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Near Wake Characteristics of a Marine Propeller in the Presence of Free Stream Turbulence

by

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Turbulence**

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Abstract

This project's goal was to determine experimentally the effects of free stream turbulence on the near wake dynamics of a marine propeller. The experiments were conducted in the USNA Hydromechanics Laboratory recirculating water channel. A turbulence generating grid was placed at the opening of the channel, upstream from the propeller plane and perpendicular to the flow direction, to induce flow turbulence with 7% intensity and integral lengthscale of $0.2D$ (here, D is propeller diameter). Two and three-dimensional Particle Image Velocimetry (PIV) measurement techniques were used to analyze the flow domain for both unconditioned velocity measurements and phase locked measurements at a single phase of the propeller. Both sets of experiments were completed with and without the turbulence grid. The instantaneous velocity vector fields from the processed PIV data were used for analysis of multiple flow characteristics in both the unconditioned and phase-locked cases.

Spatial distributions of mean velocity profiles in the near wake ($x/D < 9$) resemble an axisymmetric wake. Horizontal velocity of jet-type velocity profile exhibits a distinct dip at the propeller centerline due to the strong and persistent presence of the hub vortex. This vortex is clearly apparent on scaled velocity profiles when properly scaled with classical wake scaling. Tip vortices at the wake boundaries persist further downstream for the case with no turbulence generation in the free stream. Conditional sampling of velocity fluctuations showed the mechanisms of how mean flow energy is transported out of the wake core and into the less energetic free stream flow. The net transport of mean flow kinetic energy by means of random fluctuations was found to be 20% greater in the case with imposed free stream turbulence. The net transport by means of coherent fluctuations was greater in the quiescent case, however this net transport is smaller in magnitude by a factor of three.

Key words: marine propeller, turbulence, energy transport, near wake, re-energization

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Introduction and Literature Review

The main goal of this project is to analyze flow dynamics in the near wake ($x/D < 9$, in terms of propeller diameters downstream) of a marine propeller with imposed free stream turbulence. This being an experimental study, will provide high quality, high resolution data that can aid computer modelers in modelling a complex flow such as propeller wakes.

The study of axisymmetric wakes has been prevalent for many years due to its importance in applications such as drag reduction and propeller design. The two generalized categories of wakes are that around stationary “bluff” bodies, such as a disc or cylinder, which creates a drag-type velocity profile and that of wakes behind a propeller or a hydrokinetic turbine which form a jet-type and drag-type velocity profile in the wake, respectively [1]. A fundamental distinction of wakes behind propellers and turbines, in comparison to bluff bodies, is the continuous shedding of vortices that form at the tips of the lifting surfaces (i.e. blades) due to pressure differentials and the resulting lift generation by rotating blades. When fluid moves around a propeller blade, a pressure side and a suction side are created. Near the tips of the blades, this pressure difference causes the fluid to migrate from the pressure side to the suction side [2]. As this jump happens, the vortices are also advecting downstream with the fluid. In the wake of a propeller, tip vortices propagate in a helical pattern as seen in Figure 1.

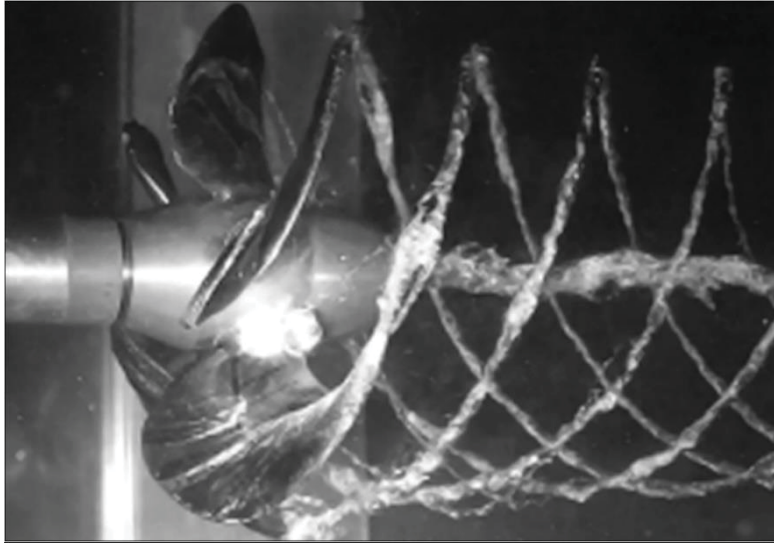


Figure 1: Example of trailing tip vortices behind a marine propeller forming a helical pattern as fluid moves downstream (left to right) [3].

There have been many experimental studies of flows around bodies in steady inflow conditions, however less work has been done with turbulent inflow conditions. In this case, the effects of turbulent inflow, or presence of turbulence in the incoming free stream, is important to understand as most propellers will operate in conditions with external turbulence present in the free stream. These categories of flows can be further segregated into computational models and experimental research.

An experiment completed by Rind and Castro [4] was of the axisymmetric wake formed around a disc placed in free stream turbulence in a wind tunnel. They first placed the disc in a quiescent stream in order to gain a baseline for the flow around the disc. They studied the effects of turbulence on the far wake ($x/D \geq 65$); to do so, they used two different turbulence grids with varying levels of solidity and bar structure. These grids were used to vary the levels of external (induced) turbulence in the tunnel. Their results showed that the external turbulence intensity had a much greater effect than the Reynolds number (for this experiment $Re = 15,000$ in the far wake);

the deficit velocity (or drag-type velocity profile) scaled mainly with the turbulence ratio, which is the ratio between the root-mean-square of the fluctuating component of velocity and the average centerline velocity (Equation 1). In the far wake, there were no longer signs of self-similar behavior. Self-similar behavior refers to the collapse of mean velocity profiles and turbulence intensities when properly scaled by representative velocity and a characteristic wake length scale. These quantities are functions of downstream distance from the wake generator [5]. Also, there was no sign of vortices in the far wake; the decay rate of the vortices was affected by the free stream turbulence resulting in a wider wake nearer to the disc and a reduced contribution to the energy spectrum by the vortex shedding process.

Numerous modelling and experiments on propellers in steady flow conditions have been conducted. For instance, one experiment was done on a propeller in free stream velocity by Cotroni, et al [6]. This experiment was done with a Reynolds number of 2×10^6 in a uniform inflow, and the propeller was studied at varying angular positions. They analyzed the very near wake ($x/D \leq 1$) using Particle Image Velocimetry (PIV) technique to study the flow field, blade wake, and tip vortices in the near wake. The PIV analysis allowed for characterization of both fluid instantaneous spatial velocity field as well as ensemble average velocity fields. In the near wake, the tip vortex strength was constant. The wake then widened as it underwent turbulent diffusion. The PIV method was found to be suitable in resolving the complex flow field behind a propeller. Another experiment used Laser Doppler Velocimetry (LDV) to analyze the flow upstream of a propeller, between the blades, and behind a propeller [7]. This experiment, however, focused primarily on the effectiveness of LDV to measure the velocity at specific points rather than on physics of the near wake development. The inflow conditions considered included steady flow conditions as well as a sheared wake, which is a wake with non-uniform velocity profile. Velocity

measurements were taken at different propeller angles and the boundary layer was also examined. These boundary layers developed on both sides of the propeller blade. On the suction side, there was a laminar boundary layer until about mid-chord where it went through the transition region and became a turbulent boundary layer by 0.7chord length. The trailing edges had thicker, turbulent boundary layers. The measurements of the boundary layer thickness correlated well with theory. The predicted location of the transition region from oil dot flow visualization was verified with the LDV technique. The tip vortices and the wake decay were not analyzed. The main contribution of this work was the advanced method to measure flow directly on and near the propeller.

Another experimental study using steady inflow conditions was an analysis of the near wake on a wind turbine by Lignarolo et al. [8]. This experiment used PIV and a two-bladed turbine in a wind tunnel. One of the key points in this paper was that there were two distinct regions with regards to the tip vortex behavior in the near wake. In the first region where the vortices first develop ($x/D < 1.4$), the vortices inhibit mixing and mean flow kinetic energy transport in/out of the wake is low. The vortices act as a shield between the wake and the external free stream flow. In the next region ($x/D > 1.5$ or 1.7 , depending on the turbine loading expressed as tip-speed ratio), the paired vortices begin to “leapfrog” which stimulates the turbulent mixing and thus energy transport between low momentum wake and the high momentum free stream. The leapfrogging motion occurs when a pair of neighboring vortices begin to move alternately one in front of the other due to pressure differences and eventually annihilate each other. This mixing then leads to a large increase in mean flow kinetic energy transport in/out of the wake. Further downstream (in the region $x/D > 2$ or 2.5 , depending on the tip-speed ratio), there are no distinguishable vortices. The external inflow turbulence was kept at a very low intensity in this experiment in order to

mitigate the effects of external turbulence and examine the turbulence from flow mixing alone. Turbulence intensity is defined as the root-mean-square of the fluctuating velocity divided by the time-averaged velocity [9]. Turbulence intensity, I_x , is calculated using the following equation:

$$I_x = \frac{\sqrt{\overline{(u')^2}}}{U} \quad (1)$$

where u' represents the fluctuations in the turbulent flow [m/s] and U is the time-averaged velocity [m/s].

Recently, Felli and Falchi conducted an experiment to analyze near propeller wake evolution at oblique angles [10]. They completed this experiment using PIV with three cameras focused on a single vertical plane to capture the downstream spatial extent of the wake, while still retaining high resolution of the 2D PIV measurements. The experiment was conducted for the propeller at no inclination, axisymmetric, as well as at three different angles of inclination. The focus of the study was the destabilization of the wake and of the tip vortices both above the propeller hub and beneath the propeller hub. Their results showed that one major component that caused the destabilization in the wake was the misalignment of the wake stream tube with the freestream. Another effect of the oblique angles was the unstable blade loading on different propeller blades affecting the blade wakes.

Another recent experiment completed by Felli and Falchi focused on the wake instability mechanisms for propellers at different loading conditions, blade number, and blade pitch in steady flows [11]. The experiment used 2D PIV as well as time resolved visualizations. PIV measurements were used to resolve large scale flow features. Time resolved visualization involves image capture at very high frame rate to capture the smallest turbulent eddies before mechanical energy is converted to heat. In this way, small scale flow features can be resolved. They found that the evolution of tip vortex grouping and destabilization is dependent on blade number and that the

tip vortex instability occurs closer to the propeller as blade number increases; both of these effects were concluded to be caused by the closer spiral spacing within the helical structure of the tip vortices. The changes in blade loading caused the instability to occur further away from the propeller at higher loading (smaller advance coefficient J , a non-dimensional term of propeller rotational speed and mean flow velocity) conditions as the tip vortices became stronger. The blade pitch greatly affected the tip vortex behavior. At positive inclinations, the wake transitioned to instability sooner, whereas the negative inclinations caused the propeller wake to remain stable longer, thus behaving like a propeller with fewer blades.

The numerical studies of marine propellers in turbulent flows are much more limited especially in the near wake ($x/D < 10$). One computational study of a propeller in turbulent flow was conducted using Reynolds-Average Navier-Stokes Equation solver (RANS) [12]. The main difficulty in this modelling was in creating the proper computational grid for the flow region subject to large variations in velocity, the need for accurate boundary layer predictions, and the need for a smooth grid in the computational network. This computational model focused mainly on the pressure fields and tip vortex flow as they were interested in propeller cavitation. Cavitation greatly affects detection as well as interference with SONAR due to self-noise; being able to control or predict the pressure fields and impending cavitation can mitigate both of these problems. The findings were that this model was more accurate than previous computational models using different methods. For turbulence, they used eddy viscosity turbulence models and Reynolds stress models. These particular models according to the authors, can more accurately model tip vortices in a turbulent flow than previous methods.

One experiment which analyzed a propeller with inflow turbulence used a propeller behind a model ship to induce a hull wake [13]. This propeller was a five bladed MAU propeller with

$D = 221.9$ mm and was tested at various angular positions. The PIV measurement technique was used and was found to be better than the LDV technique for this application as it provided much of the same data in a shorter time span; some accuracy was lost since the LDV technique provides time-averaged detailed information for a fixed location, whereas the PIV provides an instantaneous snapshot of a plane. However, this difference in detail was not enough to significantly affect experimental results. The experiment analyzed the instantaneous and average velocity fields of the propeller wake and examined the interaction of the narrow wake with the model ship's hull. The results suggested that turbulence from the hull boundary layer was present in the core of the propeller wake; the velocity fields were strongly distorted due to the hull wake induced turbulence; and that the greatest turbulence was generated where the tip vortices interacted with the hull wake. Although this experiment did analyze a propeller in a turbulent flow, its applications were limited since it focused mainly on validating the use of stereoscopic PIV as a technique for 3-dimensional flow analysis and on the velocity fields. This experiment did not focus on the tip vortex decay nor did it focus on the effects in the far wake.

Overall, the limited research on propellers in turbulent inflow conditions upholds the importance of this project in the understanding of the effects of free stream turbulence on the near wake dynamics and the subsequent development of the wake in the far field.

Experimental Set-up

This experiment focused on a near wake characterization ($x/D < 9$) behind a three bladed marine propeller model in a turbulent flow, which will be analyzed through a combination of two and three dimensional PIV measurements. The first experiment used two dimensional PIV with the turbulence generating grid placed upstream of the propeller to gain a preliminary data set for basic analysis and verification for later experiments. Subsequently, two additional experiments

were completed using three dimensional PIV measurements. The second experiment had the turbulence generating grid and the propeller, whereas the third experiment tested the propeller without the turbulence generating grid in order to have a control data set for comparison. Specific details of each experimental set-up are discussed below. All experiments were conducted in the large recirculating water tunnel at the USNA Hydromechanics Laboratory.

Recirculating Water Channel

The USNA recirculating water tunnel (Figure 2) has a 1.8 m long test section with a 0.48 m x 0.48 m cross section. A cover plate (not shown in the figure) is used to eliminate free surface effects.

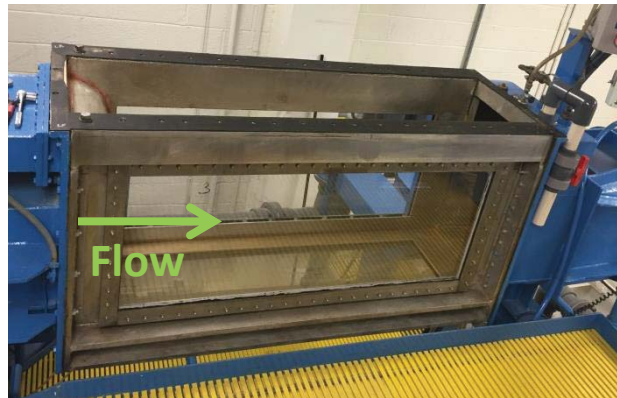


Figure 2: USNA Water recirculating tunnel. Dimensions: 0.4 x 0.4 m² cross section with 1.8 m long test section. Flow is from left to right. Tunnel velocity range is up to 6 m/s and the freestream turbulence intensity in the test section is 0.5% [14].

The tunnel features a 4.6:1 contraction section at the upstream entrance into the test section and reported turbulence intensity of the channel itself is 0.5% [15]. The recirculating water tunnel is capable of producing velocities up to 6 m/s. For the current experiment (see Figures 3 and 4), a stainless steel bar was strut welded to the stainless bossing within the tunnel to which the propeller model is connected. A fairing was attached to the steel strut to reduce wake signature and to prevent

any flow induced vibration of the propeller shaft ($\frac{1}{4}$ inch diameter), which in turn was connected to a 19 mm diameter flexible shaft that ran upstream through the tunnel contraction section, through the turbulence generating grid and the penetration on the tunnel wall and connected to the computer controlled Baldor motor.

