluated for 5 and 10 degree start and switchback gust profiles. Figure 52 shows the turbulent length plotted as a function of Strouhal number for 5 and 10 degree gust magnitude C segments.

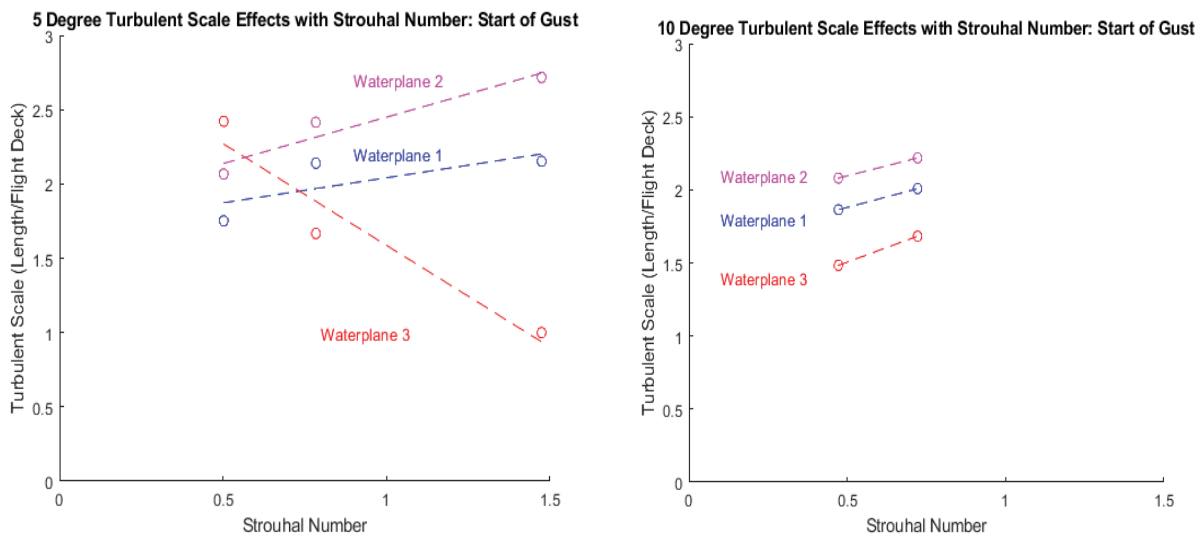


Figure 52. Turbulent length scales as a function of Strouhal number for C segments.

In Waterplanes 1 and 2, there appeared to be a consistent increase in turbulent length with increasing Strouhal number. Slopes for the four relevant trendlines were all on the order of positive 10^{-1} (23-43% of the maximum Strouhal number) which indicated a relatively strong dependence. In comparison, the slopes of the gust magnitude dependent trendlines were 10^{-3} (less than 0.02% of the maximum gust magnitude). The turbulent lengths observed in Waterplane 3 displayed inconsistent trends with the 5 degree gust showing decreasing turbulent length with Strouhal number. A possible explanation is that the ship mast, responsible for the majority of the Waterplane 3 turbulence, was too far up stream for the field of view to accurately capture the transient gust effect. Energy from all vortices is eventually dissipated via fluid viscosity. After interacting with the ship mast, the fluid travelled an additional flight deck length before being observed. The turbulent effects would therefore not be expected to correlate in the same way as in Waterplanes 1 and 2. Similar trends were observed for the A segments as shown in Figure 53.

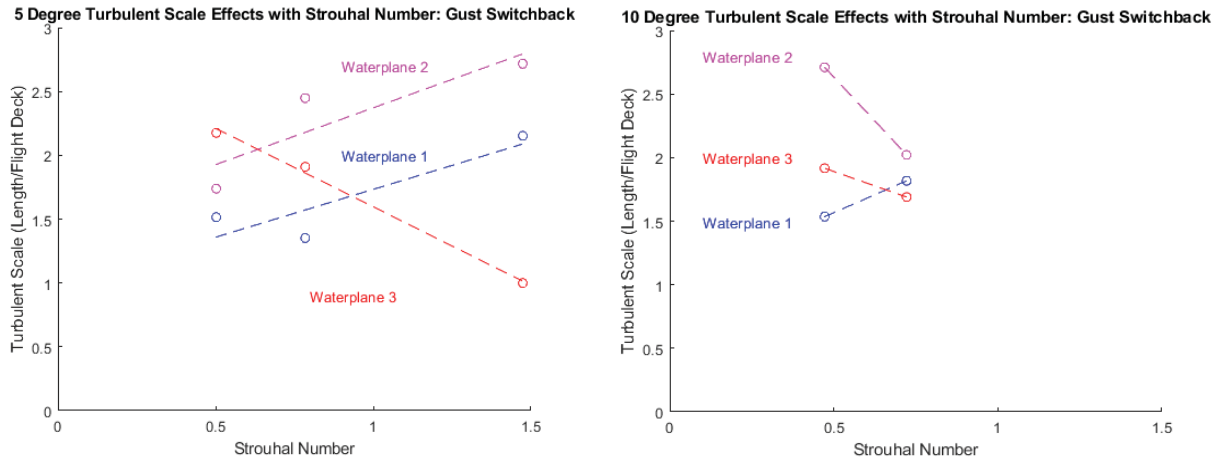


Figure 53. Turbulent length scales as a function of Strouhal number for A segments.

For the 5 degree gusts, the Waterplane 1 and 2 slopes were on the same magnitude (10^{-1}) as those observed in the C segments. The Waterplane 3 data also behaved nearly identically. For the 10 degree gust, however, Profile 2 ($St = 0.472$) had nearly 33% larger turbulent lengths than for the C segments in Waterplanes 2 and 3. This increase was only observed for Profile 2 as the turbulent, and lengths actually decreased for all other data points. The reason for this anomaly was unclear but may have been the result of dynamic stall remaining the dominant flow feature throughout the switchback. Profile 2 was longer in duration than Profiles 5 and had a higher gust magnitude than Profiles 1, 4, and 6. That specific profile experienced more aggressive dynamic stall than Profiles 1, 4, and 6, and it experience the stall for a longer time period than Profile 5. The combination of factors could have resulted in dynamic stall vortices, which would have a higher turbulent length than a separation vortex, remaining in the airwake throughout the entire switchback.

