Volumetric Velocity Measurements on Underwater Turbines

Daniel R. Troolin¹,* , Leonardo P. Chamorro², Seung-Jae Lee²

¹: Fluid Mechanics Research Instruments, TSI Incorporated, St. Paul, MN, USA
²: Saint Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN, USA
* Correspondent author: dtroolin@tsi.com

Abstract Instantaneous volumetric velocity measurements were performed in the wake of one, two, and three miniature axial-flow turbines placed in series along the centerline of a water flume operating under subcritical conditions. The turbine height from the floor of the flume was such that the blades operated within the turbulent boundary layer. Flow statistics were computed to determine the effects of the boundary layer on the shape and turbulence levels of the turbine wakes. In addition, velocity mean and fluctuations were investigated to understand the differences in wake forms based on the addition of one and two turbines upstream. Ensemble-averaged phase-locked measurements based on the position of the turbine blade were calculated. The location, evolution, and interaction of the blade tip and hub vortices were analyzed as a means of understanding turbulence levels within the wake. Tip vortices were found to migrate faster downstream at the furthest wall normal location (closest to the freestream) and slower closer to the floor boundary. This velocity gradient, typical in turbulent boundary layers, caused the helical pattern of blade tip vortices to tilt resulting in collisions, interactions, and vortex merging in the downstream wake. Specifics of the instability in the evolution of the tip vortices, and the subsequent interactions are discussed in detail.

1. Introduction

The turbulent nature of the river and marine currents is expected to affect the functionality of marine and hydrokinetic (MHK) devices operated in these environments. A particular case is given when MHK turbines are deployed within an array. The interaction of several turbulent wakes modifies the turbulence structure of the flow around MHK devices. The flow structure has spatial variability, and thus, complicates the design of MHK devices since every turbine operates, in principle, under different loading conditions.

In this paper we investigate the very near wake characteristics of three turbines placed in series. The focus was placed on observing the mean turbulence characteristics of the wake as well as the evolution and stability of the vortical structures shed by the turbines tip and hub. Because the turbines are operated under different turbulence conditions, i.e., they function under the presence of upstream wake(s), we visualized how the flow characteristics and vortical structures in the wake of each turbine are altered with the approach flow. Volumetric 3-component velocimetry (V3V) was used to measure the flow behind the three turbines. The methods are detailed in section 2; results are discussed in section 3; and a summary is given in section 4.

2. Methods

A simple array of three miniature axial-flow turbines placed in series was placed in a water flume with dimensions 0.5m wide, 0.7m depth, and 10m test section located at St. Anthony Falls Laboratory at the University of Minnesota. The three-bladed turbines, of rotor diameter \( d = 0.126 \) m, were mounted along the centerline of the flume with the hub axis aligned with the direction of
the mean flow at 0.11m above the floor, where the mean velocity was 0.265 m/s.

A TSI V3V system (Pereira et al. 2000, Troolin and Longmire, 2009) was used to capture three-dimensional velocity fields downstream of the turbine. A 200 mJ/pulse dual-head Nd:YAG pulsed laser was mounted above the flume with a 45° mirror positioned at the output after light-cone generating optics, to reflect the illuminating light volume into the flow downstream of the turbine. A transparent Plexiglas plate mounted at the surface of the water was used to limit free-surface effects of the illumination. A schematic and photograph of the experimental setup are shown in Fig. 1.

![Fig. 1 Schematic (left) and photograph (right) of the experimental setup.](image)

Pairs of laser pulses separated by 2.1 ms were imaged by a three-aperture camera mounted 768mm from the back plane of the measurement volume, 90° to the illuminating light. Tracer particles of 65 micron size, where identified and tracked in 3D space using a 3D particle tracking scheme based on the technique of Pereira et al. (2006). The resulting measurement volume was a rectangular prism 120mm × 140mm × 60mm which encompassed half of the downstream wake in the spanwise direction, and one full diameter downstream of the turbine. Figure 2 shows the locations and dimensions of the measurement volumes downstream of the three turbines. The figure is not to scale, and the streamwise spacing of the turbines was seven rotor diameters. Data was taken with one, two, and three turbines in place. A typical single capture yielded approximately 12,000 independent randomly-spaced velocity vectors. The vectors were interpolated onto a rectangular grid using Gaussian-weighting. The average spatial resolution for the instantaneous velocity fields was approximately 4mm. For each configuration, 1305 vector fields were acquired. Instantaneous and mean fields were analysed.

To aid in the understanding of coherent structures within the turbine wake, phase averaging of the vector fields was performed. Velocity fields occurring at the same phase (± 5°) were ensemble-averaged in order to achieve a phase-locked sequence of velocity fields through a complete 360° rotation of the turbine. The phase position of each realization was done through image analysis. Each turbine blade was marked with an identifier that was visible in the images but would not affect the flow in order to uniquely identify each blade in the images (i.e. blade 1, blade 2, or blade 3). The blade was then positioned at top dead center (TDC = 0°) and the pixel location of the blade tip was recorded. The pixel location for the turbine hub was also recorded. Using the TDC and hub locations as references, pixel locations in between were assigned an angular position based on the trigonometric relationship, $\cos \theta = y/L$. Where $\theta$ is the blade angle, $y$ is the pixel position of the blade tip relative to the center of the hub, and $L$ is the blade length in pixels (Fig. 3).
Each image in the sequence was analyzed to determine its angular position. The velocity fields were then binned in 10° increments to establish 36 phases. Approximately 35 realizations were averaged for each phase position.