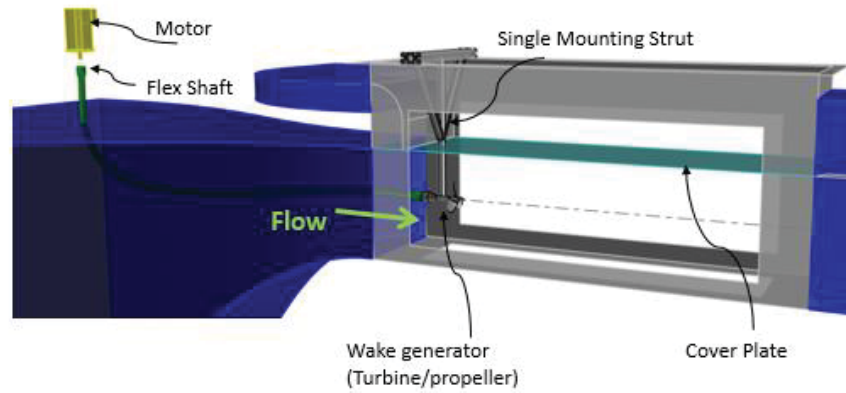


Figure 3: CAD rendering of the water tunnel and propeller set-up for the present experiment

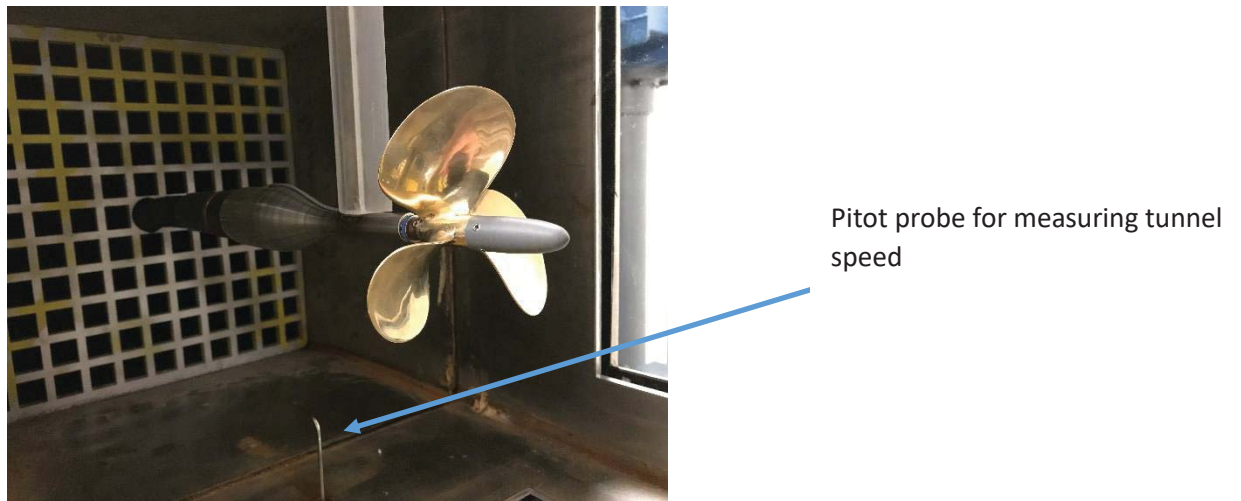


Figure 4: Details of the propeller mount in the water tunnel. Note the turbulence generating grid just upstream from the propeller. Pitot probe shown is used to measure free stream velocity U_{inf} .

Propeller

The propeller used in these experiments (Figure 4) was a left-handed, three-bladed brass propeller model with a diameter $D = 130$ mm (5.1 inches). More propeller model details are

provided in Table 1.

Table 1: Propeller Model Measurements and Details

Propeller Model Details	
Diameter	130 mm
Pitch to Diameter Ratio (P/D)	1.17
Hub Diameter	15mm
Expanded Area Ratio (A_e/A_o)	0.643
Number of Blades	3
Left-Handed	

In order to further describe the propeller model used in the present experiments, an open water test was conducted in the USNA Hydromechanics Laboratory's 120 ft towing tank to obtain propeller performance curves including K_t , K_q and η as a function of advance coefficient J . Thrust developed by the propeller was measured along the propeller shaft, whereas the torque was measured at the motor where rotational speed was set at 25 rps, corresponding to approximately 17 rps at the propeller. As is a standard procedure for open water tests, measurements were first conducted with no propeller to determine the torque caused by friction of the system. Variation in advance coefficient was accomplished by varying the tow carriage speed from 1 ft/s up to 8 ft/s, which corresponds to Reynolds numbers based on chord length $Re_{0.7R} = \frac{U_{rel} c}{\nu}$ (Equation 2) between 2.0×10^5 and 2.3×10^5 , where $U_{rel} = \sqrt{U_{inf}^2 + (0.7R\Omega)^2}$ (3), $c = 0.7R$, Ω is propeller angular velocity [s^{-1}], and ν is the fluid kinematic viscosity [m^2/s]. In this experiment the kinematic viscosity used was at a temperature of 17°C which is $1.09 \times 10^{-6} m^2/s$. The resulting performance curves for the propeller are shown in Figure 5. The horizontal axis is the advance coefficient,

defined as $J = \frac{U_{inf}}{nD}$ (4), and on the vertical axis, the thrust coefficient $K_T = \frac{Thrust}{\rho n^2 D^4}$ (5), torque coefficient $K_Q = \frac{Torque}{\rho n^2 D^5}$ (6), and propeller efficiency $\eta = \frac{K_T}{K_Q} \frac{J}{2\pi}$ (7) are plotted. In calculating these non-dimensional quantities, ρ is the density of the water; n is the rotational speed of the propeller in rps; D is the diameter of the propeller and U_{inf} is the speed of advance of the propeller (i.e. inflow velocity upstream of the propeller – carriage speed).

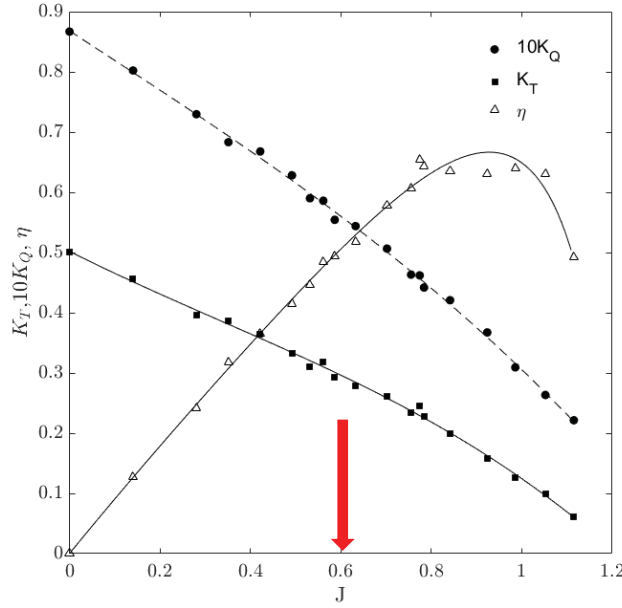


Figure 5: Propeller model open water performance characteristics. The horizontal axis represents the advance coefficient. The squares are the thrust coefficient, the circles are the torque coefficient, and the triangles are the propeller efficiency. All PIV measurements in the near wake were conducted at the propeller advance coefficient of $J=0.6$ (marked by the red arrow).

For all PIV experiments, the propeller operating point was chosen at an advance coefficient of $J=0.6$ which corresponds to the following conditions: a rotational speed of $n = 27$ rps and a free stream velocity $U_{inf} = 2.1$ m/s. The resulting Reynolds number based on diameter $Re_D = \frac{U_{inf} D}{\nu}$ (8) is 2.63×10^5 and the Reynolds number (Re) based on chord length is 3.51×10^5 . The critical Re, where a turbulent boundary layer develops for a flat plate is $Re = 5 \times 10^5$. Thus, the Re for these

experiments are of the same magnitude so it is assumed that a turbulent boundary layer will form on the blade faces. Note that this is at least an order of magnitude larger Re than any previous computational work with propeller wakes.

Additionally, an in-house designed shaft position indexing system featuring a Hall Effect sensor, similar to the one described in Lust, et al [17] is mounted to the propeller hub so as to phase lock the PIV image pairs (discussed in the next section) with the reference propeller blade position. The Hall Effect sensor built by the Hydromechanics laboratory staff provides a single pulse for each complete blade rotation. The sensor firmware allows a user to select multiples of 2, 5, or 10 pulses and then the electronic system counts those multiples (i.e. blade passages) and sends a one Transistor-Transistor Logic (TTL) pulse. It is this TTL signal which triggers the firing of the laser and the PIV image capture. The above modifications to the Hall Effect sensors were necessary since the propeller is operating at 27 Hz, and the PIV laser used in the experiment has a maximum repetition rate of 15 Hz. Thus, a multiple of 10 was selected while the blade is operating at 27 Hz, thus a TTL signal was sent to the PIV synchronizer for every 10th blade rotation, which then triggered the system to capture the PIV image pair at a resulting 2.7 Hz.

Turbulence Generating Grid

The turbulence generating grid used in the experiment is shown in Figure 6. It has been designed and fabricated prior to the start of this Trident project and information on the turbulence grid is included in this report for completeness. It is a uniform square bar grid with mesh width $M=3.86$ cm, bar thickness $t_0 = 0.97$ cm, a streamwise thickness of 1 cm, and resulting solidity of 44%, similar to the conventional grid used by Krogstad and Davidson [18]. The grid patterns differ from the published design by a circular hole of diameter 4.30 cm in the middle that accepts a flexible propeller shaft connected to the wake generator. The grid was placed approximately 3.5

propeller diameters upstream of the propeller.

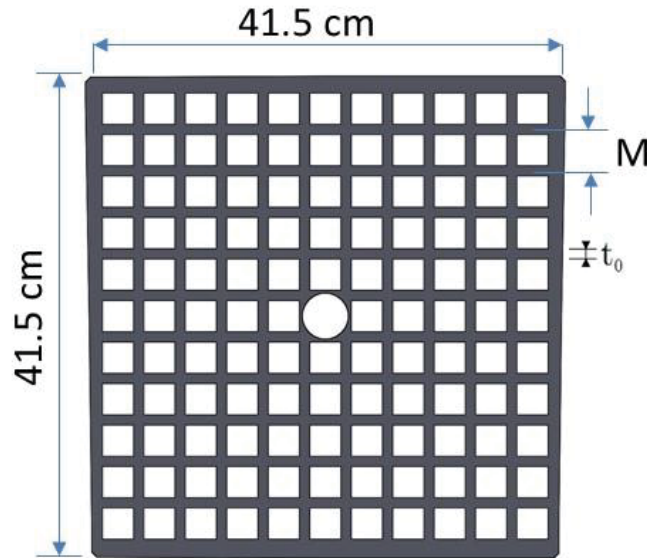


Figure 6: Rectangular grid mesh used in the present experiment. Design is based on Krogstad and Davidson [19].

Results in the water tunnel with this grid and without the propeller model and the supporting strut are presented in Figure 7. It can be observed that the obtained turbulence intensity at the location of the propeller plane is about 7% and the realized integral scale L_{11} is approximately $0.2D$ which correspond to 26 mm; both agree well with the models from Roach [20]. The integral scale L_{11} refers to the size of the largest eddies (in streamwise direction) in the turbulent flow, and it has units of length [21].

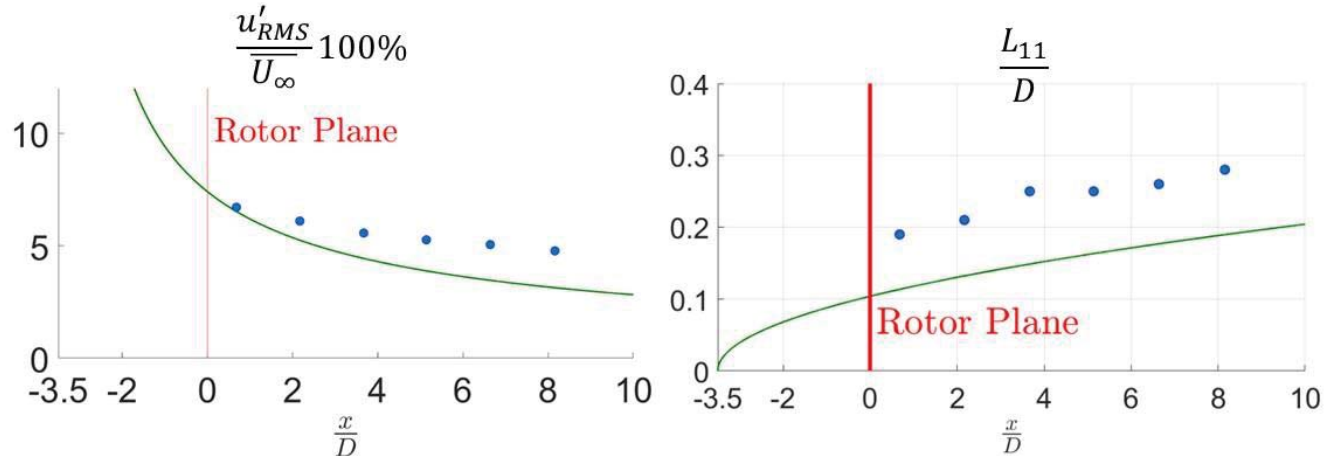


Figure 7: a) Turbulence intensity distribution in the near wake. (b) Distribution of streamwise integral scale L_{11} in the near wake. Subscript 1 indicates integral scale in the streamwise direction. Green line: predictions from Roach [22]. Blue circles are present results. Note these results are for rectangular mesh without the presence of the propeller model and the supporting strut.

Particle Image Velocimetry (PIV) Technique

Particle image velocimetry, or PIV refers to a method used in experimental fluid dynamics to obtain instantaneous velocity fields by measuring the displacements of numerous fine particles (seed particles) that accurately follow the motion of the fluid. The typical PIV system comprises of double pulsed laser, laser sheet forming optics, particle seeding, one or multiple digital cameras (with CCD technology), synchronizer, and a computer for data storage and analysis.

Typically, the seeded flow field is illuminated with thin ($<1\text{mm}$) laser light sheet by two short laser pulses fired with a known time separation Δt . Images of the illuminated particles are captured by a single digital camera (planar or 2D PIV) or multiple cameras (stereoscopic or 3D PIV) onto a single or two different image frames, with each laser pulse illumination per image. Once the images are acquired and stored onto a computer, image processing of each image pairs is conducted. The entire field of view (FOV) is divided into a small “interrogation regions”

typically with 32×32 or 64×64 pixels², and cross-correlation is conducted using the image pairs of the particles lying within the interrogation region. This process results in an estimate of particle displacement, d (in pixels) within the interrogation region. With a known magnification, M [m/pixel], i.e. ratio of actual image physical dimension and CCD sensor dimension, the velocity can be calculated as:

$$V \left(\frac{m}{s} \right) = \frac{d}{\Delta t} M \quad (9)$$

The same process is repeated for all interrogation windows within an image resulting in an instantaneous vector field. Typically with 32×32 pixel² interrogation region and 50% overlap and 8MP camera yields about 33,000 vectors per instantaneous vector field. The process is then repeated for the entire ensemble of images.

The present experiment was conducted in three major divisions; each will be discussed in greater detail below. The first was a 2D PIV set-up with the turbulence generating grid and the propeller in place; this data was the initial data to be used as a point of verification for follow-on experiments. The next was a 3D PIV set-up with both the grid and the propeller. The third and final part was the 3D PIV set-up with the propeller but without a grid in order to have comparative data.

2D PIV Experiment

For this experiment, 2D PIV measurements were taken in a vertical plane at the tunnel centerline. This experiment included both the propeller and the turbulence generating grid. The data was collected as free runs, using the maximum repetition rate of the system. A top-view of the two-dimensional PIV set-up is shown in Figure 8.

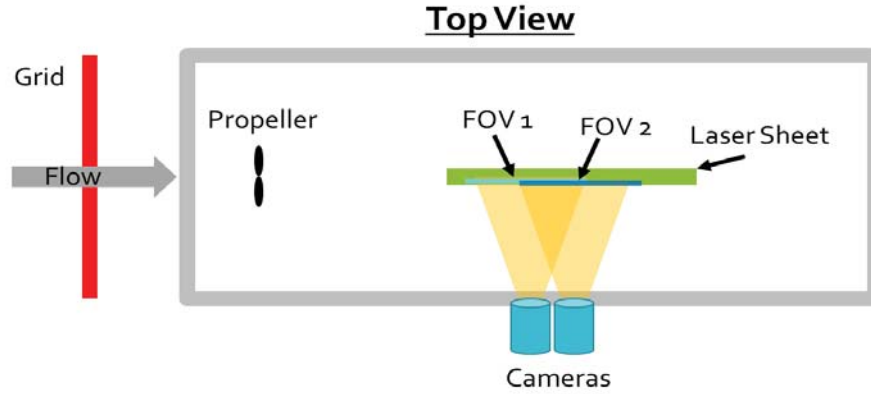


Figure 8: Schematic of the 2-D PIV experimental set-up from a top view. Grey arrow indicate direction of flow (left to right). The cameras are placed perpendicular to the flow. The blue rectangles represent the cameras' fields of view; there is an overlap between them. The laser sheet is denoted by the green rectangle.

Two high resolution 29 MP (6600x4400 pixels²) LaVision cameras at approximately 0.5 Hz repetition rate (low repetition rate with high spatial resolution due to large CCD sensors) were used in this experiment. Flow field was illuminated by the ND-Yag 200mJ (532nm) laser. The cameras were placed on their sides for higher resolution across the wake (6600 pixels in the vertical direction and 4400 pixels in the horizontal direction). The seeding particles used were Potter Industries SG02S40 silver coated glass spheres with average particle diameter of 2 microns and specific gravity (SG) of 1.1. Spatial coverage of the propeller wake was accomplished via “tiling” of individual fields of view (FOV) of nominally 11x16.7 cm² area covering downstream distance from the wake generator (propeller) plane up to approximately 8.5D downstream. Approximately 7.3% and 73% overlap between FOV's was attained in streamwise and vertical directions, respectively. Before each run, the cameras were carefully focused on the seeding particles. This focusing was to ensure that particle traces were in focus across the entire image and as a check that the density of the seeded particles in the flow is sufficient. If an insufficient number of particles was observed, more particles would be added for adequate spatial coverage. At each location, an

ensemble of 600 PIV image pairs, in two 300 pair sets, was collected to ensure statistical convergence of the calculated quantities. A diagram of the experiment spatial coverage is shown in Figure 9, which depicts the 10 fields of view (5 horizontal locations and 2 vertical locations) with corresponding overlap.