Section 3.3 demonstrated that the largest vortex in the first mode increased in size with gust magnitude for Profile B. There were no measurable effects in Profile B due to changing Strouhal number. In contrast, there was a strong dependence on Strouhal number for Segments C and A with little to no dependence on gust magnitude. Assuming that Profile 2A represented a dynamic stall, these differences in dependence confirmed that the vortices generated in Segments C and A were entirely different than those generated in Profile B. Most importantly, aerodynamic theory indicates that different vortices are caused by different natural phenomenon. In this case, the vortices in Segments C and were predominantly caused by bluff body flow separation while those in Profile B were exclusively the result of dynamic stall.

3.5 Separated Shear Layer Angles

A comparative metric developed specifically for this experiment was the separated shear layer angle with both the windward and leeward hangar edge. As the flow separated off the back edge off the hangar, high vorticity magnitude layers (referred to as separated shear layers) propagated downstream at a repeatable angle. Given that the transient gusts caused significant deviations from the static ship results, these angles were expected to vary significantly across the test matrix. Figure 54 shows the method used to calculate these angles.

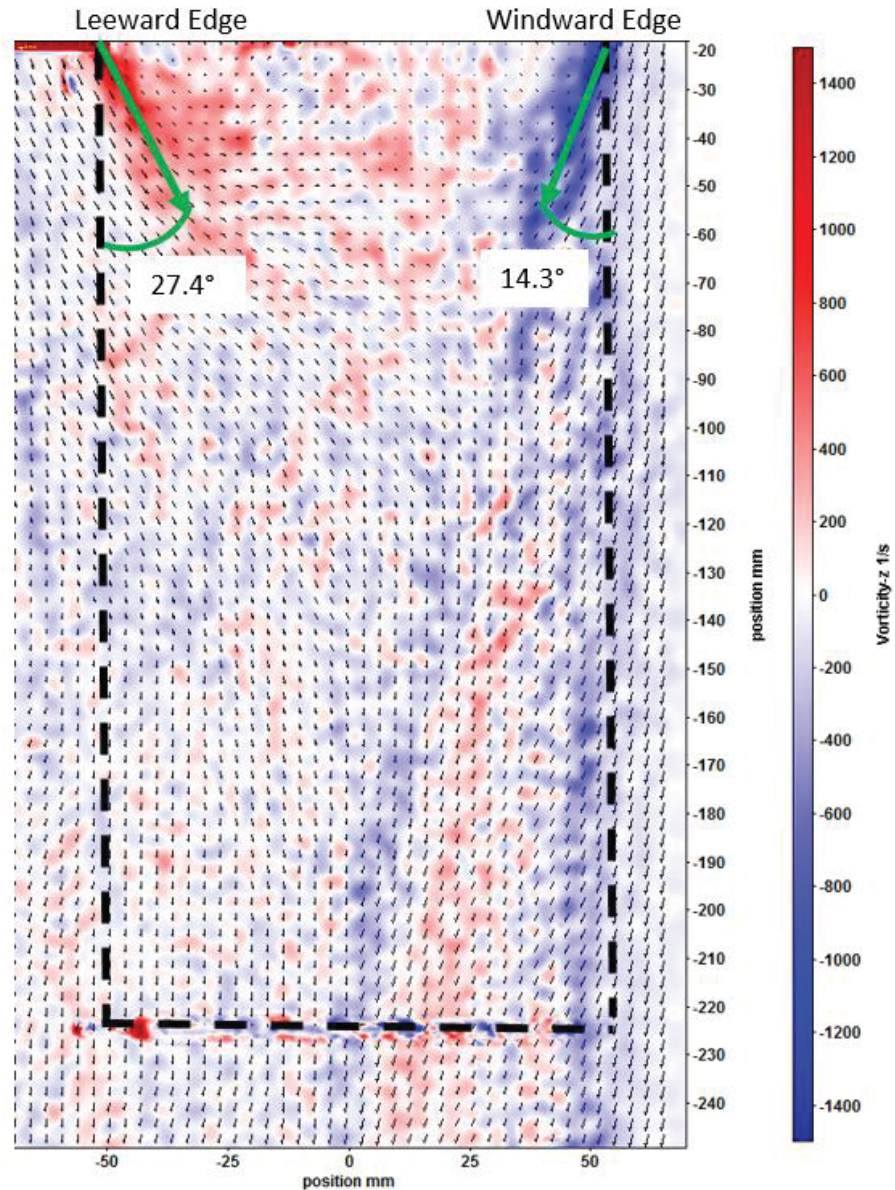


Figure 54. Separated shear layer angle measurement method.

All angles were measured in degrees inboard from the flight deck edge in Waterplane 1. All values were positive and varied from 4.5 to 30 degrees. Angles were only observed for the first 50 mm downstream of the hangar face.

3.5.1 Gust Magnitude Dependence

Intuitively, the separated shear layer angle on the windward angle would be expected to increase with increasing gust magnitude. As the relative wind direction rotates, the angle at which the freestream approaches windward hangar edge would increase and the flow around the edge would angle move towards the center of the ship. On the leeward side, there was not expected to be a significant change. Figure 55 shows the experimentally observed relationships between gust magnitude and separated shear layer angle on both sides.

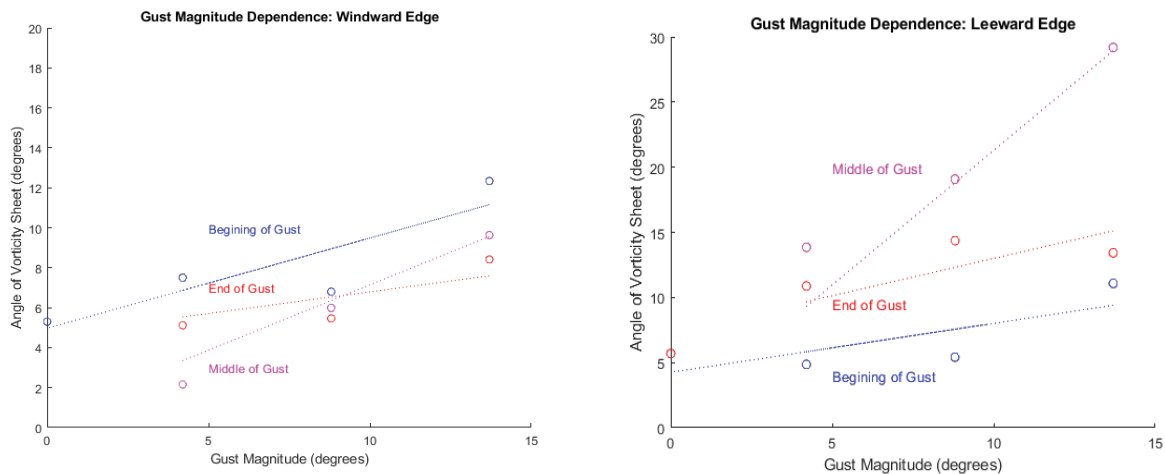


Figure 55. Gust magnitude dependence for separated shear layer angle.