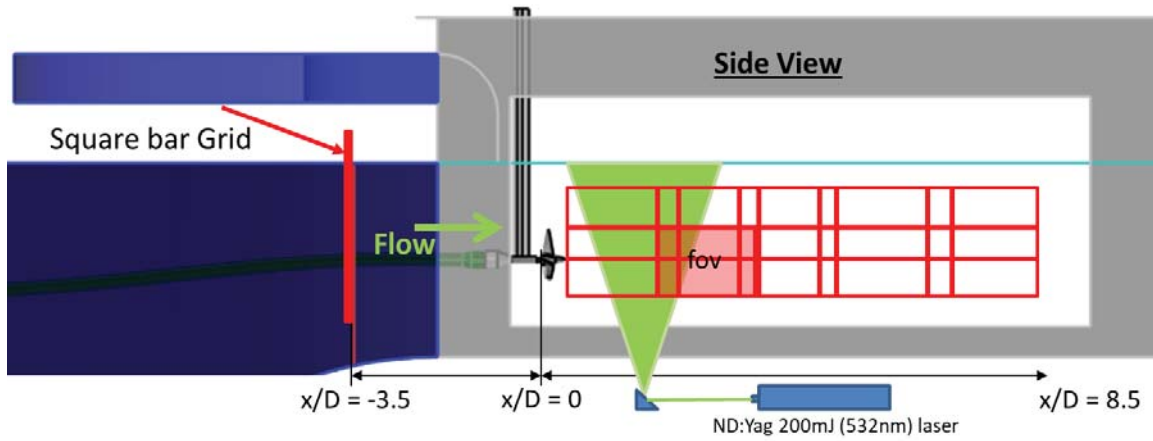


Figure 9: Side view of the tunnel with individual fields of view (FOV) shown. Green arrow indicate direction of flow (left to right). An example field of view is shown as the shaded red box. The red lines represent the remaining fields of view. Together there are 10 tiles at five horizontal locations and then two vertical locations.

During the experiment, data from the water tunnel pitot probe was recorded in order to ensure the water channel was operating at the proper speeds. A minimum of 4 readings were taken during each run. The propeller rotational speed (rps) was monitored to ensure a consistent speed of 27 rps. The water level was adjusted on several occasions during the experiment to ensure that a free surface was not created beneath the cover plate.

A large calibration grid (not shown) was placed in the water channel after each run with the purpose to acquire calibration images. This calibration of images was necessary to correct for distortion from imperfections in the camera lenses, optical travel through water tunnel glass walls,

and optical travel through interface between air and water as well as slight offsets between adjacent FOV locations.

After calibration, the images were processed using the LaVision acquisition software. The image processing included a pre-processing, processing, and post-processing of calculated velocity vectors. For the pre-processing, a background image (CCD image taken in the dark and with lens cap on) was subtracted from each acquired image pairs and a local image intensity enhancement was performed with a window of 64×64 pixels². Then, a multi-pass correlation of image pairs was performed with the final interrogation window of 32×32 pixels with a 1:1 circular weight and 50% overlap for a final resolution of 64×64 pixels. The LaVision software correlation routine is a standard Fast Fourier Transform (FFT) correlation method with no padding at the interrogation window edges. In the multi-pass post-processor and the vector post-processor, mode, newly found vectors were removed if different from the average of its neighbors by more than 1.5 standard deviations. The vectors would be reinserted after the pass if they were within 2.5 standard deviations of the neighbors. At the end of the process, if any remaining holes were present (i.e. correlation routine could not find reliable correlation peak) they were filled by interpolation using the local mean of its neighbors. The processed data was then converted into files that could be used in MATLAB for subsequent analysis.

3D PIV Experiment with Turbulence Grid

With stereoscopic PIV set up two separate set of measurements were performed: i) phase locked, that is PIV image pairs were triggered at every tenth blade rotation when the reference propeller blade was vertical and ii) “free runs” where PIV measurements were performed at the maximum repetition rate the PIV system will allow (8 Hz). For both sets of measurements, 600

frames (image pairs) were collected. Images were collected at 15 spatial locations (5 horizontally and 3 vertically). A diagram of spatial “tiling” is illustrated in Figure 10.

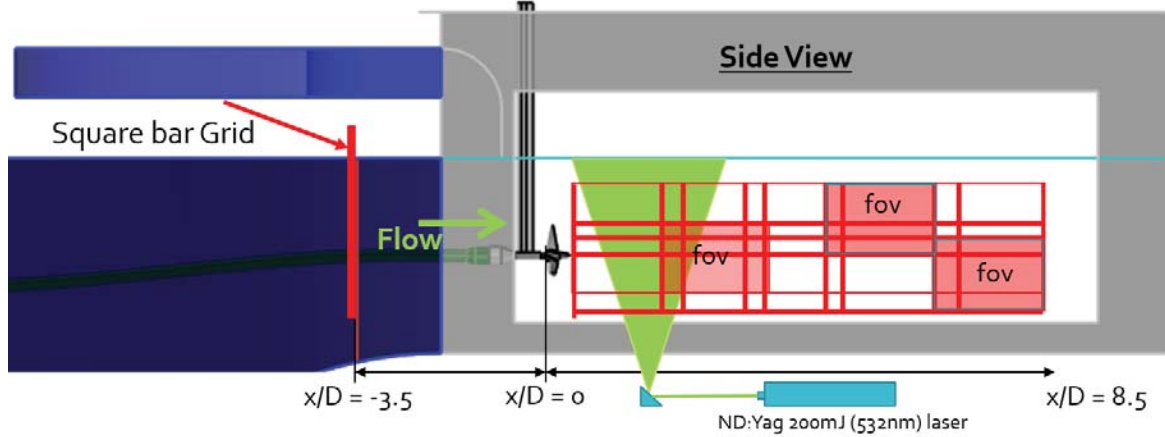


Figure 10: Side view of the tunnel with individual fields of view (FOV) shown. Green arrow indicate direction of flow (left to right). Example fields of view are shown as the shaded red boxes. The other red lines represent the remaining fields of view. Together there are 15 tiles at five horizontal locations and the three vertical locations.

The propeller operated at an advance coefficient $J=0.6$ and the tunnel speed was kept constant at $U_{inf}=2.1\text{m/s}$ as discussed in the previous section. For this experiment, three dimensional PIV measurements were made in the vertical plane through channel centerline using two 8MP ($3320 \times 2496 \text{ pix}^2$) in stereoscopic configuration and the same laser as in the previous experiment. Cameras were oriented with 3320 pixels horizontally and 2496 pixels vertically. This set-up resulted in a nominal FOV of $18.1 \times 9.4\text{cm}$ with approximately 1% overlap in the streamwise direction and 16% overlap between the top and bottom positions (the center position had complete overlap). The seeding particles used had $\sim 12\mu\text{m}$ diameter and specific gravity (SG) of 1.1. A top view of the 3D PIV set-up is shown in Figure 11, which illustrates the positioning of the two cameras for the stereoscopic configuration. Two Plexiglas prisms filled with water were used to minimize optical aberrations as recommended in Adrian and Westerweel [23].

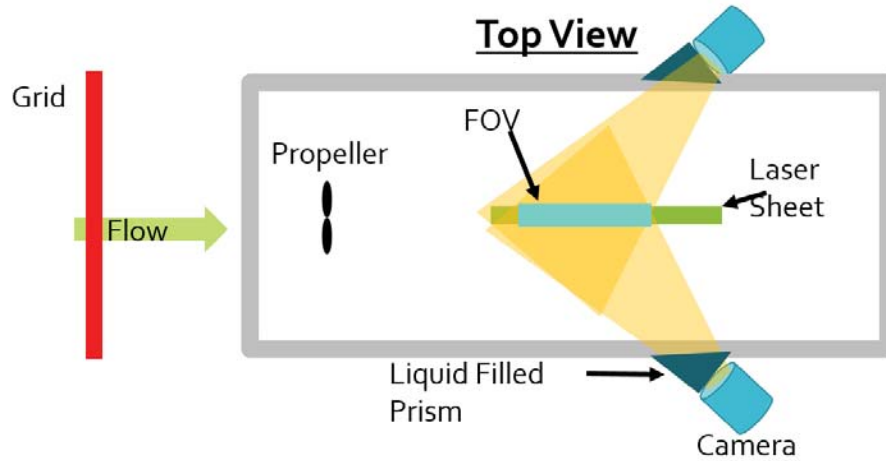


Figure 11: Schematic of the stereoscopic PIV experimental set-up from a top view. Grey arrow indicate direction of flow (left to right). The cameras are placed at 45° angle with respect to the channel centerline and two liquid filled prisms are installed on the outer wall of the tunnel to minimize optical aberrations. The overlap between the cameras' spatial resolutions is the field of view utilized. The laser sheet is denoted by the blue rectangle and approaches the FOV from below.

It should be noted that 8MP cameras have significantly smaller CCD size, and consequently smaller spatial resolution in comparison with the 29MP cameras used in the 2D experiment. These cameras were selected because they allowed for phase locked measurements due to their high frame rate (8.5 frames/s). Thus by preselecting Hall Effect sensor electronics to a multiple of 10 and propeller rps of 27, data was collected at 2.7 Hz or 2.7 PIV image pairs/s. The stereoscopic PIV set-up allows for the reconstruction of the particle displacements in three orthogonal directions, which means that all three components of velocity were measured [24].

3D Data Experiment without Turbulence Grid

The third and final experiment was a repeat of the 3D experiment discussed above with the turbulence generating grid removed. The goal of this experiment was to gain a baseline data set

for the propeller tip vortex formation and decay in the near wake. Stereoscopic PIV set-up was the same as discussed previously with both phase locked and free run measurements.

Theory

The PIV processing produces instantaneous velocity vectors, either in 2D or 3D depending on the set-up. These spatial measurements of velocity vectors can then be used to calculate many quantities in the flow such as spatial development of mean velocities, downstream evolution of mean flow kinetic energy, wake expansion parameters, turbulence Reynolds stresses, turbulent kinetic energy, and vorticity. Several of those quantities mentioned are described in this section. The unconditioned data sets (i.e. free runs) are used for ensemble averaging in time, whereas the phase-locked data is used for phase ensemble averaging; the need for both types of averaging is discussed later in this section.

Wake expansion occurs as the shear layer, interfacing between the wake core and the surrounding free stream, begins to dissipate and the wake begins to reenergize and expand. In this work, the wake expansion is defined by identifying the wake half-width [25] following Tennekes and Lumley (1972) definition. Wake half-width is defined as a lateral (y-direction) location where the local velocity is half of the peak velocity:

$$\delta = y\left(\frac{U_{max}}{2}\right) \quad (10)$$

where δ is the wake half width [mm] and U_{max} is the maximum time-averaged velocity [m/s] at any spatial location downstream from the propeller plane. Figure 12 illustrates these quantities.

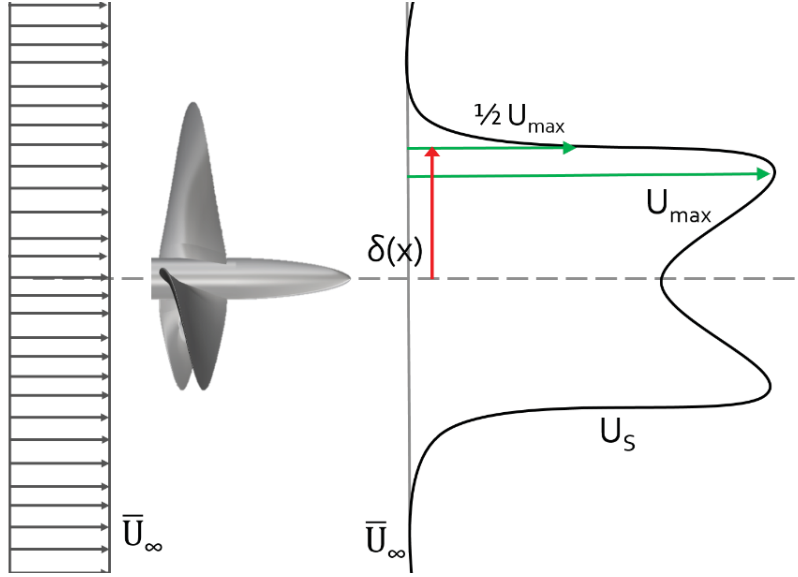


Figure 12: Illustration depicting the calculation of the wake half width. The red line represents the wake half width. In the present experiment, it is measured in meters. The fluid enters propeller plane with a uniform mean velocity from the left. The black curve on the right is an example velocity distribution (i.e. velocity surplus) representative for marine propeller. The vertical grey line represents the magnitude of free stream velocity.

Turbulence fluctuations are calculated using Reynolds decomposition [26]:

$$u_i(x, y, t) = U_i(x, y) + u_i'(x, y, t) \quad (11)$$

where $u_i(x, y, t)$ is instantaneous (measured) velocity, $U_i(x, y)$ is the time averaged velocity [m/s] and $u_i'(x, y, t)$ are random velocity fluctuations [m/s]. In all subsequent work, capital letters will indicate average quantities and overbar averaging process. Subscript $i=1, 2, 3$ indicates streamwise (x direction) velocity u , vertical (y direction) velocity v , and cross stream (z direction) velocity w , respectively. Since PIV measurements are performed in a single vertical (x, y) plane, velocity dependence in z is not shown. With velocity fluctuations defined, turbulence quantity known as Reynolds stress can be calculated by first finding the random velocity fluctuations from Equation (11), and creating a product of velocity fluctuations in form of $\overline{u_i' u_j'}$. Reynolds stresses are a measure of the shear force in a fluid resulting from differences in

velocity and account for momentum transfer [27]. Reynolds stresses are important terms as they appear in the “turbulence form” of Navier-Stokes equations, which describe the flow of incompressible fluid. Reynolds stresses have nine components shown in the matrix:

$$[u'_i u'_j] = \begin{bmatrix} \overline{u'u'} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'v'} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'w'} \end{bmatrix} \quad (12)$$

The Reynolds stress matrix is symmetrical about diagonal since, for example, $\overline{u'w'} = \overline{w'u'}$. In the present 3D PIV measurements we measured all nine terms of the Reynolds stress matrix.

Phase-locked data sets were obtained in order to calculate the periodic velocity fluctuations. For these data sets, Reynolds triple decomposition is utilized and defined as:

$$u_i(x, y, t) = U(x, y)_i + \tilde{u}(x, y, t)_i + u(x, y, t)_i' \quad (13)$$

where $\tilde{u}_i$ is the periodic velocity fluctuations [m/s]. The remaining terms were discussed previously [28]. In order to solve for this periodic fluctuation term, the phase average and time average of the instantaneous velocity is taken. The resulting terms are:

$$\langle u_i(x, y) \rangle = U(x, y)_i + \tilde{u}_i(x, y) \quad (14)$$

for the phase averaging and

$$U(x, y)_i = U(x, y)_i \quad (15)$$

for the time averaging where the new term $\langle u_i \rangle$ is the phase-averaged velocity [m/s]. In all subsequent work, “ $\langle \rangle$ ” symbol will indicate phase averaging. The periodic fluctuations are time dependent; however, the present phase-locked data were captured at a single phase of the propeller’s cycle (when one of the blades was directly vertical, $\phi=0$). Since this data is obtained

at a single phase, the terms in Equation (14) are shown without dependence on time. It should be understood that both fluctuating periodic velocity $\tilde{u}$ and $\langle u \rangle$ are dependent on time, or in other words they change with the blade position. If the data existed, the phase-averaged velocity could be calculated for any blade location, and since the blade location is dependent on time, the time component would remain. Combining these two equations and solving for the periodic fluctuation term gives the equation:

$$\tilde{u}_i(x, y) = \langle u_i(x, y) \rangle - U(x, y)_i \quad (16)$$

The phase-locked and free runs are both required in order to calculate this term. The same process is applied to the other velocity components.

The equation for transport of mean kinetic energy [29] using velocity triple decomposition is calculated as:

$$\begin{aligned} (U_j + \tilde{u}_j) \frac{\partial}{\partial x_j} \left(\frac{1}{2} U_i U_i \right) = & -\frac{1}{\rho} U_i \frac{\partial}{\partial x_i} (P + \tilde{p}) - U_i \left(\frac{\partial \tilde{u}_i}{\partial t} + U_j \frac{\partial \tilde{u}_i}{\partial x_j} \right) \\ & - \frac{\partial}{\partial x_j} (U_i \langle u'_i u'_j \rangle + U_i \langle \tilde{u}_i \tilde{u}_j \rangle) \\ & - (-\langle u'_i u'_j \rangle - \langle \tilde{u}_i \tilde{u}_j \rangle) \frac{\partial U_i}{\partial x_j} \end{aligned} \quad (17)$$

This equation is derived by starting with Navier Stokes equations, substituting triple decomposition (Equation 13), multiplying by U_i and phase averaging. The first term on the right hand side of the equation represents transport by mean pressure, P , and coherent pressure fluctuations, $\tilde{p}$; the second term is the convection by mean flow of coherent velocity fluctuations; the third term is the transport of the mean flow kinetic energy by Reynolds stresses $\langle u'_i u'_j \rangle$ and coherent velocity fluctuations $\langle \tilde{u}_i \tilde{u}_j \rangle$. The fourth term in Equation (17) is the production term of the Turbulent Kinetic Energy, which is a measure of the rate that mean flow kinetic energy is

transferred to and from the turbulent fluctuations [31]. To calculate the Production, P, the following equation is used:

$$P = -(-\langle u'_i u'_j \rangle - \langle \tilde{u}_i \tilde{u}_j \rangle) \frac{\partial U_i}{\partial x_j} \quad (18)$$

as before i and j both range from 1-3 representative of the 3 dimensions, $\langle u'_i u'_j \rangle$ are phase averaged Reynolds stresses [m^2/s^2], $\langle \tilde{u}_i \tilde{u}_j \rangle$ are the coherent stresses [m^2/s^2], and $\frac{\partial U_i}{\partial x_j}$ are the nine component mean velocity gradient matrix [s^{-1}]. Velocity gradient matrix has the form:

$$\begin{bmatrix} \frac{\partial u_i}{\partial x_j} \end{bmatrix} = \begin{bmatrix} \frac{\partial U}{\partial x} & \frac{\partial U}{\partial y} & \frac{\partial U}{\partial z} \\ \frac{\partial V}{\partial x} & \frac{\partial V}{\partial y} & \frac{\partial V}{\partial z} \\ \frac{\partial W}{\partial x} & \frac{\partial W}{\partial y} & \frac{\partial W}{\partial z} \end{bmatrix} \quad (19)$$

With the 2D PIV set-up, only four in-plane velocity gradients can be measured, namely $\frac{\partial U}{\partial x}$, $\frac{\partial U}{\partial y}$, $\frac{\partial V}{\partial x}$ and $\frac{\partial V}{\partial y}$. With the 3D PIV set-up, in a single vertical plane as is for the present experiment, an additional two terms are available $\frac{\partial W}{\partial x}$ and $\frac{\partial W}{\partial y}$. Consequently, the production term Equation (18), which in its entirety has nine terms, can be estimated with only four available terms from the 2D data and six available terms from the 3D data available. The velocity gradients with respect to z are the missing terms in both cases as measurements were taken at a single vertical plane. The full equations are shown in Equation 20.

$$\begin{aligned}
P = & -\overline{u'u'} \frac{\partial U}{\partial x} - \overline{u'v'} \frac{\partial U}{\partial y} - \overline{u'w'} \frac{\partial U}{\partial z} - \overline{v'u'} \frac{\partial V}{\partial x} - \overline{v'v'} \frac{\partial V}{\partial y} - \overline{v'w'} \frac{\partial V}{\partial z} - \overline{w'u'} \frac{\partial W}{\partial x} - \\
& \overline{w'v'} \frac{\partial W}{\partial y} - \overline{w'w'} \frac{\partial W}{\partial z}
\end{aligned} \tag{20}$$

$$\begin{aligned}
P = & -\langle \tilde{u}\tilde{u} \rangle \frac{\partial U}{\partial x} - \langle \tilde{u}\tilde{v} \rangle \frac{\partial U}{\partial y} - \langle \tilde{u}\tilde{w} \rangle \frac{\partial U}{\partial z} - \langle \tilde{v}\tilde{u} \rangle \frac{\partial V}{\partial x} - \langle \tilde{v}\tilde{v} \rangle \frac{\partial V}{\partial y} - \langle \tilde{v}\tilde{w} \rangle \\
& \frac{\partial V}{\partial z} - \langle \tilde{w}\tilde{u} \rangle \frac{\partial W}{\partial x} - \langle \tilde{w}\tilde{v} \rangle \frac{\partial W}{\partial y} - \langle \tilde{w}\tilde{w} \rangle \frac{\partial W}{\partial z}
\end{aligned}$$

The third term of Equation (17), the Transport term, is the next area of focus. This term represents the local transport (or flux) of mean flow kinetic energy due to the Reynolds stresses and the coherent counterparts [32]. With the 3D PIV, all in-plane (x and y) mean kinetic energy fluxes are measured. The focus, however, is on the flux terms perpendicular to the propeller axis (the y direction), i.e. transport of energy across horizontal surfaces, as this is the main direction of wake re-energization between the inner core and the free stream. The transport terms for both the random and coherent fluctuations in the y-direction are calculated as:

$$T_{random} = -\frac{\partial}{\partial y} (U \langle u'v' \rangle + V \langle v'v' \rangle + W \langle w'v' \rangle) \tag{21}$$

$$T_{coherent} = -\frac{\partial}{\partial y} (U \langle \tilde{u}\tilde{v} \rangle + V \langle \tilde{v}\tilde{v} \rangle + W \langle \tilde{w}\tilde{v} \rangle)$$

In order to better understand the dynamics represented in Equations (11) to (21), conditional sampling was performed. Specifically, conditional sampling is used to determine how the mean kinetic energy is transported between the random velocity fluctuations and the mean flow. Further, the spatial distribution in the wake of these interactions can be determined. Conditional sampling, or quadrant analysis is based on the sign of correlation between two velocity fluctuations u' and v' [33]. The four quadrants and their definitions are depicted in Figure 13.

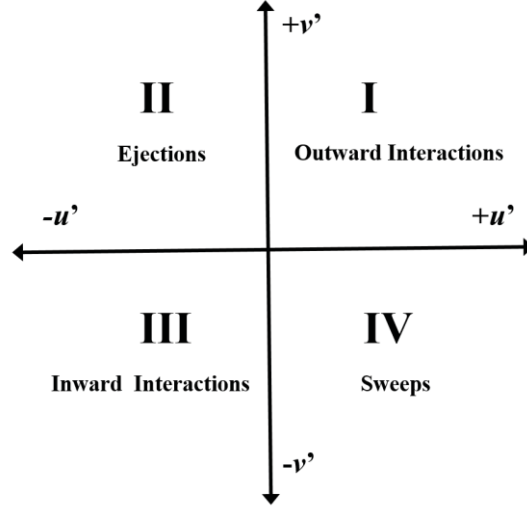


Figure 13: Quadrant analysis description. Axes are based on fluctuations of the u and v components of velocity.

Conditional sampling of the Reynolds stresses is calculated as [34]:

$$\langle u'v' \rangle |_K = \frac{1}{N_K} \sum_{l=1}^{N_K} u'_l v'_l q_k \quad (22)$$

$$q_k = \begin{cases} 1, & \text{if } u' \text{ and } v' \text{ are in quadrant } K \\ 0, & \text{otherwise} \end{cases}$$

where N_K is the number of occurrences of the combination u'_l and v'_l in quadrant K . The summation of all four quadrants represents the total phase averaged shear stress $\langle u'v' \rangle$.

Similarly, coherent fluctuations, $\tilde{u}$ and $\tilde{v}$ are used to calculate the coherent stresses $\langle \tilde{u} \tilde{v} \rangle$.

Furthermore, the net transport of mean kinetic energy due to random fluctuations is calculated over discrete spatial regions of the flow as:

$$K_{T_random}|_q = \int_{y_1}^{y_2} \int_{x_1}^{x_2} T_{random}(x, y)|_q dx dy \quad (23)$$

$$K_{T_coherent}|_q = \int_{y_1}^{y_2} \int_{x_1}^{x_2} T_{coherent}(x, y)|_q dx dy$$

where $|_q$ represents the quadrant $q=1$ to 4. Integration limits in the above integral are discussed later. Of specific interest is the term $U\langle u'v' \rangle$ since it will be shown, consistent with literature [35], that this term has the largest magnitudes. In quadrants II and IV (ejection and sweep events, respectively), where u' and v' are anti-correlated there is a positive downward transport of mean kinetic energy from the random velocity fluctuations to the mean flow. Calculating this spatial distribution identifies where in the flow the wake begins to recover.

The next quantity of interest is vorticity. Vorticity is a measure of local fluid rotation and is mathematically expressed as:

$$\vec{\omega} = \nabla \times \vec{u} \quad (24)$$

Since vorticity is a vector [36], only the out of plane vorticity component ω_z can be calculated from the present data (both 2 and 3 D PIV), which is vorticity in the z axis, as:

$$\overline{\omega_z} = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \quad (25)$$

where ω is the vorticity [s^{-1}] and the other components are the spatial velocity gradients discussed above. The phase-averaged and time-averaged vorticity can both be calculated with the current experimental data sets. The phase-averaged vorticity is found by replacing V and U with $\langle v \rangle$ and $\langle u \rangle$.

Results and Analysis

2D LaVision Data Results

The following results pertain to the data collected during the first experiment, which included the 2D PIV set-up, the propeller, and the turbulence generating grid. These results were used as preliminary results and the analysis is limited in extent.

Mean Profiles

The 600 image pairs for each field of view are time averaged to create a spatial field of mean velocities. As defined in the Theory section, horizontal direction, x , is along the streamwise direction of the channel and the vertical direction, y , is perpendicular to this axis, in-plane with the laser light sheet, and centered at the propeller hub. The spatial distribution of horizontal mean velocity $\bar{U}$, and the vertical mean velocity, $\bar{V}$, fields are shown in Figure 14.

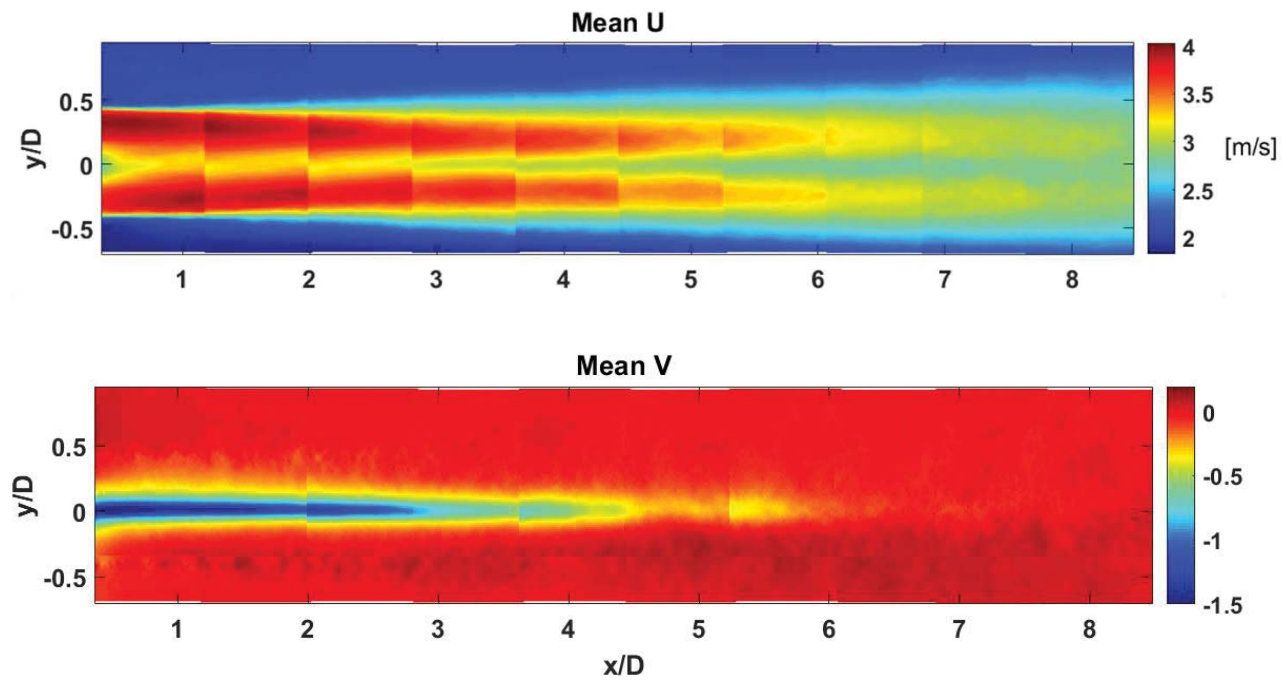


Figure 14: Top: Spatial distribution of U ; Bottom: Spatial distribution of V with downstream distance x/D . Each plot is comprised of 10 fields of view tiled together. Ensemble time averaging is performed over the 600 image pairs. The velocity is measured in [m/s]. Flow is from left to right

The time-averaged field matches with expectations as the highest velocities are found in the wake core. Specifically, there are two local velocity maximums at approximately $0.7R$ (45.5mm) on both sides of the propeller centerline. These maximum velocities are due to the propeller design, where maximum thrust occurs at approximately $0.7R$ due to the radial change in

pitch. Reduction in velocity close to the propeller centerline is due to the presence of the propeller hub wake. This velocity minimum is also clearly visible in Figure 16 where several velocity profiles are shown as a function of downstream direction. Visible discontinuity in horizontal velocity (Figure 14) at the FOV' edges was a concern and a great deal of time was spent on trying to identify the cause. Discontinuities are also present in the 3D results and are attributed to the meandering of the hub vortex in and out of the vertical measurement plane resulting in non-convergence of velocity profiles. The vertical velocity V in Figure 14 shows that the hub vortex is the region of highest vertical velocity whereas the magnitude of vertical velocity elsewhere is approximately 0.

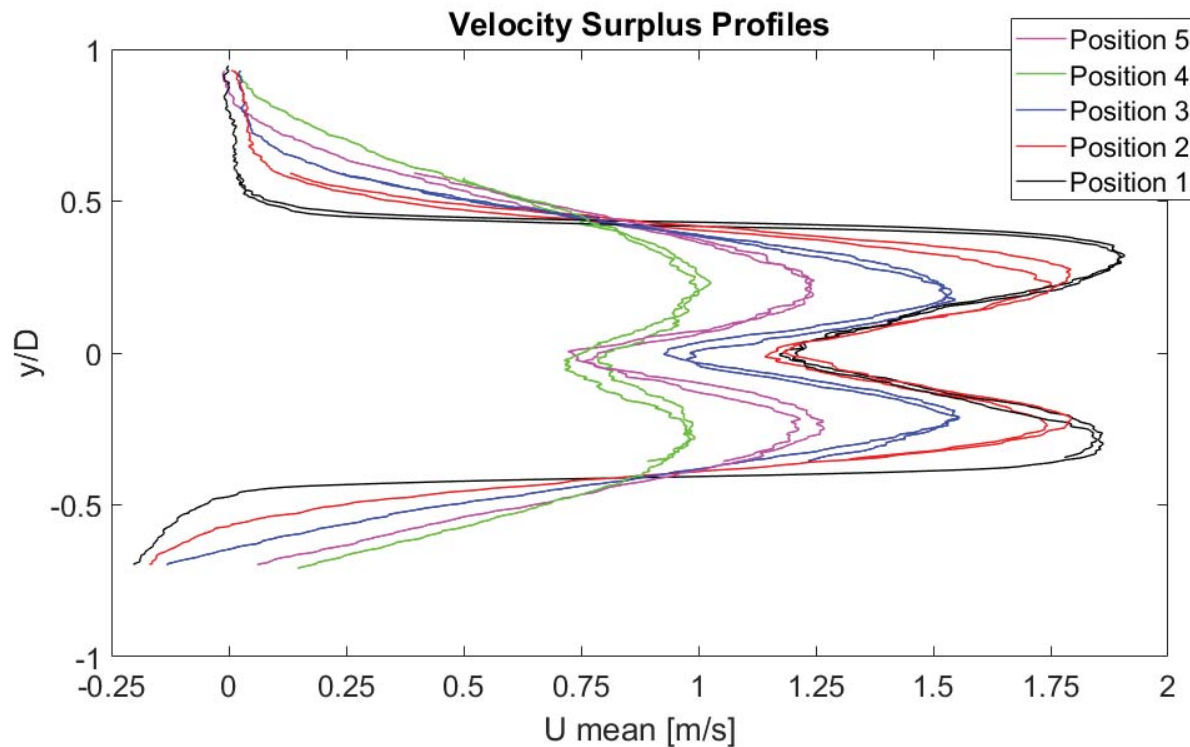


Figure 15: Mean velocity surplus profiles extracted from the time-averaged horizontal velocity component. The inflow mean velocity (2.07 m/s) has been subtracted from all velocity data. The velocity is measured in [m/s]. The profiles at each position are extracted from the same column for the top and the center FOV's. Profiles shown are extracted at $x/D=0.84, 2.47, 4.10, 5.73$, and 7.24 , respectively.

The velocity profiles in Figure 15 represent the surplus in velocity as the free stream (2.07 m/s) was removed. The profiles shown are taken at $x/D=0.84, 2.47, 4.10, 5.73$, and 7.24 . Where double line are shown, are an indication of measurement overlap. The velocity minimum occurring at approximately $y/D=0$ discussed above, shows a gradual reduction with downstream distance, and by $x/D=7.24$ it is small compared to $x/D=0.84$. Further downstream, this minimum in velocity surplus is expected to disappear and the velocity profile will have a bell shaped distribution characteristic of “far wake” velocity profiles.

This data set was used for a convergence study to address the question as to how many realizations are needed to obtain convergence of calculated statistics. Figure 16 shows the convergence plot for the time averaged horizontal velocity at a certain location in the flow ($x/D = 0.78, y/D = -0.76$) measured by camera 0 and ($x/D = 1.59, y/D = -0.76$) measured by camera 1. These spatial locations correspond to the central location in each camera’s FOV frame (row 200, column 140).