As predicted, the windward edge shear layer angle generally increased with gust magnitude for all stages of the gust. The trendline slopes varied across gust segments with the middle of the gust (Segment B) having the steepest slope at a value of 0.65. The end of the gust (Segment A) had the shallowest slope at a value of 0.22. These correlated to 4.7% and 1.6% of the maximum gust magnitude value, respectively. Surprisingly, the leeward edge shear layer angle was more strongly affected by the gust magnitude for all gust stages except for the beginning of the gust (Segment C). The angle increased with gust magnitude for all stages of the gust with Segments B and C respectively representing the steepest and shallowest trendline slopes with values of 2.06 and 0.38 (15% and 2.8% of the maximum gust magnitude).

The reason for the strong leeward side dependence is uncertain, but a possible explanation is that flow separation on the windward edge caused a low pressure area directly in the lee of the hangar. The flow around the leeward side of the ship, largely unaffected by the change in wind direction, would then be drawn more strongly around the leeward corner. This

would then increase the shear layer angle observed on the leeward hangar edge as the separated shear layer was turned further inboard.

3.5.2 Strouhal Number Dependence

Based on the Strouhal number definition given in this experiment, there was not expected to be a strong shear layer angle dependence with increasing Strouhal number. When isolated, the Strouhal number primarily defined the wind direction rate of change and should not have had an effect on the overall angle. Figure 56 shows the Strouhal number dependence for the shear layer angles on both sides of the flight deck.

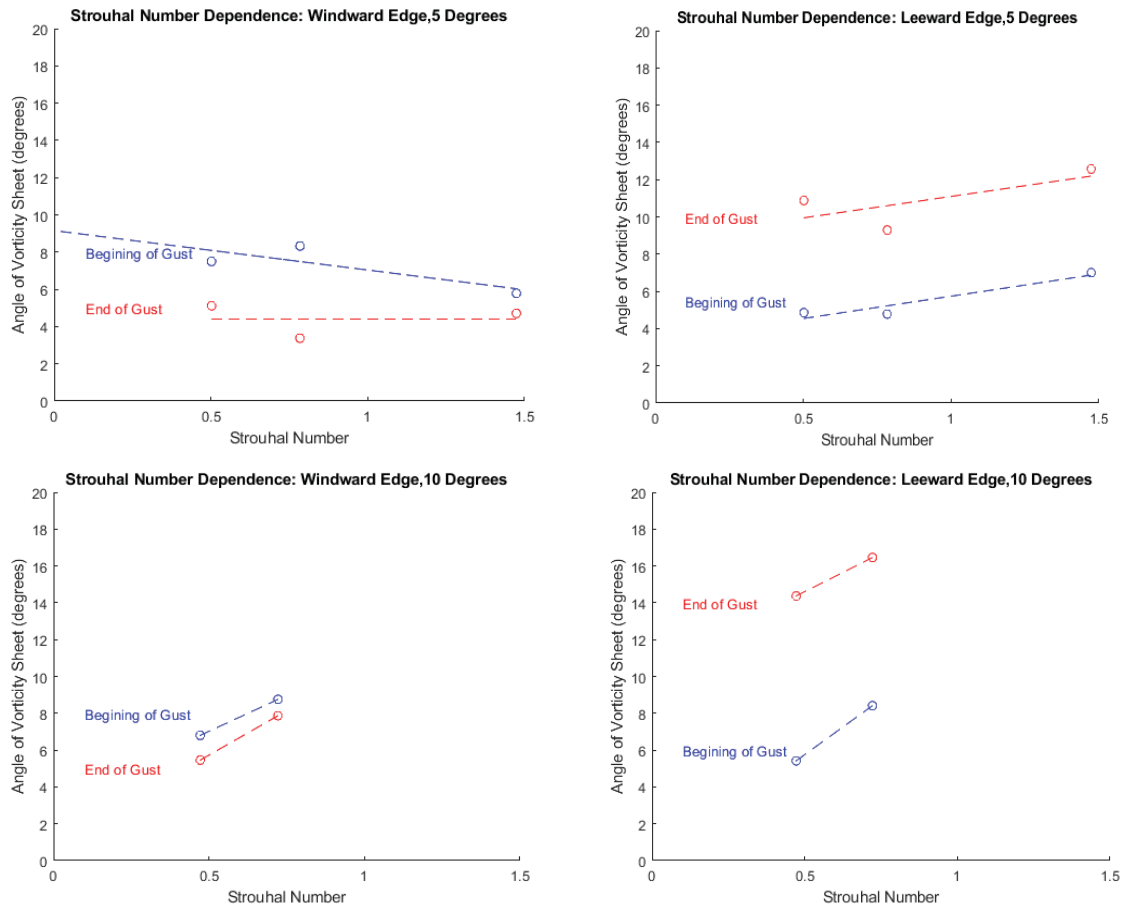


Figure 56. Strouhal number dependence for separated shear layer angle.

In general, there was a very weak dependence on Strouhal number for the 5 degree gust magnitude profiles for both the windward and leeward edges. Trendline slopes for these cases varied between -2.1 and 2.4 indicating maximum changes of about 2 degrees across the entire Strouhal number spectrum. In contrast, changes of 5 to 10 degrees were observed across the varying gust magnitude runs. For the 10 degree runs, there was insufficient data points to

calculate a meaningful trendline. There did, however, appear to be a much stronger dependence on Strouhal number for both the windward and leeward edges. Across half of the Strouhal number range, there were changes of 3 to 4 degrees in all cases.

A likely explanation was that the 10 degree shifts were more likely to cause large changes in shear layer angle at the beginning and end of the gusts (Segments C and A). Since the ship model was moving at a higher lateral speed, the differences in acceleration for the varying Strouhal numbers may have had a more significant effect on the flow. Specifically referring to dynamic stall induced flow effects, differences in gust magnitude would have had resulted in significant changes to the overall flow structure. Observations implied that higher gust magnitudes increased sensitivity to variations in Strouhal number.

4 Conclusions

The primary effect of a transient gust on a ship airwake was to generate a dynamic stall vortex near the point of maximum variation in wind direction. This stall vortex manifested in a large, outboard rotating vortex located downstream of the windward hangar edge. Within the time-average flowfield, the phenomenon was observed as a triangular shaped separation bubble which decreased in size with increasing gust magnitude and covered more than 50% of the total flight deck area. As the airwake transitioned from the expected bluff body separation flowfield to dynamic stall, large changes in both the turbulent length scales and the angles of the hangar edge separated shear layers were also observed. Notably, these factors showed a dependence on Strouhal number which was observed across all waterplanes. The relevant effects to a helicopter attempting to land on a flight deck experiencing a transient gust included a decrease in predictability and an increase in overall flow energy across the flight deck.

Whereas transient gusts are generally less common in the open ocean, new strategic challenges will likely soon force the US Navy to operate within the confines of near shore locations. During the early 1980s, prior to the large scale adoption of small ship helicopter operation, US carrier strike groups would routinely operate within Norwegian fjords to avoid radar detection. Tall mountain ranges protected the fleet from Soviet radar but also drastically increased the quantity of transient gusts. As near-peer adversaries force the US Navy to once again emphasize hiding from radar, the fleet will inevitably return to conducting flight operations within sight and effect of land. The transient gust effects observed in this report will be introduced to small ship helicopter operations for the first time, and adaption of existing flight envelopes to this phenomenon will be crucial for operational safety.

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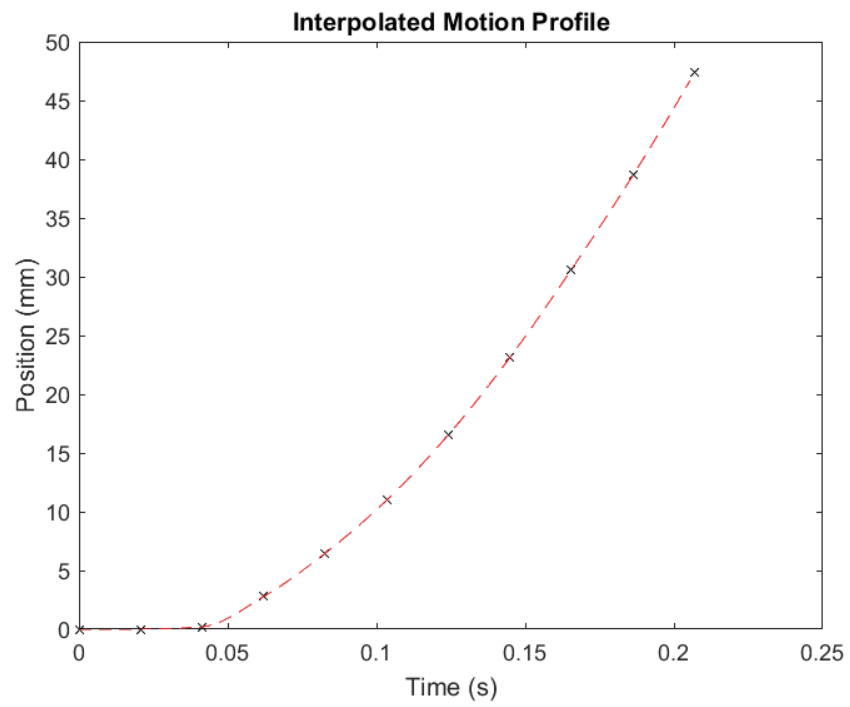
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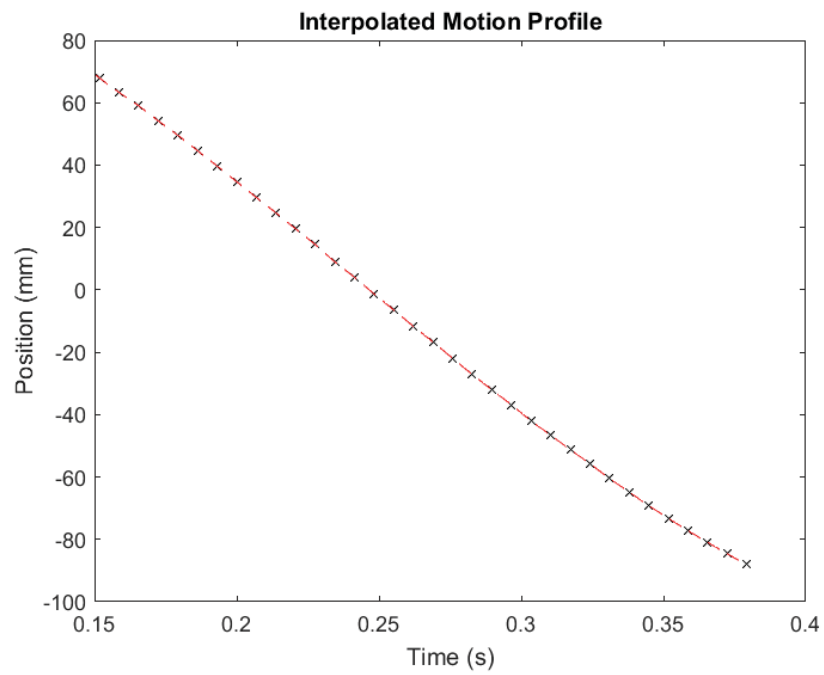
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Appendix A: Interpolated Gust Motion Profiles