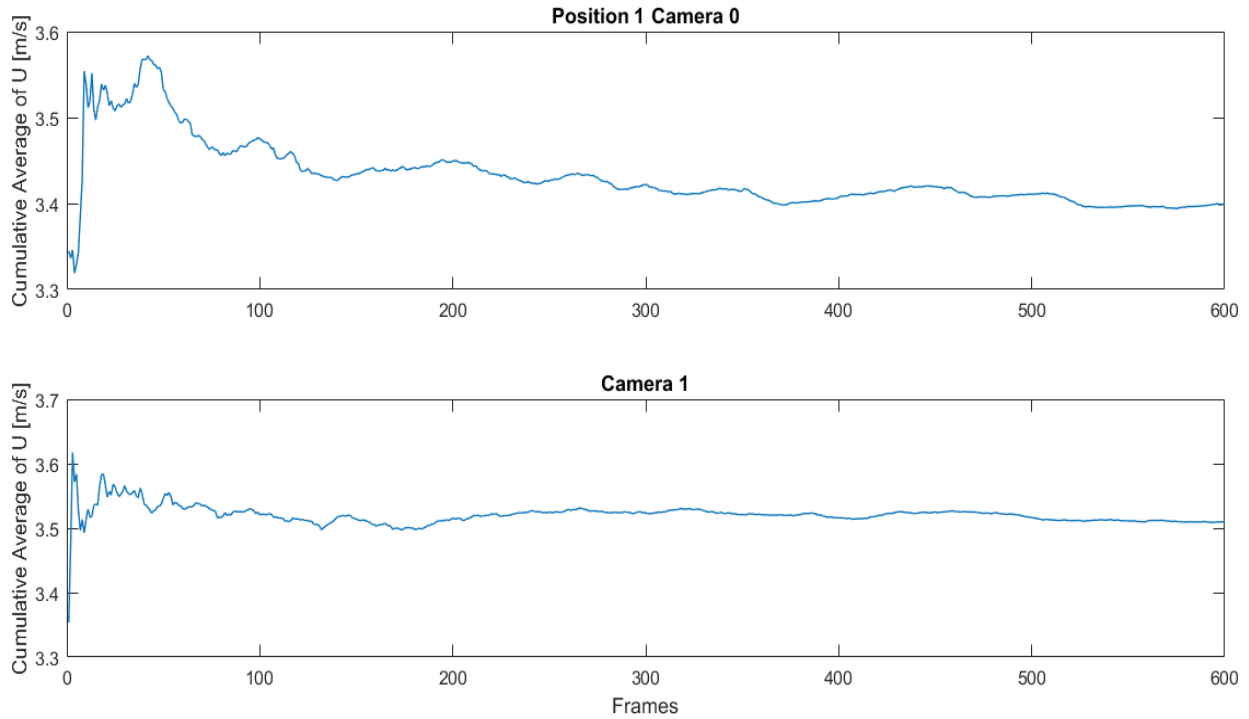


Figure 16: Cumulative average of horizontal velocity component at two different locations in the flow. The velocity is measured in [m/s]. The profiles at each position are extracted from the 200th row and 140th column for each camera (a random central location).

Convergence of mean velocity both cameras definitively converges at the 600th frame, and convergence seems to be achieved even earlier after about the 350th frame.

Normalized Mean Velocity Profiles

The normalized velocity profiles for the horizontal velocity component at five locations in the near wake are shown in Figure 17. These profiles are from the same locations as Figure 16. The velocity profiles were normalized by the local maximum mean velocity $U_{\max}$ and vertical coordinate y is normalized using the local wake half-width defined in Equation (10).

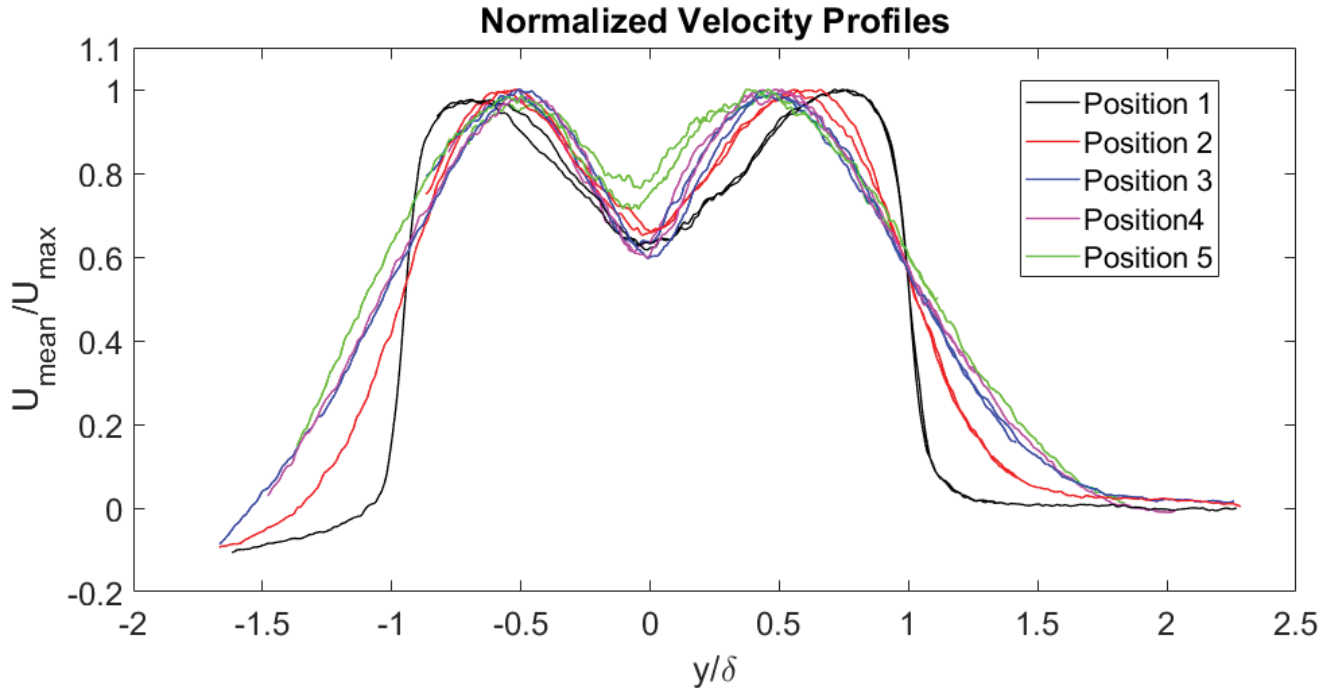


Figure 17: Normalized velocity of the horizontal component U with free stream velocity removed. The velocity is measured in [m/s]. Both the top and center positions are plotted in the respective colors of the horizontal locations. The distance from the center of the propeller is normalized by the wake half width.

The normalized profiles for Position 1 and 2 have a large velocity change over a small distance. This gradient represents a strong shear layer in the flow, which defines the bounds of the wake core. The profiles for Position 3, 4, and 5 have collapsed together, which indicates diffusion into the free stream as the shear layer no longer protects the wake core so the wake starts to expand. The velocity gradient is more gradual, indicating that the shear layer is diffusing. The profiles collapse around $x/D = 2.8$.

The distribution of wake half-width length scale as a function of downstream direction is shown in Figure 18. Two different wake widths are shown: positive for the upper shear layer (top of the propeller) and negative for the bottom shear layer (bottom tip of the propeller). The wake half width was calculated using the local velocity maximum as shown in Figure 14.

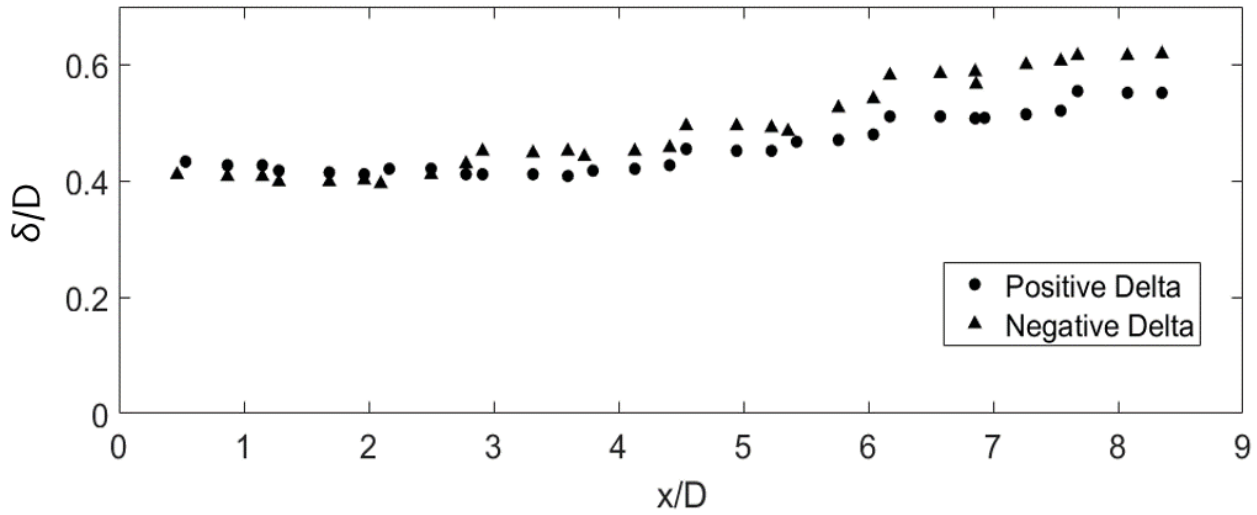


Figure 18: Downstream distribution of wake half-width δ normalized by D . The circles represent the data taken from the upper shear layer; the triangles represent data taken from the bottom shear layer.

Although there is a small difference between top and bottom wake half-widths, the trend is similar. The wake widths remains constant through $x/D = 2.5-3$ downstream from the propeller plane and then start to gradually increase in magnitude signifying wake expansion. This approximate location of change in slope coincides where the normalized mean profiles start to collapse on top of each other. This region $x/D = 2.5-3$ represent the part of the near wake that is bounded by the presence of strong and coherent tip vortices shed from the propeller blades, creating a strong shear layer between the wake core and the free stream as found in the experiment by Lignarolo and colleagues [37]. The distribution of wake half widths will be revisited with 3D data.

Reynolds Stresses

Since this experiment was conducted in 2D, the measured components of the Reynolds stresses are $\overline{u'u'}$, $-\overline{u'v'}$, and $\overline{v'v'}$. These stresses are calculated using the Reynolds decomposition as described in Equation (11) since 2D PIV experiment was performed without phase locking.

The spatial distribution of measured in-plane Reynolds stresses are shown in Figure 19.

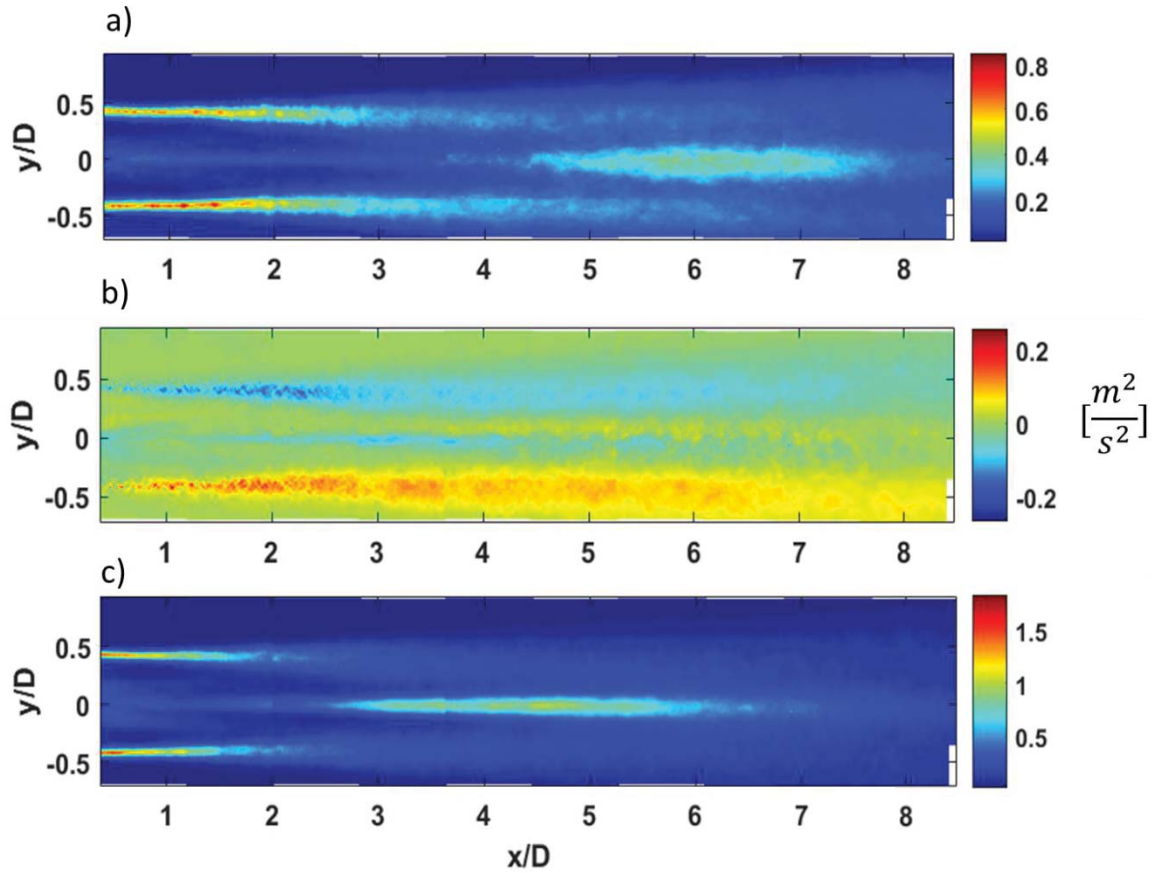


Figure 19: Spatial distribution of in-plane Reynolds stress components: a) $\overline{u'u'}$ b) $-\overline{u'v'}$ c) $\overline{v'v'}$. The units are m^2/s^2 . The streamwise direction x is normalized by the propeller diameter D .

The regions of highest shear stresses are within the first $3D$ downstream at the wake boundary where the velocity gradient is the largest between the fast moving jet behind the propeller and the slower moving free stream bounded by the coherent tip vortices. This shear layer maintains the wake structure. When this shear layer begins to diminish between $x/D = 2$ to 3 , the wake also begins to expand (using wake half width as a proxy) as seen in Figure 18. After this shear layer weakens, the wake begins to expand as it mixes with the free stream. The other area of relatively high shear stress is along the centerline of the propeller where the strong hub vortex is present. The shear stress is high there as it is an area of high velocity fluctuations from

the meandering of the hub vortex. These plots show how the hub vortex is strong and persists far downstream from the propeller before it starts to dissipate around $x/D=4$ and more fully dissipates after $x/D=5$. This strength is due to the design of the propeller model where the propeller hub is long relative to the blades. Although not shown in the subsequent analysis, the distribution of Reynolds stresses is similar from the 3D experimental data.

The statistical convergence of the velocity fluctuations and the Reynolds stress components $u'u'$ and $u'v'$ are shown in Figure 20. These values were extracted from a location in the wake's shear layer (row 350, column 120) in both cameras for Position 1. This location corresponds to $x/D = 0.84$ in camera 0, $x/D = 1.65$ in camera 1, and $y/D = 0.50$. This location was chosen as it is a location with high variation.

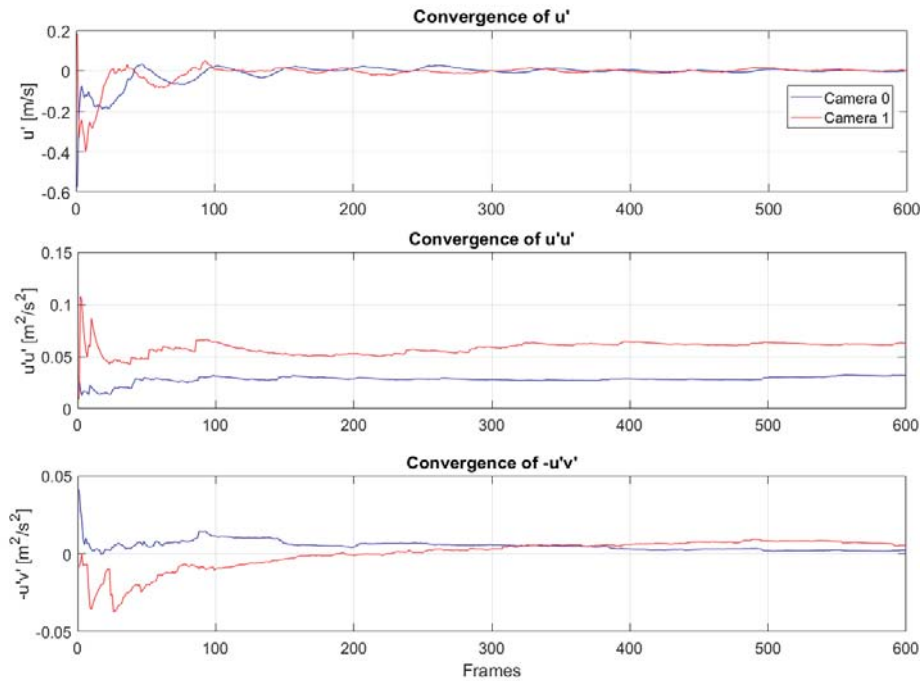


Figure 20: Convergence of the fluctuations of the horizontal velocity component and Reynolds stresses $u'u'$ and $-u'v'$ extracted from row 350 column 120 for both cameras. This data is from Position 1.