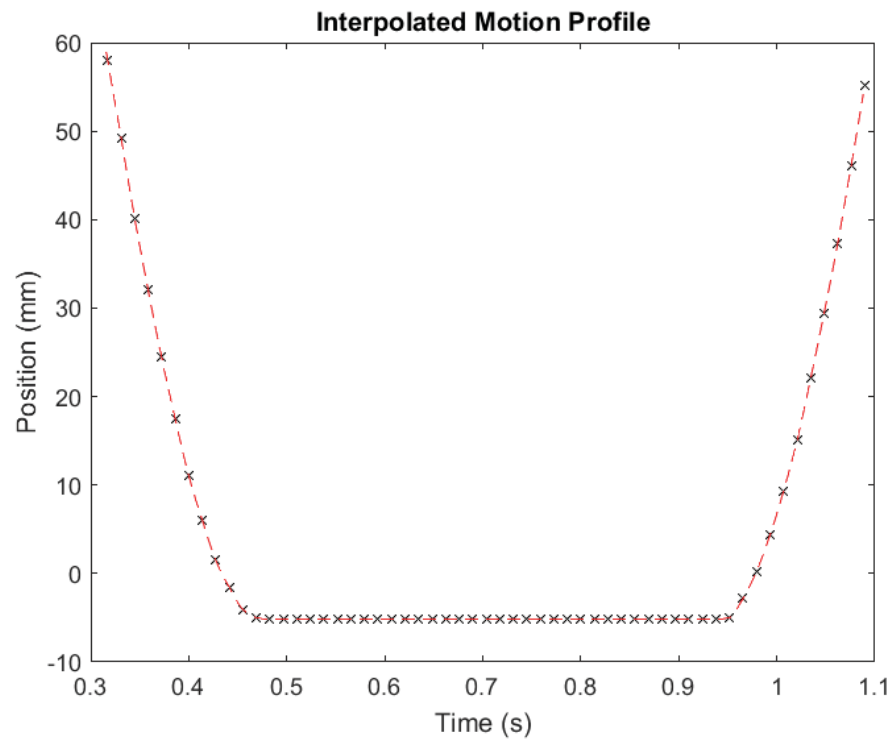
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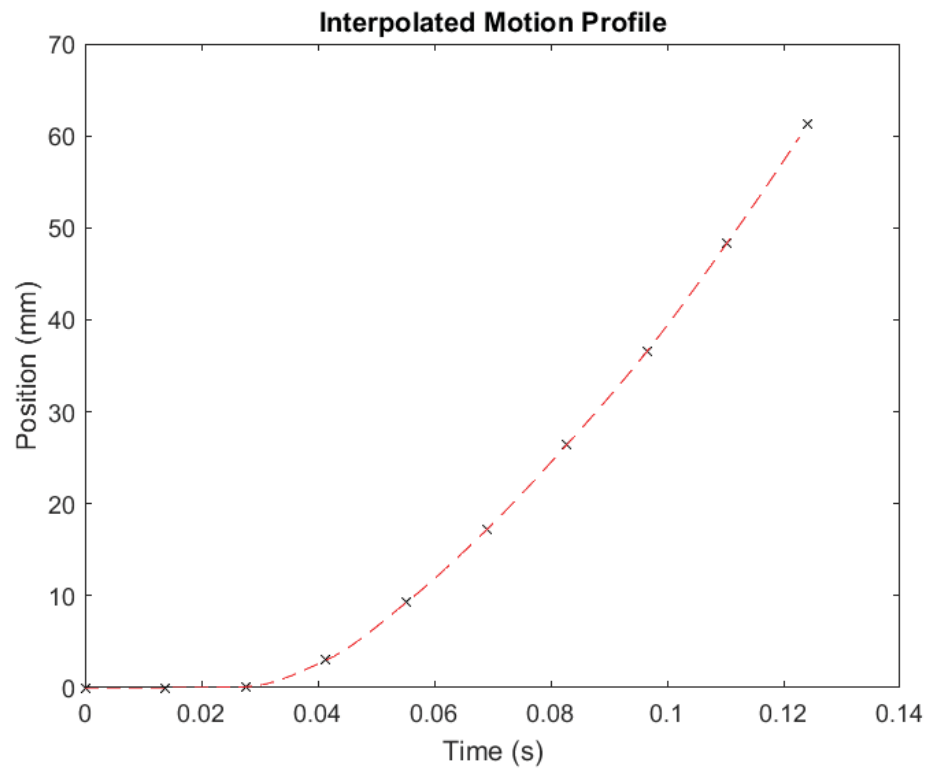
Profile 1B



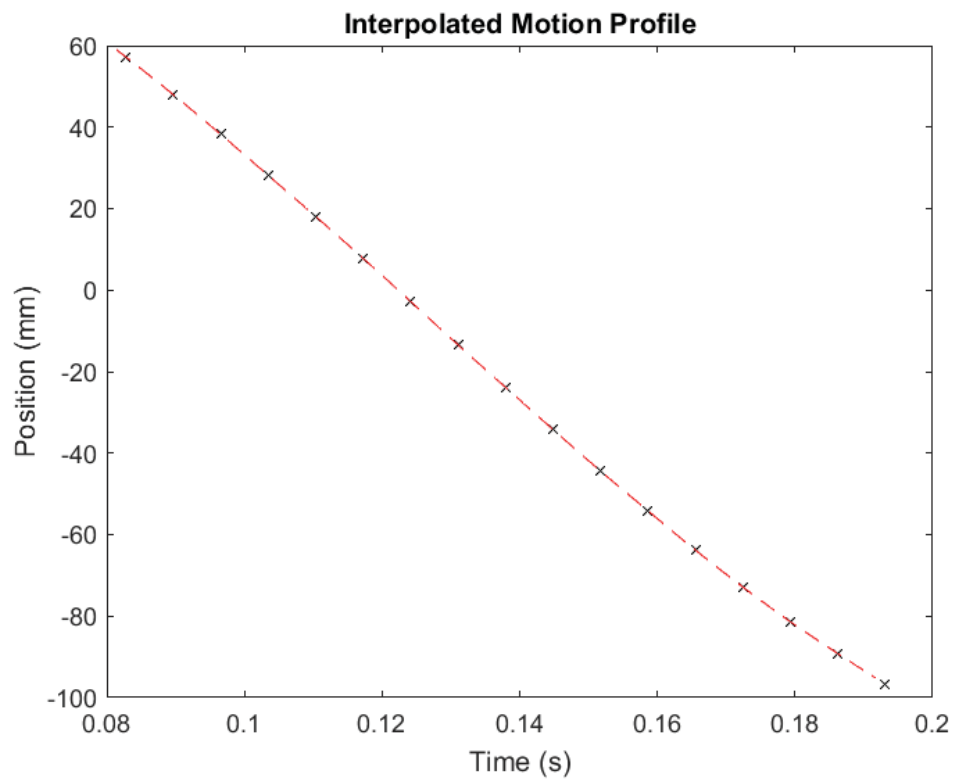
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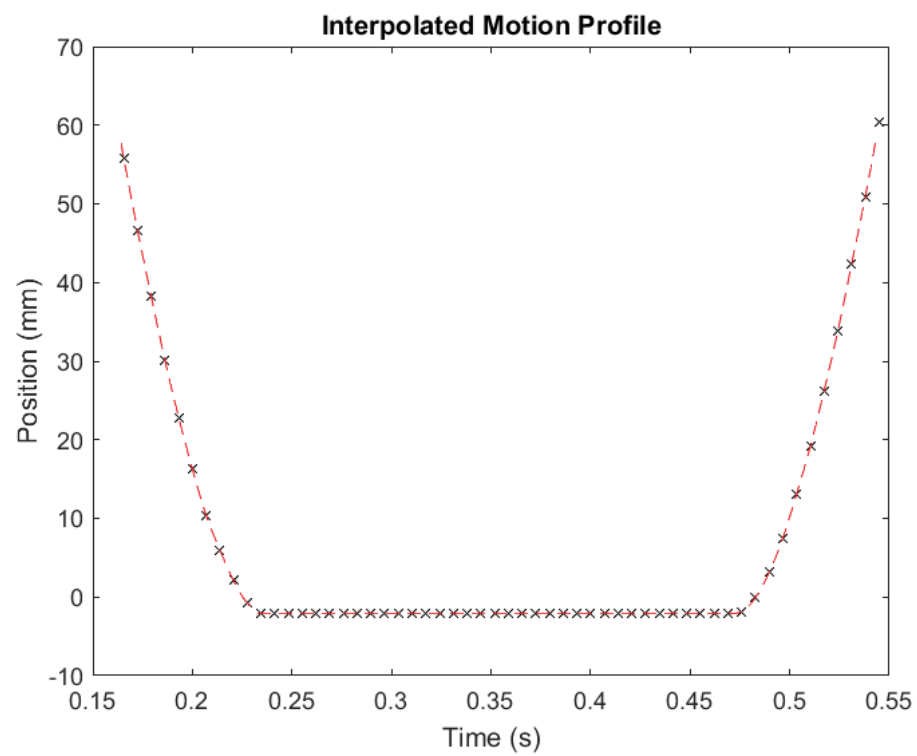
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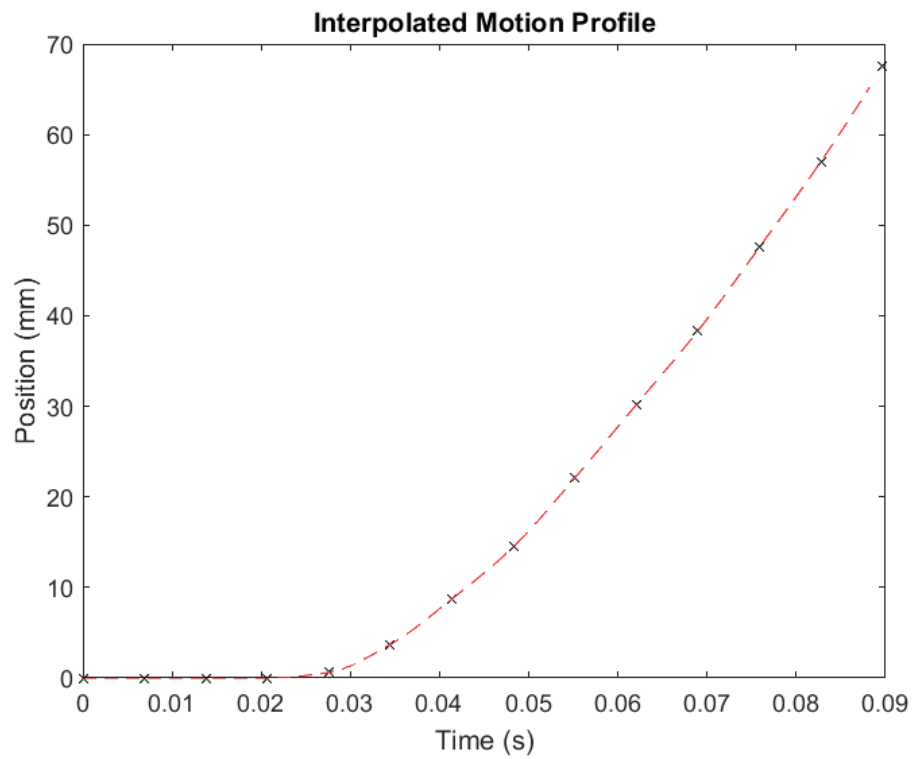