The horizontal velocity fluctuations do converge, signifying that 600 frames is sufficient

for analysis of mean quantities. The cumulative average of u' converges to 0, as it should since the mean of the fluctuations should be 0 by definition. The Reynolds stresses also converge around 450 frames after which the variation in magnitude is minimal. Based on these preliminary results, the decision to collect 600 frames at each spatial location in the wake was deemed sufficient for convergence of second order turbulence statistics.

3D TSI Data Results

The following results pertain to the data collected during the second and third experiment, which included the 3D PIV set-up and propeller model; the second experiment included the turbulence generating grid while the third experiment did not. The second experiment will be labeled ‘with imposed free-stream turbulence’ in figures while the third experiment will be labeled ‘Quiescent’ in reference to the state of the free stream.

Mean Profiles

At each location, the 600 image pairs were time averaged using the free run data. The individual fields of view were tiled together but no attempt was made to “stitch” velocities at the edges. The coordinate system is the same as discussed previously. The resultant fields for time averaged velocities are shown in Figures 21 to 23.

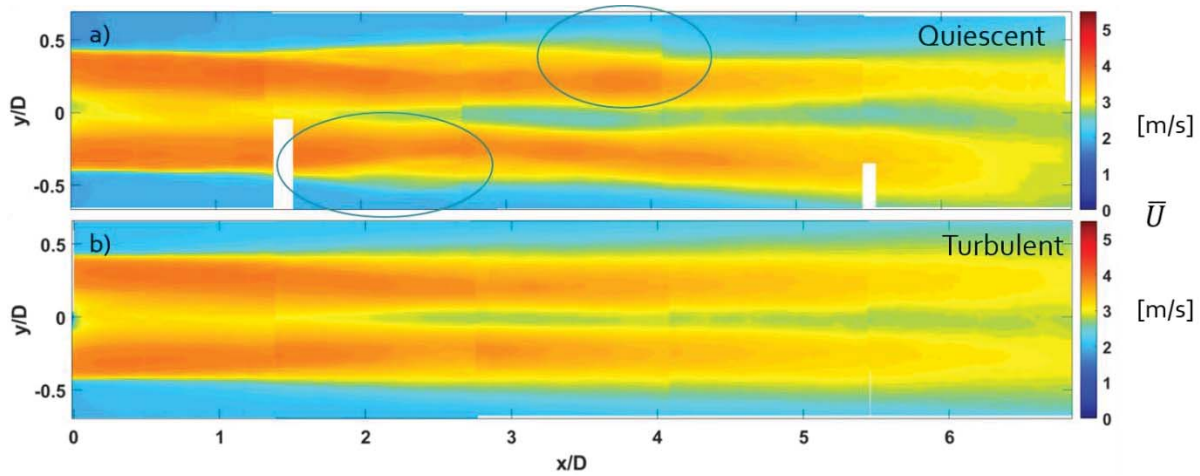


Figure 21: Time averaged horizontal velocity for 3D PIV data. a) is for the quiescent, and b) is with imposed free stream turbulence. Velocity is measured in [m/s]. Both horizontal axes are normalized by the propeller diameter. The circles are visual aids for discussion in the main body.

Two small portions of the velocity field shown in Figure 21(a) with missing data there are due to the camera mount loosening during one of the experimental runs; the same region of data is missing in all subsequent analysis for the runs with a steady free stream. The distribution of $\bar{U}$ shown in Figure 21 is very similar to the one obtained with 2D measurements. The highest velocities are found in the wake core as expected for both the quiescent and turbulent fields. The circled portion of the profile highlights the region of a sudden expansion in the shear layer as well as discontinuity in U at the edges as observed in 2D data. This region will be discussed in more detail later on when analyzing tip vortices and vorticity. In Figure 21(b) sudden expansion observed in quiescent wake is not present in the case with free stream turbulence. Also, in the quiescent case, the hub vortex, which forms in the center of the field, is more prominent and meanders more than in the case with a free stream turbulence. The vertical velocity V in Figure 22 shows consistent negative velocity in wake core and small velocity in the outer wake similar to Figure 14.

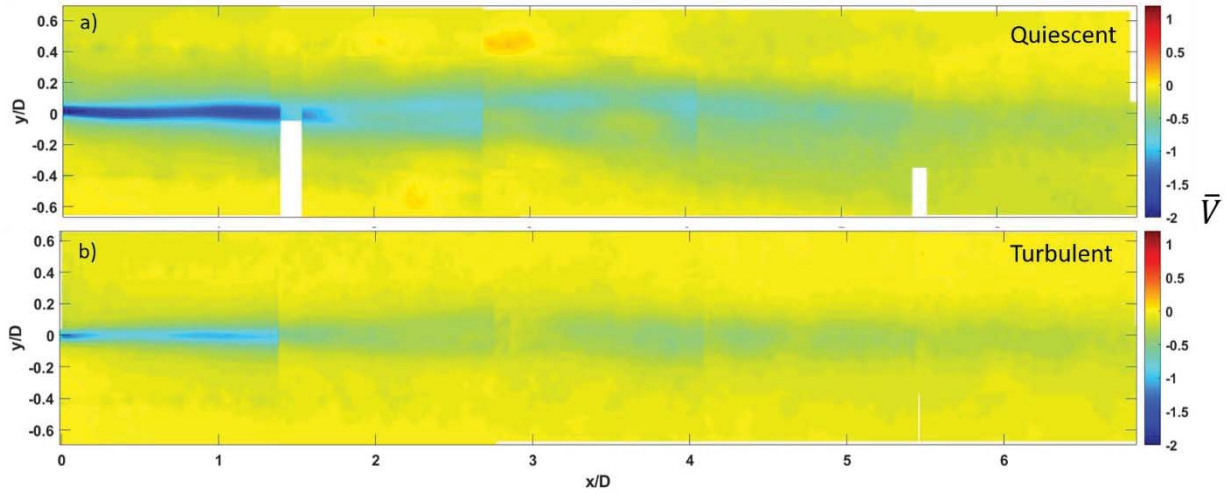


Figure 22: Time averaged vertical velocity spatial fields for 3D PIV data. a) is for the quiescent, no grid data and b) is for the turbulent free stream. Velocity is measured in [m/s]. Both axes are normalized by the propeller diameter.

The region of maximum vertical velocity magnitude occurs in the hub vortex. The hub vortex persists further and with more meandering in the quiescent flow conditions. The out-of-plane velocity W component is presented in Figure 23.

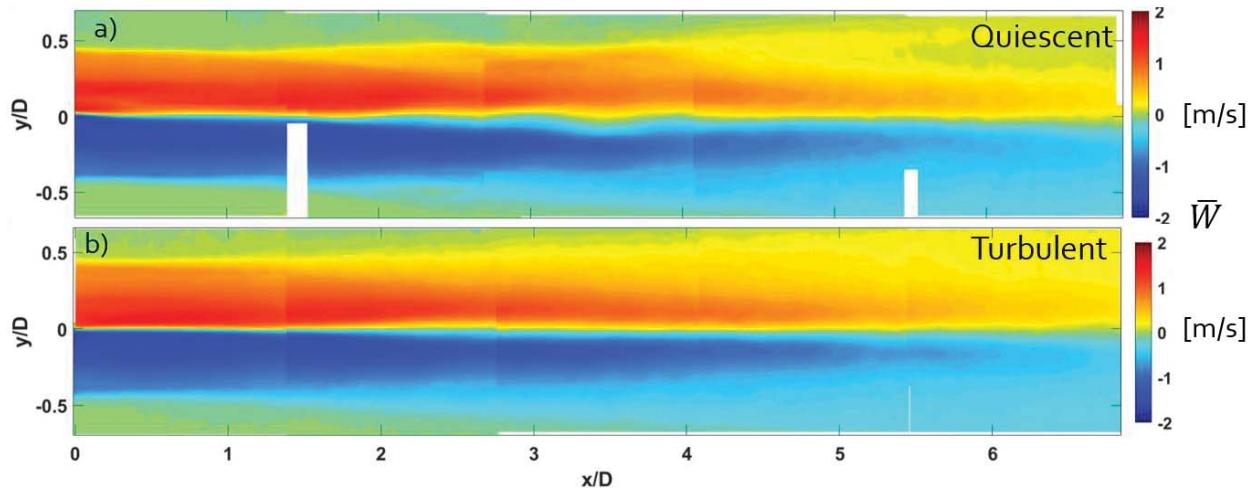


Figure 23: Time averaged out of plane velocity spatial fields for 3D PIV data. a) is for the quiescent, no grid data and b) is for the turbulent free stream. Velocity is measured in [m/s]. Both axes are normalized by the propeller diameter.

As the propeller was rotating counter-clockwise looking upstream, the positive out of plane

velocity is in the top half of the wake and the negative out of plane velocity is in the bottom half of the wake. These profiles also show that the hub vortex meanders slightly more in the quiescent case.

The next step of analysis was calculating the phase-averaged velocity of the 600 phase-locked image pairs for both free stream conditions. The horizontal component is shown in Figure 24.

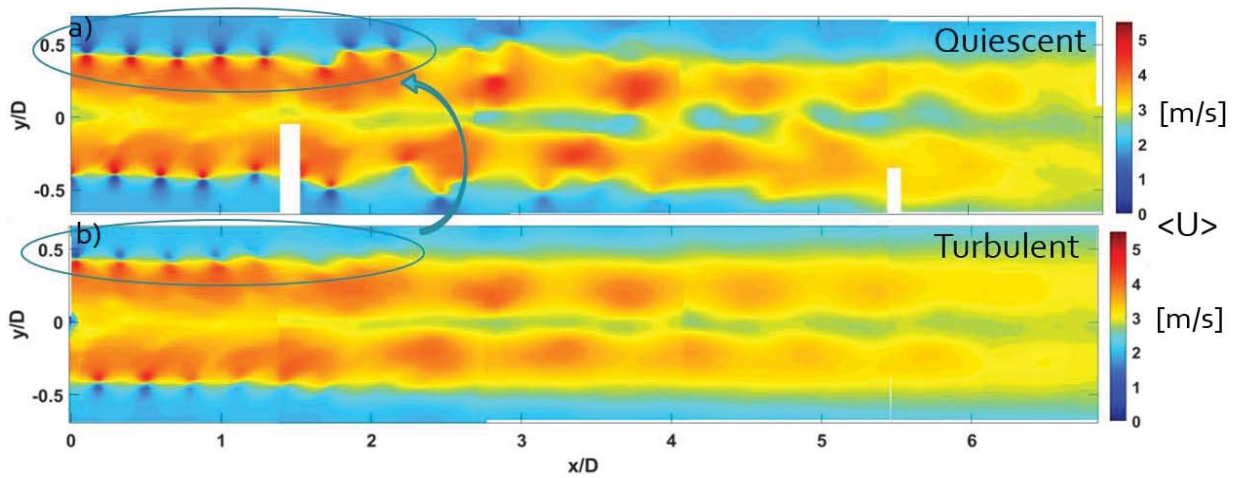


Figure 24: Phase-averaged horizontal velocity spatial fields for 3D PIV data. a) is for the quiescent, no grid data and b) is for the turbulent free stream. Velocity is measured in [m/s]. Both axes are normalized by the propeller diameter. The circles are a region of interest and are discussed below.

These profiles represent a single phase in the propeller's rotation. One key observation is the prominence of the tip vortices. In the quiescent inflow case, the tip vortices are prominent until about $x/D=2$. The tip vortices begin pairing and rotating around $x/D=1.5$ and then begin to diminish. In the turbulent inflow case, these tip vortices are less prominent to begin with and then diminish at about $x/D=1$ due to the randomness in the turbulent flow and phase averaging does not “lock” vortices in one spatial position. The top half of the wake is highlighted, although this behavior is observed in the bottom half of the wake core as well. A similar pattern is

observed in the following phase averaged profiles of vertical velocity in Figure 25.

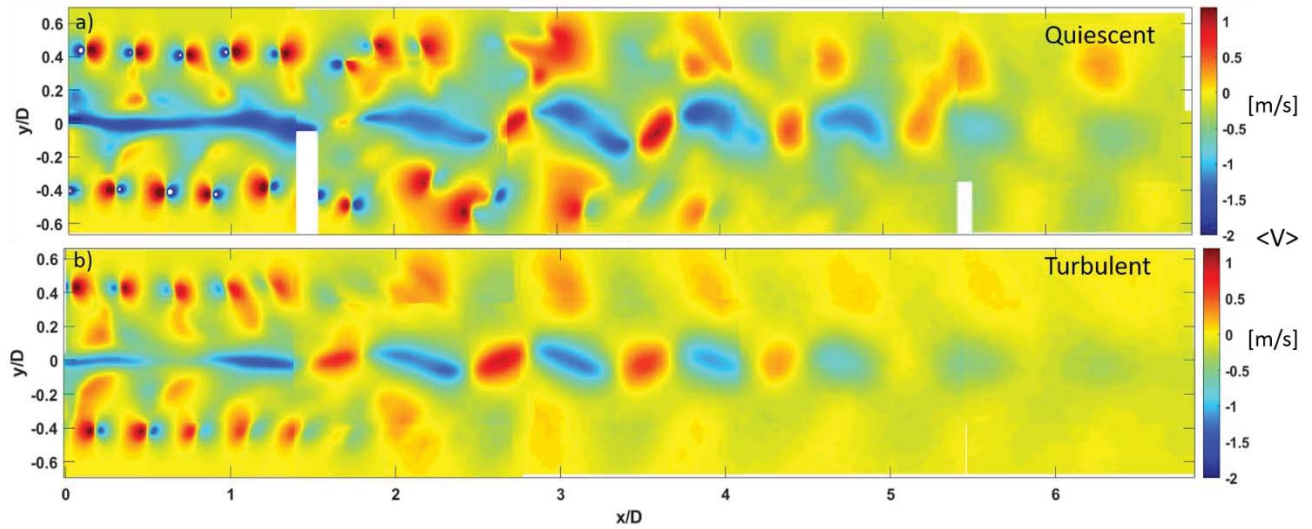


Figure 25: Phase-averaged vertical velocity spatial fields for 3D PIV data. a) is for the quiescent, no grid data and b) is for the turbulent free stream. Velocity is measured in [m/s]. Both axes are normalized by the propeller diameter.

The phase-averaged vertical velocity fields show that the tip vortices propagate further downstream in the steady free stream than in the case with a turbulent free stream. The hub vortices follow a similar pattern although the hub vortex in the quiescent case has larger spatial regions of vertical velocity and also higher velocity magnitudes. The third component of phase-averaged velocity is shown in Figure 26.

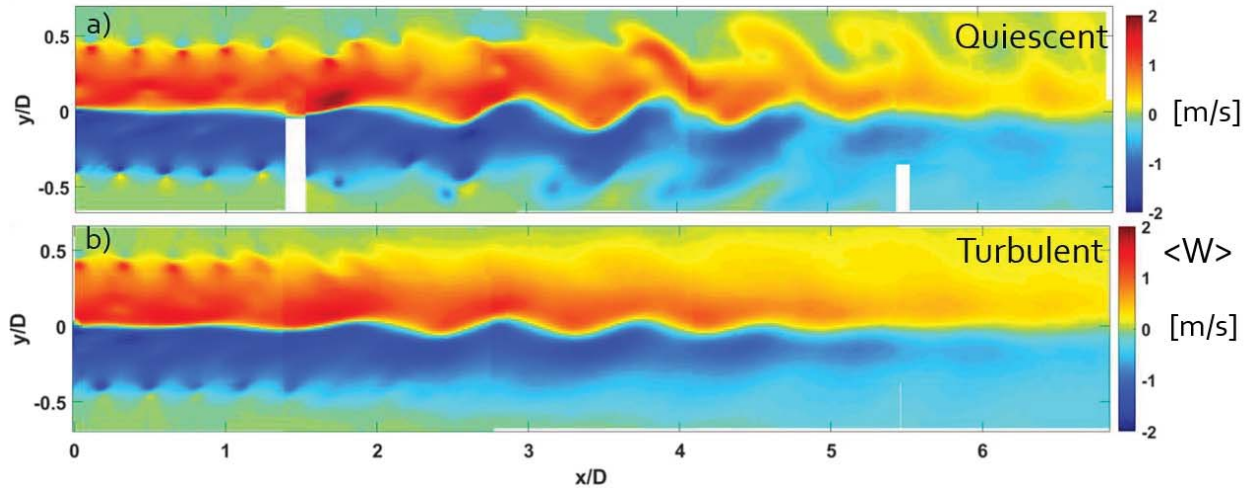


Figure 26: Phase-averaged out of plane velocity spatial fields for 3D PIV data. a) is for the quiescent, no grid data and b) is for the turbulent free stream. Velocity is measured in [m/s]. Both axes are normalized by the propeller diameter.

The third component of the out of plane velocity demonstrates similar characteristics seen in the other two velocity components such as the tip vortex prominence and the hub vortex meandering. Another difference observed in these profiles is the interaction with the free stream. In panel a), there is a distinct separation between the core and the outer wake on the top half of the wake core. However, in panel b) with the turbulent free stream, the wake is ‘smeared’ with the free stream; it no longer has a distinct separation between the wake core and the free stream. This observation suggests that the turbulent free stream is interacting with the wake re-energization to the free stream, which will be analyzed in further detail in later work.

Wake Expansion

As done in the previous section, the wake half width was calculated using Equation (10) for both the cases with and without the turbulence generating grid. Both of these wake expansions are included in Figure 27 along with the wake width from the 2D data.