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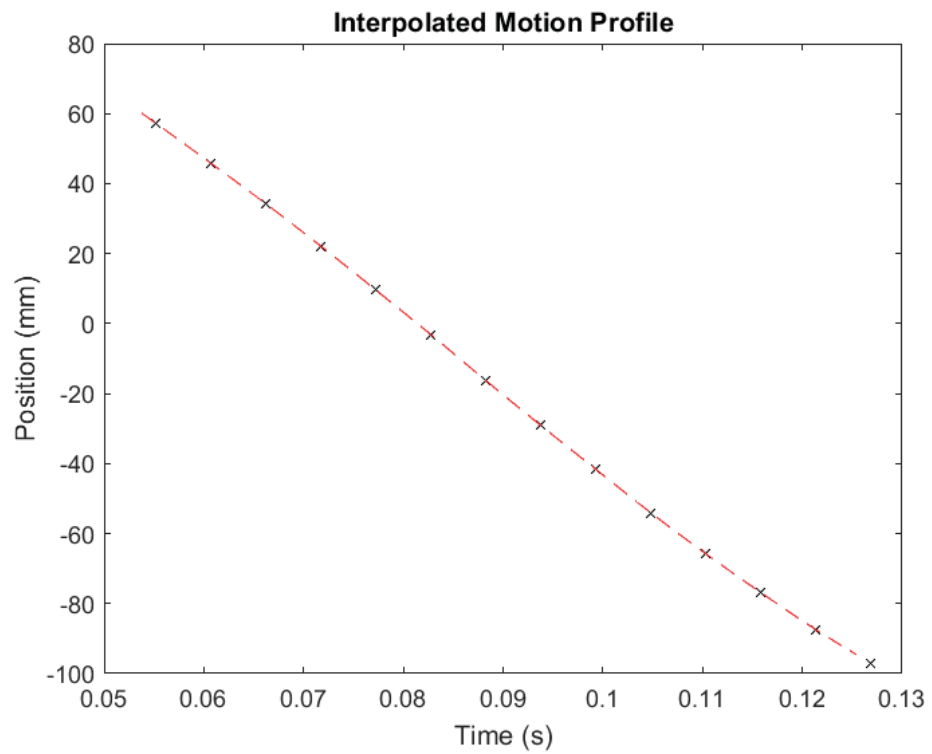
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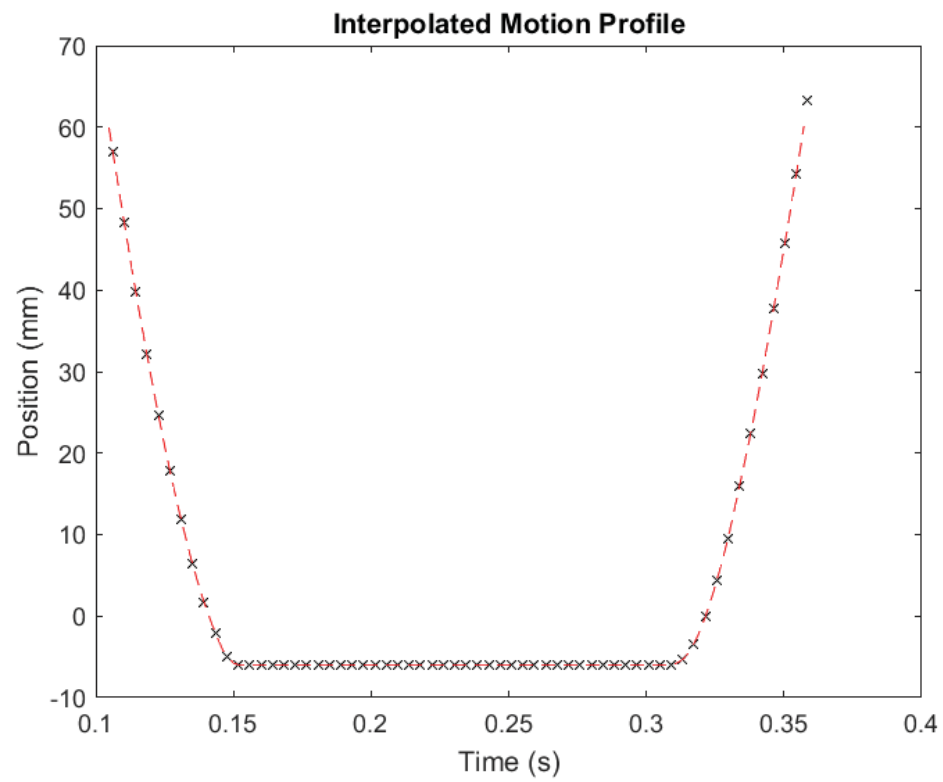
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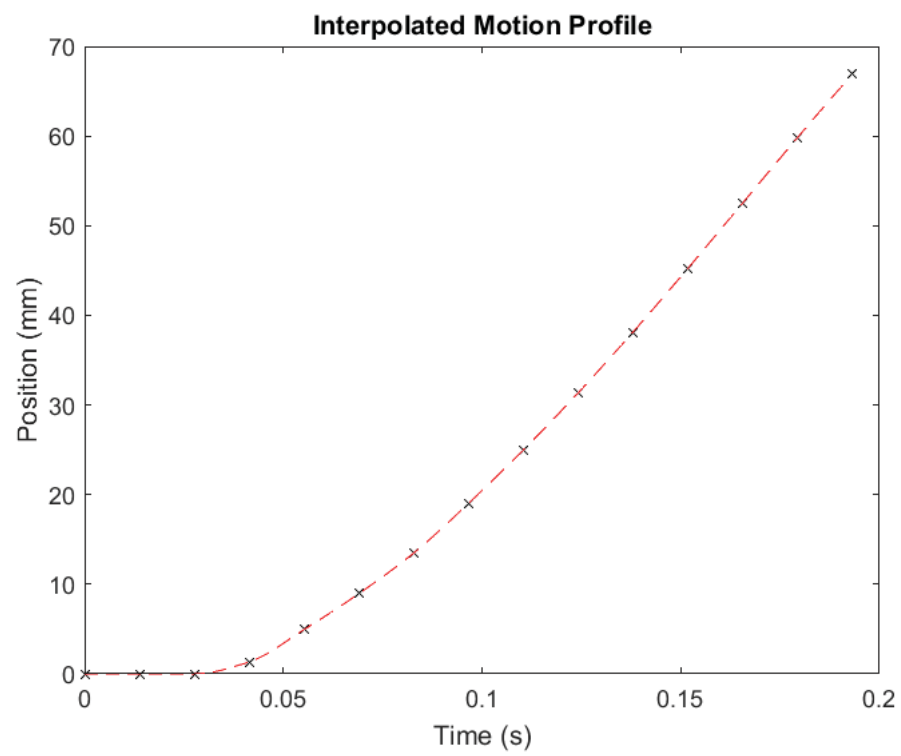
Profile 3B



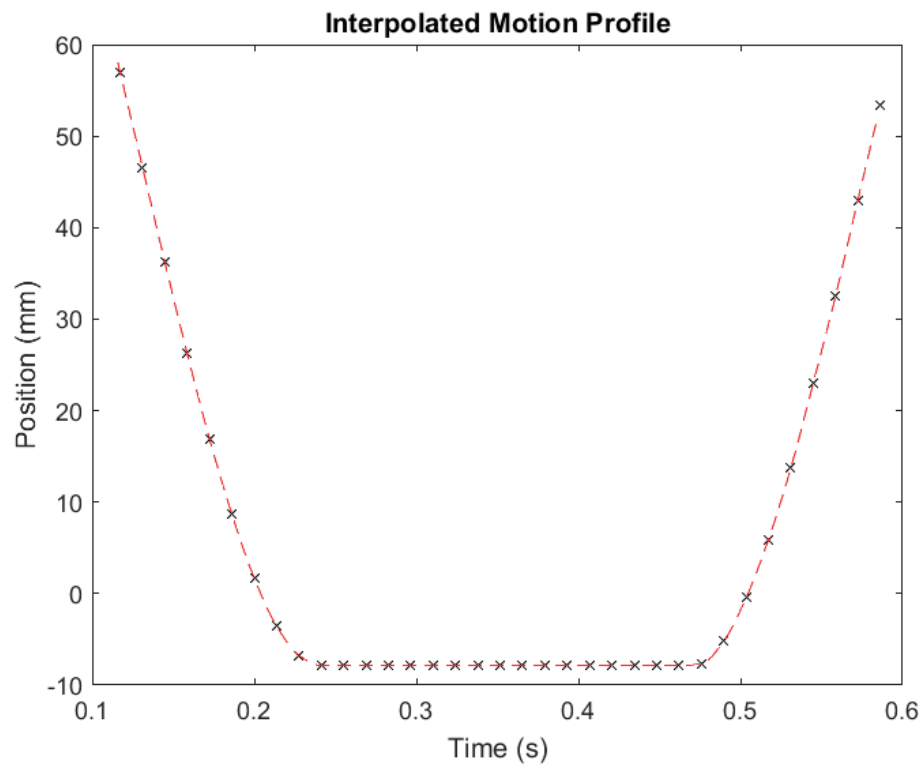
Profile 3A



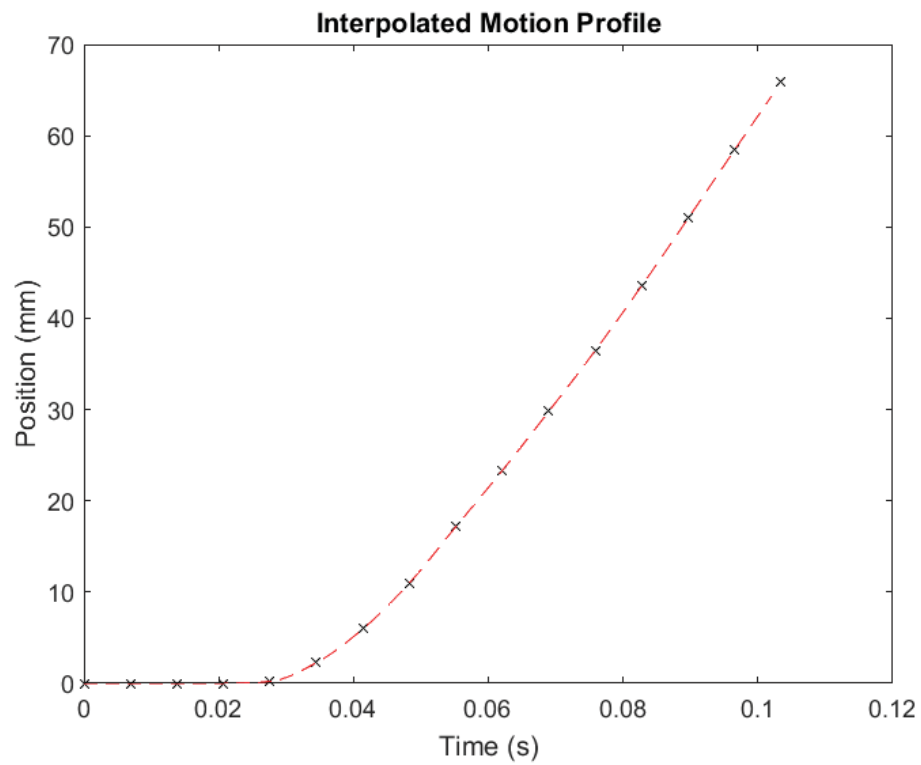
Profile 4C



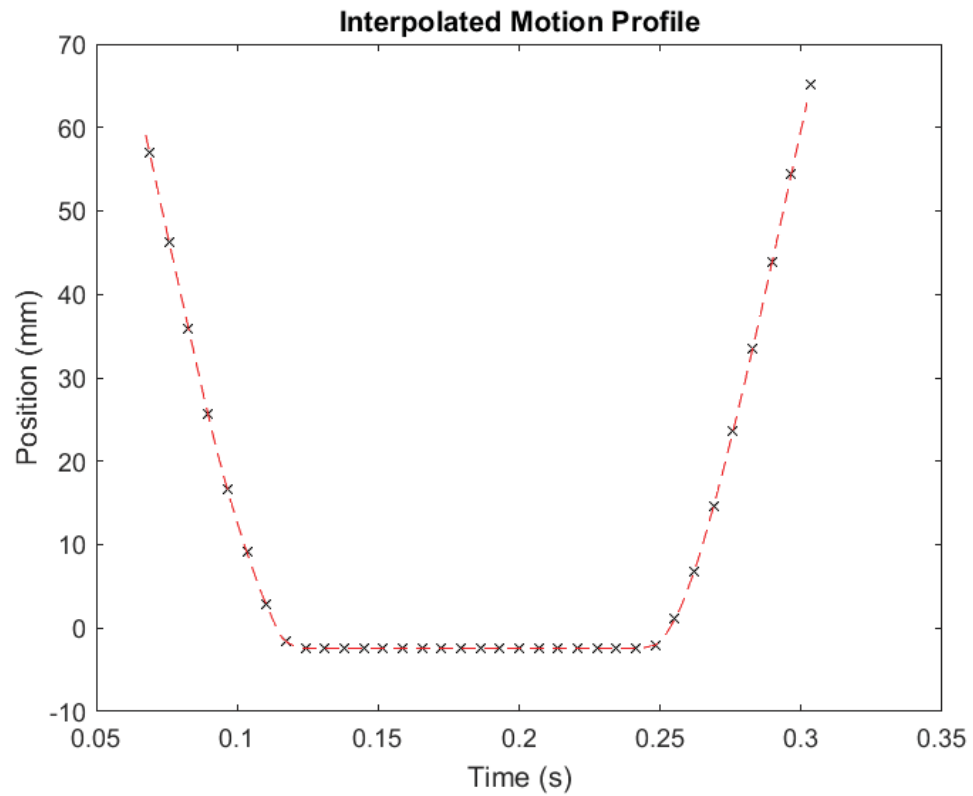
Profile 4A



Profile 5C



Profile 5A



Profile 6C/6A (Segments were identical but in opposite directions)