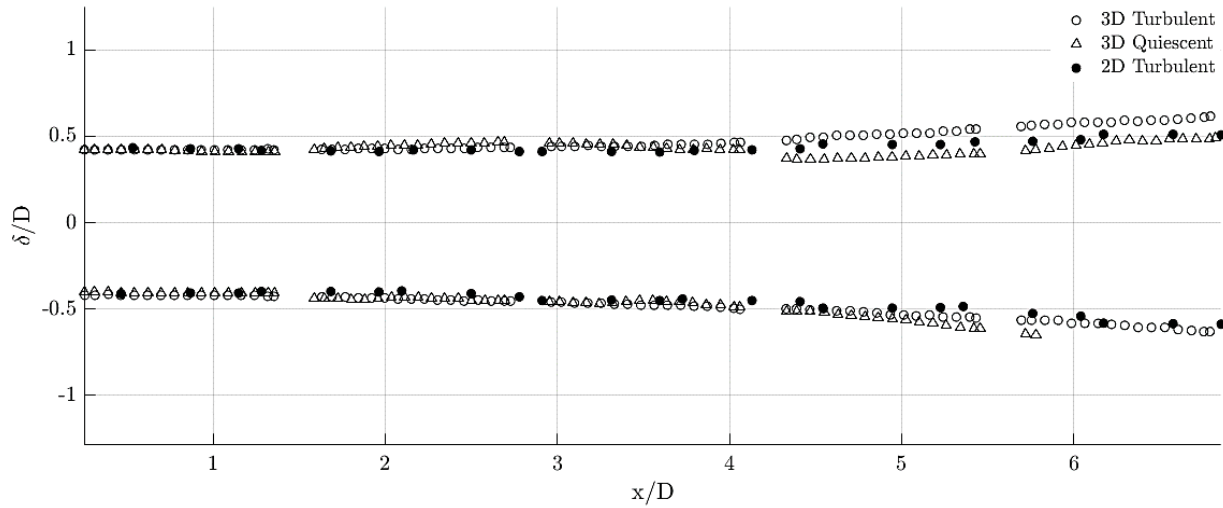


Figure 27: Wake half widths for the 2D experiments (solid black dots), 3D with turbulence in the free stream (open black dots), and 3D with a quiescent free stream (open black triangles). The axes are normalized by the propeller diameter ($D=130\text{mm}$). These represent the wake expansion.

Through $x/D = 4$, the wake half width for the turbulent and quiescent free stream cases remain the same. After $x/D = 4$, the turbulent case begins to expand sooner in the top half of the wake and expands approximately $0.1\delta/D$ more than the quiescent case. In the bottom half of the wake, however, this behavior is not observed. Both cases begin expanding at approximately $x/D = 4.5$ and it appears that the quiescent case expands wider. The data for the quiescent case is not available further downstream due to limitations of the camera view. Some reasons for the inconsistencies between the top and bottom half of the wake expansion could be due to the strong meandering of the hub vortex or that the turbulence intensity of 7% was not high enough to significantly affect the wake expansion. Another reason could be a slight misalignment in the propeller mounting and shaft since they had to be removed in order to remove the turbulence generating grid. Further testing at a higher turbulence intensity and with more coverage downstream would be needed to draw any firm conclusions between the two cases. Having said

this, in all subsequent analysis (and in figures), wake half width will be used as a proxy for the boundary between wake core and the outer layer of the wake.

Mean Periodic Velocity Profiles

Using Equation (11), Reynold's triple decomposition, and with both the phase-averaged the time averaged data, the mean periodic velocity fluctuations were calculated. This process was done for all three components of velocity in both the quiescent and turbulent free stream cases.

These periodic fluctuations are in Figure 28.

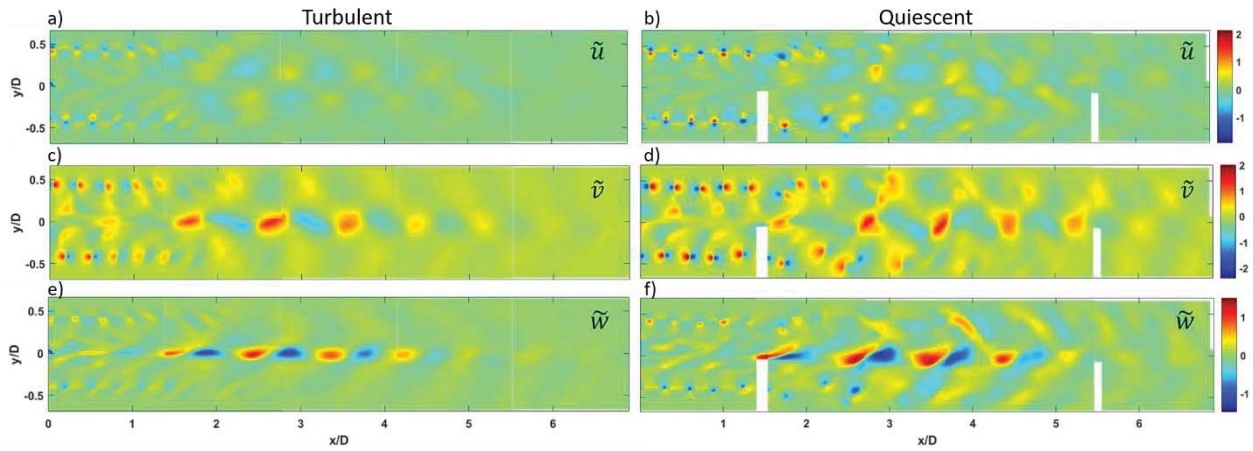


Figure 28: Mean periodic velocity fluctuation spatial fields for a) the horizontal component $\tilde{u}$ with turbulence in the free stream, b) $\tilde{u}$ with a quiescent free stream, c) the vertical component $\tilde{v}$ with a turbulent free stream, d) $\tilde{v}$ with a quiescent free stream, e) the out of plane component $\tilde{w}$ with a turbulent free stream, and f) $\tilde{w}$ with a quiescent free stream. Both axes are normalized by the propeller diameter. Velocity is measured in [m/s].

As noted before, these periodic velocity fluctuations represent one phase ($\phi=0$) of the propeller rotation. Most of the periodicity near the tip vortices occurs before $x/D = 2$ in both free stream cases. After about $x/D = 2$, these vortices begin to pair and rotate as discussed previously. Without stable, coherent vortices, the fluctuations become random and not periodic. For the out of plane component $\tilde{w}$, the largest magnitudes of velocity occur in the hub vortex as it meanders.

For the horizontal $\tilde{u}$ and vertical $\tilde{v}$ components, the quiescent free stream case has higher magnitudes and distinguishable vortices further downstream than in the turbulent free stream case. This difference is due to the turbulent free stream's chaotic motion interrupting the tip vortices' motion randomly, which decreases the signature of periodicity. Without the interruption from external turbulence, the tip vortices in the quiescent free stream case are able to keep their location relatively constant for almost 1 diameter further downstream.

Quadrant Analysis

Quadrant analysis was performed on the data to determine the modes in which energy is transported from the random fluctuations. The quadrant analysis for the phase locked data in the turbulent free stream is presented in Figure 29. The quantity shown is the distribution of $\langle u'v' \rangle|_{q=1 \text{ to } 4}$.

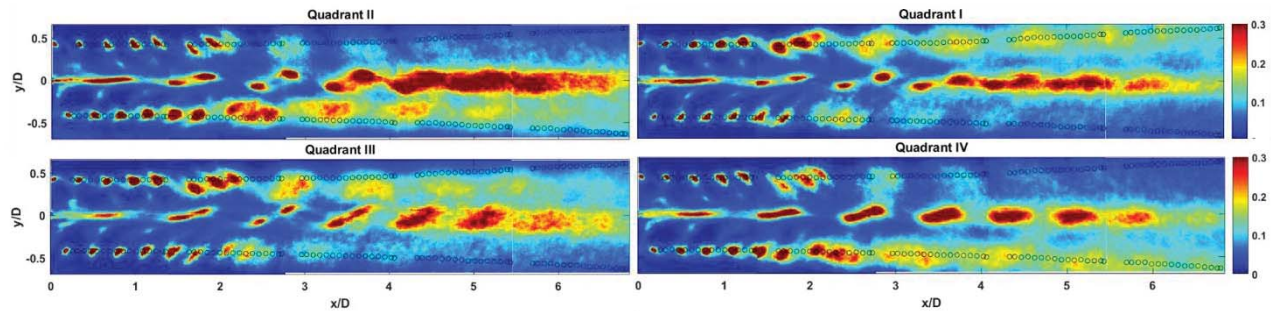


Figure 29: Spatial distribution of $\langle u'v' \rangle$. The units are $[m^2/s^2]$. Counterclockwise from top right: outward interactions, ejections, inward interactions, and sweeps. The ejection and sweep events are multiplied by -1 to maintain the same color scale. The wake half width is superimposed on the plots for reference.

The main regions of interest are the shear layers along the wake half width where the mixing of the wake core and free stream occurs. Within $x/D < 3$ there is little interaction between the wake core and the free stream as the tip vortices act as a shield in this region. After $x/D > 3$, outward interactions in Quadrant I dominate the upper wake boundary, whereas sweeps in Quadrant IV

dominate the lower wake boundary. When this quantity is used in the transport equation, these outward interactions and sweeps represent the transport of energy out of the wake core. The outward interactions produce an upward kinetic energy flux while sweeps produce a downward kinetic energy flux [38]. These random fluctuations are part of the wake re-energization process after approximately $x/D = 3$. On the other hand, ejection and inward interaction events (quadrants II and IV) have high magnitudes on the inner side of the wake, and indicate inward transport of energy towards the propeller centerline. We postulate that this is the mechanism of gradual reduction of “dip” in velocity surplus shown in Figures 15, 17 and 21.

The quadrant analysis of phase locked Reynolds stresses in the quiescent free stream case are shown in Figure 30.

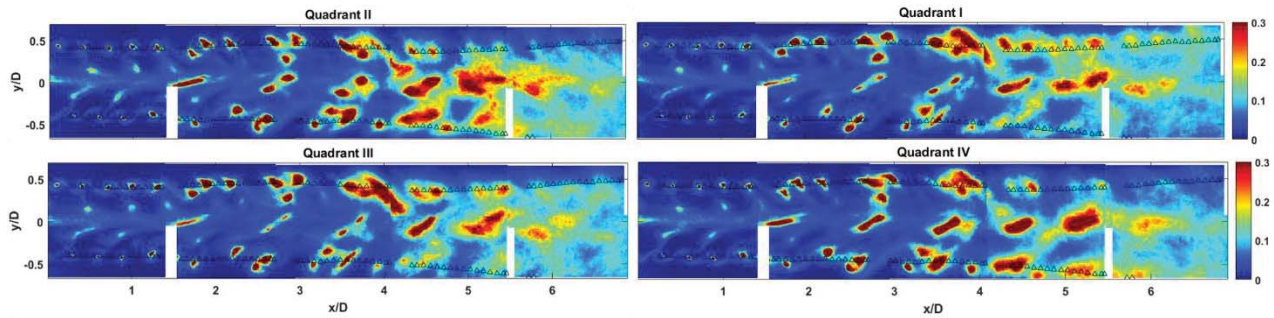


Figure 30: Spatial distribution of $\langle u'v' \rangle$ for the quiescent free stream. The units are $[m^2/s^2]$. Counterclockwise from top right: outward interactions, ejections, inward interactions, and sweeps. The ejection and sweep events are multiplied by -1 to maintain the same color scale. The wake half width is superimposed on the plots for reference.

A similar pattern is observed in Figure 30 as was observed in the turbulent free stream case where there is an outward flux of kinetic energy at the wake boundaries. However, in this case the vortices are more concentrated and have strong signatures through up to $x/D=4$. The magnitudes are larger within these vortex pairs than in the turbulent free stream case although

they are more localized. This localization of the Reynolds stresses suggests that the random fluctuations are not contributing greatly to the wake re-energization within the first 4 diameters.

The coherent stresses were then calculated in Figure 31. These plots represent the total coherent stress, $\langle \tilde{u}\tilde{v} \rangle$; they were not conditionally sampled.

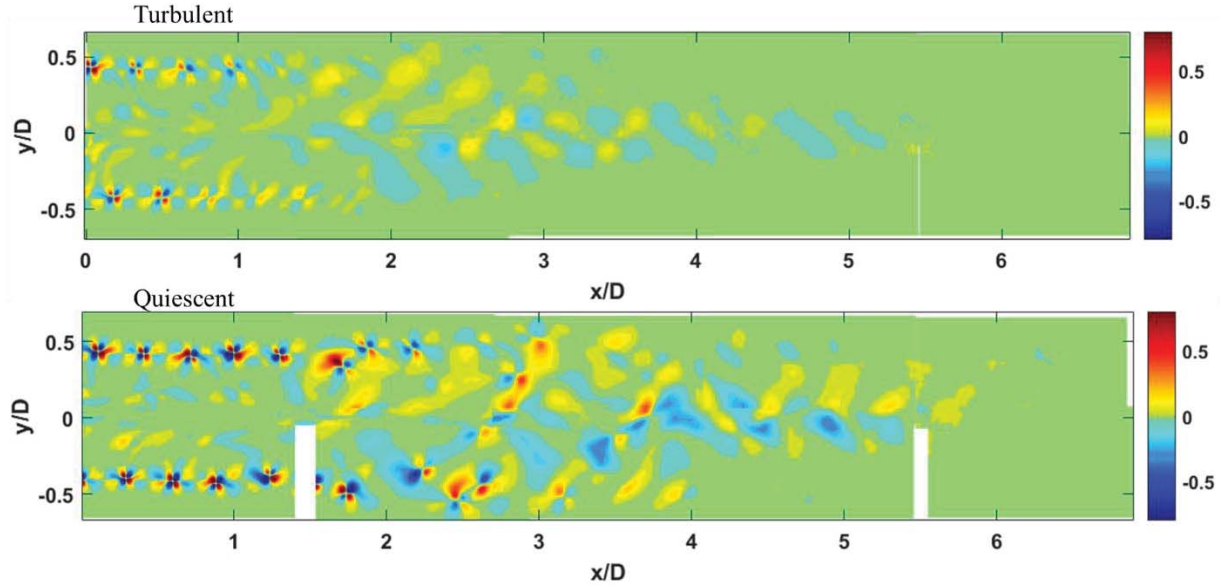


Figure 31: Spatial distribution of the coherent stresses, $\langle \tilde{u}\tilde{v} \rangle$, for both the turbulent and free stream cases. The units are $[m^2/s^2]$.

The coherent shear stresses persist until a downstream distance of $x/D = 3$ in the quiescent case, whereas in the turbulent case, stresses of any meaningful magnitude are smeared by external turbulence by $x/D = 1$. This difference is due to the random behavior of the turbulence in the free stream interrupting the normal pattern of the vortices. The turbulence is aiding the vortex pairing and mixing at the wake boundaries.

The K_{T_random} defined in Equation (23) is used to analyze the net transport of mean kinetic energy due to random fluctuations defined here as the integral over all phases and quadrants as:

$$K_{T_random} = \int_{y_1}^{y_2} \int_{x_1}^{x_2} T_{random}(x, y) dx dy \quad (26)$$

The integration areas were chosen to exclude the hub vortex region. The lateral limits of integration were from $y=0.5\delta$ to the edge of the field of view. Horizontally, each field of view was divided into 12 separate slices along the x direction with an increment of approximately 1.5 cm. The results for all components of the integral of the transport equation are presented separately in Figure 32.

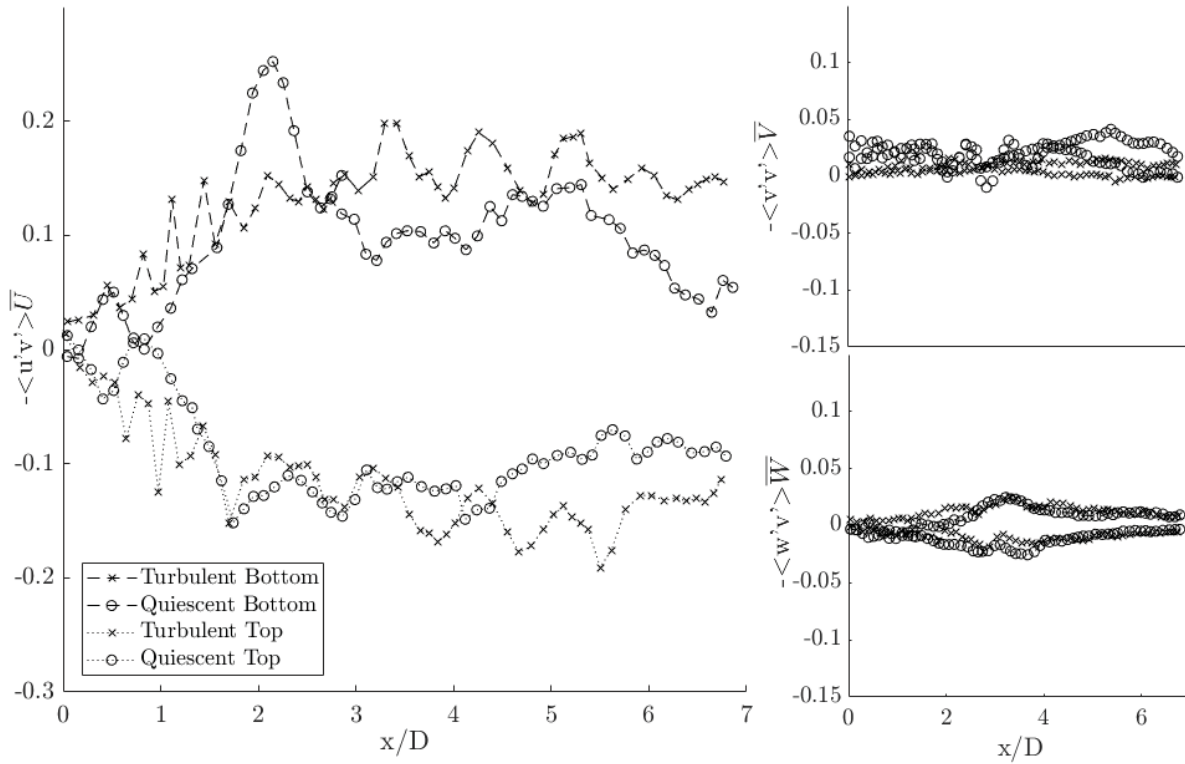


Figure 32: Net transport of mean kinetic energy by the random fluctuations. Both the turbulent (cross markers) and the quiescent (circle markers) cases are shown. Note the scale for the vertical and out of plane component are half the magnitude. Each marker is the magnitude of the mean kinetic energy in its integration area. Both the top (dotted line) and bottom (dashed line) half of the wake are shown.

The components, $-\langle v'v' \rangle V$ and $-\langle w'v' \rangle W$, used in equation 14 are both small contributors to the net transport of mean kinetic energy compared to the component,

$-\langle u'v' \rangle > U$. This term is the streamwise component where the velocity magnitude is the greatest. In the first diameter for both cases, the net transport hovers near zero as the tip vortices shield the wake core from the free stream. The slope between $1 < x/D < 2$ is the region where the tip vortices are beginning to interact with the adjacent vortices. For $x/D > 2$, the tip vortices have begun to pair and rotate which encourages the transport of energy to the mean flow as seen by the larger magnitudes in net transport. In downstream region $x/D > 3$ the net transport is greater in the case with the turbulent free stream. To highlight this finding, the cumulative average of $-\langle u'v' \rangle U$ is presented in Figure 33.

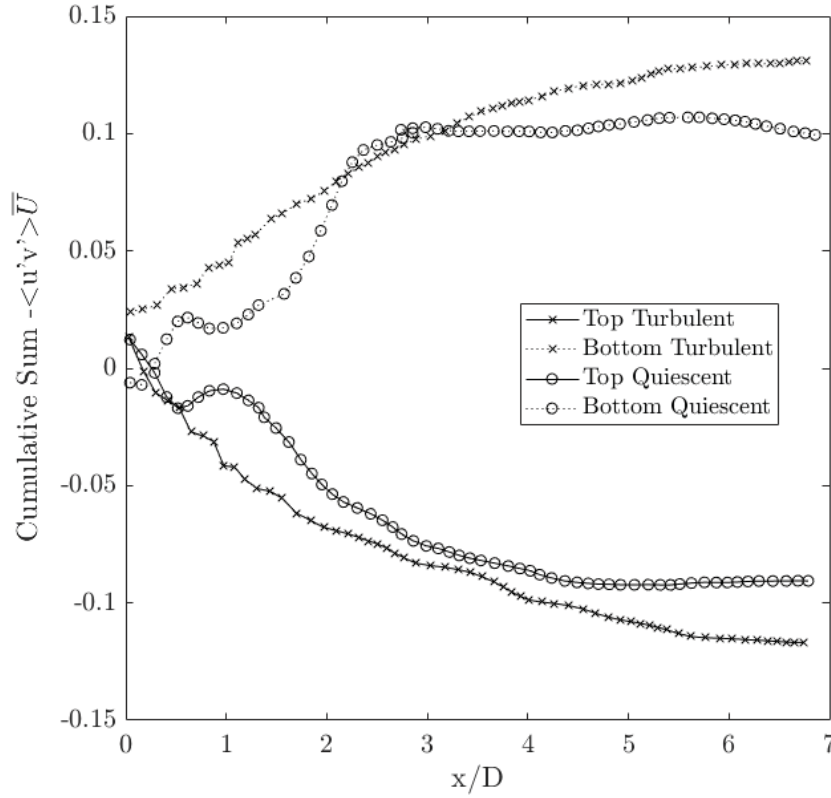


Figure 33: Cumulative average of the net transport of mean kinetic energy by the random fluctuations. Both the turbulent (cross markers) and the quiescent (circle markers) cases are displayed. Both the top (solid line) and bottom (dotted line) half of the wake are shown.

In both the top and bottom half of the wake, the net transport by means of random fluctuations is greater for the turbulent case than the quiescent case. The cumulative average of the turbulent case is approximately 20% larger than the quiescent case.

Next, the net transport of mean flow kinetic energy by coherent fluctuations was calculated. $K_{T_coherent}$ is plotted in comparison to the net transport by random fluctuations - $U\langle u'v' \rangle$ in Figure 34. Only the bottom half of the wake is shown for clarity. The top half of the wake followed a similar pattern.

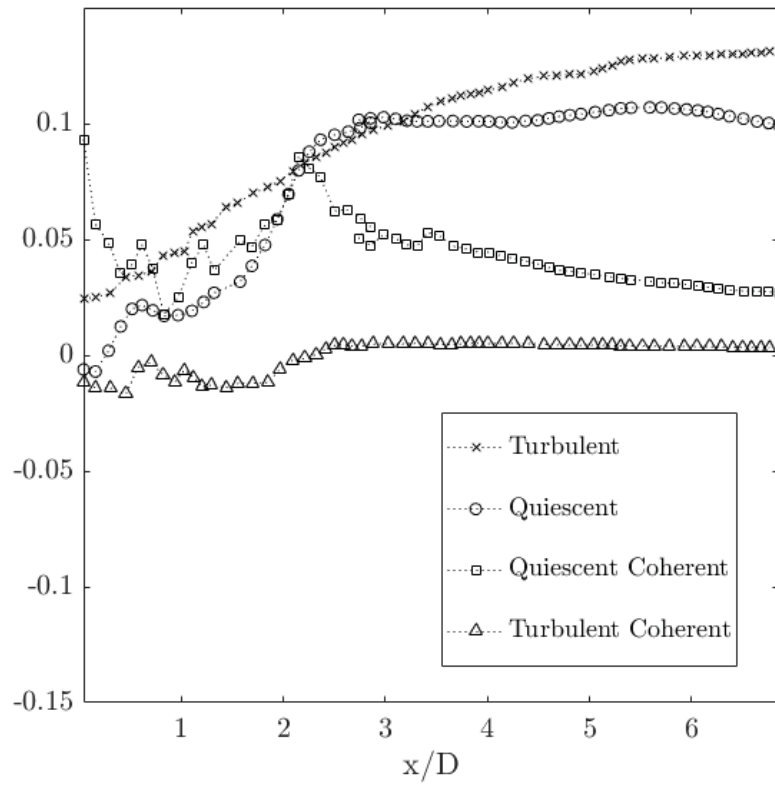


Figure 34: Cumulative average of the net transport of mean kinetic energy by the random fluctuation component $-U\langle u'v' \rangle$ and the sum of all coherent fluctuation components ($-U\langle \tilde{u}\tilde{v} \rangle - V\langle \tilde{v}\tilde{v} \rangle - W\langle \tilde{w}\tilde{v} \rangle$). Both the turbulent and quiescent cases are shown. Only the mean transport of the bottom half of the wake is shown for clarity.

As seen in Figure 34, the sum of all components of the coherent fluctuations' net mean flow kinetic energy transport contribution is about 3 times less than the contribution from the random fluctuations. In the quiescent free stream, the coherent fluctuations contribute a much higher magnitude of net transport than in the turbulent free stream. This difference is due to the prominence of the tip vortices in the quiescent case. The net transport by coherent fluctuations decreases after $x/D=2$ in the quiescent case when the tip vortices have begun to pair and dissipate.

Production of TKE

For the three dimensional data, six out of nine production terms (Equation 20) remain after expansion since out of plane gradients are not measured. The remaining terms are $\overline{u'u'} \frac{\partial U}{\partial x}$, $\overline{u'v'} \frac{\partial U}{\partial y}$, $\overline{v'u'} \frac{\partial V}{\partial x}$, $\overline{v'v'} \frac{\partial V}{\partial y}$, $\overline{w'u'} \frac{\partial W}{\partial x}$, and $\overline{w'v'} \frac{\partial W}{\partial y}$. The production of turbulent kinetic energy is presented in Figure 35.

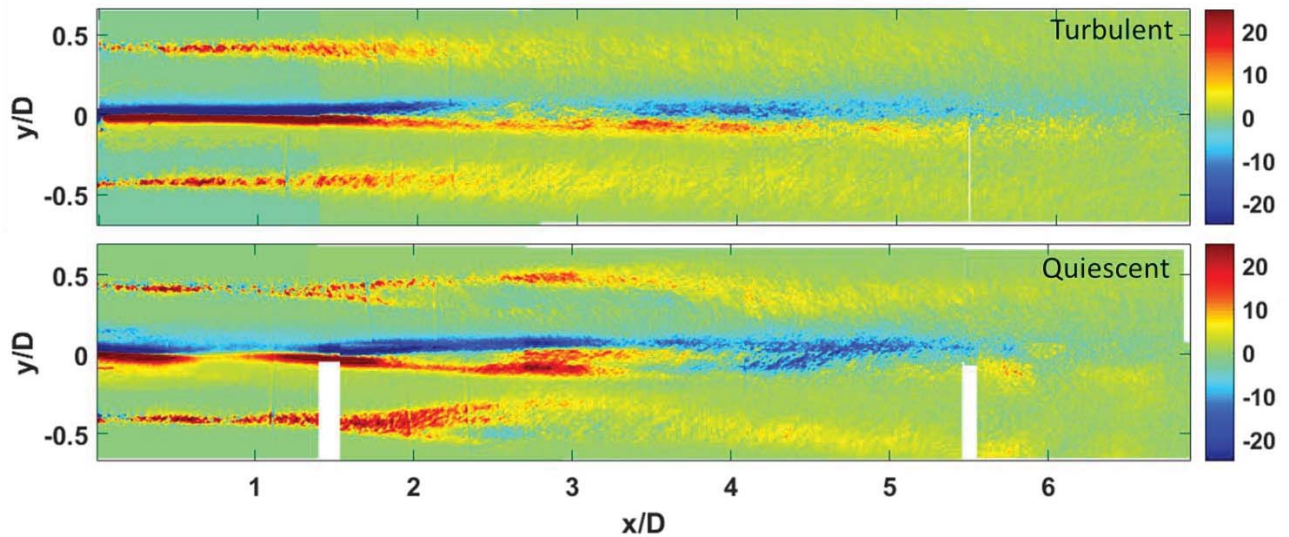


Figure 35: Spatial distribution of turbulent kinetic energy production in both the turbulent and quiescent free stream. This production is from the free run data.

The regions with the highest production occur at the wake boundaries where there is a region of high shear and presence of coherent vortex structures. This presence corresponds to the regions with high Reynolds shear stresses in Figure 19. The region where the hub vortex is located also has a large magnitude of production as there is a large gradient of velocity behind the hub of the propeller. The regions of positive production are where the turbulent fluctuations are gaining energy from the mean flow. After $x/D > 6$ the hub vortex signature is greatly diminished as it reenergizes with the rest of the wake. Future analysis will include separating and identifying which term in equation (20) contributes most to production as well as the spatial integration of production similar to the one described previously. Of specific interest will be the region at $x/D = 1.5$ (lower panel in Figure 35) where the signature of vortex pairing and rotation is evident. This region is discussed next.

Vorticity

Out of plane vorticity was calculated for the free run data using equation (25). Figure 36 has the time averaged out of plane vorticity for both the turbulent and quiescent free stream cases.

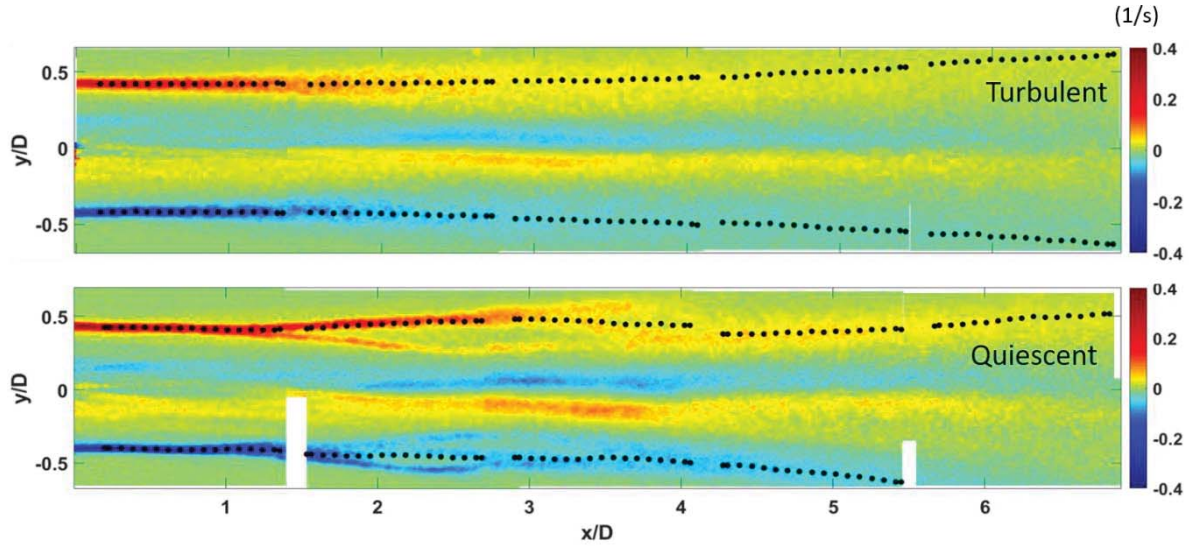


Figure 36: Spatial distribution of $\bar{\omega}$ for the turbulent and quiescent free stream. This out of plane vorticity is from the free run data. The units are [1/s]. The wake half widths are superimposed.

In the quiescent case for the unconditioned vorticity, a bifurcation, or splitting of the shear layer, is observed around $x/D=1.5$ in both the positive and negative shear layers. This bifurcation coincides with the beginning of the vortex pairing and leapfrogging. Progressing further downstream to around $4D$, the vorticity sheet diffuses as the vortices have begun dissipating and mixing into the free stream. In the turbulent case, the bifurcation is not apparent. Vortices have begun to pair and rotate, however, the vortices are not as stable or coherent, and as a result do not cause the splitting of the vortex sheet. Instead, the shear layer enlarges when the vortices pair at $x/D=1.5$ and then begins diffusing earlier around $x/D=2.5$.

Conclusions

Two dimensional and three dimensional PIV measurements were conducted in the near wake of a marine propeller model and used to observe and quantify the effects of inflow turbulence on the near wake development. The experiments were completed as unconditioned, free runs and as phase-locked runs in order to calculate the periodic fluctuations. The 3D

experiment was completed both with and without the turbulence generating grid in order to have a data set for comparison. All of the data was processed in the commercial software to produce the instantaneous velocity vectors. Early stages of this Trident work were used to develop codes to analyze properties of the 2D data, which was used for data verification and to support the 3D data. Starting with mean velocity profiles, there is a surplus velocity “dip” in the center of the wake due to the strong and persistent hub vortex. An observed difference was that the wake appeared more “smeared” or diffused in the turbulent free stream than in the quiescent free stream which may signify its early re-energization. The mechanism of downstream reduction of this velocity “dip” is proposed to be the ejections and inward interactions of in-plane velocity fluctuations, namely u' and v' .

In both experimental cases, the tip vortices act as shields of the inner wake for the first diameter downstream as observed in the mean kinetic energy transport analysis. This conclusion is consistent with the published results by Lignarolo et al. [39] who studied turbine near wake development. Similar results from this study of a propeller has not been published before. Conditional sampling of the Reynolds stresses and their coherent counterparts was performed and used to determine the modes in which energy is transported between the wake and the free stream. At the wake boundaries (both top and bottom), energy is being pushed outward by the stresses and into the free stream. Within the wake boundaries, the energy is being pushed in towards the hub vortex where there is the velocity deficit. At 7% turbulence intensity of the free stream, the random fluctuations contribute to a 20% greater net transport of mean flow kinetic energy in the turbulent case than in the quiescent case. Surprisingly, in the quiescent case, the coherent fluctuations contribute more net transport of mean flow kinetic energy than in the turbulent case as the vortices persist further downstream; however, their existence is short-lived.

As a result, the overall contribution to the net transport of mean kinetic energy by coherent fluctuations is 3 times less than the contribution by random fluctuations. Levels of free stream turbulence created in this experiments however, do not contribute significantly to the lateral widening of the wake as it progresses downstream. The overall expansion of the wake appears to be similar in both cases. More work at further positions downstream or with a greater turbulence intensity would be needed to draw any greater comparisons in the wake expansion. Future work will be to continue working on flow visualizations to better represent the differences between the turbulent and quiescent free stream cases.

Endnotes

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