3. Results

The spatial characteristics of the turbulent wakes are discussed and illustrated in this section. Various planes of the time-averaged velocity components and turbulence have been included to provide a comprehensive insight into the structure of the wake. Ensemble-averaged phase-locked vorticity contours in the near wake region were also investigated in order to observe the dominant vortical structures with the distance from the turbines and their particular propagation patterns.

For each case, 1305 instantaneous velocity fields were ensemble-averaged in order to analyze the mean and turbulence characteristics in the wake downstream of the turbines. In Figs. 4 and 5, the flow is from left to right, the plot on the left indicates the wake of the first turbine, the plot in the center indicates the wake of the second turbine, and the plot on the right indicates the wake of the third turbine. The distance between turbines was seven rotor diameters for the experiments but plots are shown adjacent to each other for visual clarity.
Figure 4 illustrates characteristics of the averaged streamwise velocity component \((u/U_{hub})\) in the three measurement volumes through spanwise and stream-wise vertical planes. There is a clear expansion of the shape of the wake as can be seen by the region of red (fast-moving, nearly freestream velocity) at the upper border of the plots, and the manner in which it diminishes radially as it progresses downstream from the location of the turbine blades and backward into the wake. The wake expansion is also shown in Fig. 5, which shows a stream-wise velocity iso-contour behind the first turbine (level of \(u/U_{hub}=0.75\)) for the instantaneous (left), phase-averaged (right) and ensemble-averaged (top) velocity fields. The affect of the blade rotation in the wake is evident from the ripples occurring in the iso-contours of instantaneous and phase-averaged plots.

![Figure 4](image1.png)

**Fig. 4** Non-dimensional distribution of the streamwise velocity component \(u/U_{hub}\) behind the first (left), second (center) and third (right) turbine.

![Figure 5](image2.png)

**Fig. 5** Streamwise velocity iso-contour behind the first turbine (\(u/U_{hub}=0.75\)). Top: Average field; bottom left: instantaneous field; bottom right: phase-locked field. Flow is from right to left.
The spatial distribution of streamwise turbulence intensity $I_u (= \sigma_u / U_{hub}$, where $\sigma_u$ is the standard deviation of the streamwise velocity fluctuations), is shown at various spanwise planes behind each turbine in Fig. 6, clearly illustrating differences between the three cases. In general, turbulence levels are consistently higher in the 2nd and 3rd turbines (center and right plots, respectively). Around the location of the tip vortices, the third turbine shows comparatively higher, more diffuse, and not concentrated enhanced turbulence levels after one-half rotor diameter. It is a signature of vortex stability loss, which will be clearer in the visualization of the vorticity field.

Instantaneous realizations of tip and hub vortical structures behind each turbine are depicted in Fig. 7. Isosurfaces represent Q-criterion ($Q = 4.7$) and the color represents distance from the axis of the turbine hub. It is observed that those structures are more coherent behind the first turbine (left plot), which does not face any wake flow from a turbine upstream. Although the tip vortices are clear in the wake of the 2nd turbine (center plot), they appear to be not as coherent as the case of the first turbine. The apparent lack of stability is more obvious in the wake of the third turbine (right plot) as evidence by the increased disorder and smaller length scales associated with the location of vortex cores. Several mechanisms can be interacting in this process, where the enhanced level of turbulence with number of turbines is probably one of the major mechanisms of vortex destabilization.

Phase-averaged data is shown in Figs. 8-10, where flow is from right to left, and blue iso-surfaces
represent the presence of vortex cores determined by the Q-criterion. Isosurfaces within $r/R = 0.5$, where $r$ is the distance from the hub axis and $R$ is the length of the turbine blade have been blanked to eliminate the hub vortex structures and clarify the presence of the tip vortices. In Figs. 8 and 9, four instances are shown with phases 10° apart and in Fig. 10, two instances are shown with a phase difference of 10°. The plots clearly reveal the presence of helical tip vortices as they form at the blade tip and how they are convected downstream (to the left) of the turbine. Lines in the plots represent a helical fit to the propagation of the tip vortices with the blue line representing blade 1, green representing blade 2, and red representing blade 3. The colours are arbitrarily chosen and provide clarity in understanding the path of vortices generated by each blade.

![Fig. 8](image.png)

**Fig. 8** Propagation of the tip vortices within the first rotor diameter behind the first turbine. Q-criterion with $Q = 4.7$.

Of interest, is that the measurements show one of the types of vortex-to-vortex interactions that can destabilize the tip vortices behind the first turbine (see Fig. 8). In Fig.8a, the tip vortex interaction starts with a radial expansion of the vortex spiral at $x/d = 0.5$ (indicated by “i”). This is a result of the lower convection velocity present at the bottom of the plot (closer to the floor boundary) and the subsequent deceleration of vortex “ii”. In this process the spiral-to-spiral distance is altered giving rise to unsteadiness and triggering complex vortex-vortex interactions. In Fig. 8b, vortex “i” begins...
to overtake vortex “ii” and by Fig. 8c, the borders of the vortices represented by Q in the figures have begun to interact. Figure 8d shows that the two vortices have merged spatially such that the total size of the tip vortex structure has expanded and the vortices then continue to propagate downstream in an intertwined manner. This complex dynamic is also observed behind the second turbine in Fig. 9, albeit with lower Q-values and apparent instability occurring over a larger streamwise distance than for the first turbine, as can be seen by comparing Figs. 8a and 9a where the merging occurs between streamwise positions, \(x/d = 0.65-0.75\) in Fig. 8a, and between \(x/d = 0.65-0.85\) in Fig. 9a.

![Fig. 9](image)

**Fig. 9** Propagation of the tip vortices within the first rotor diameter behind the second turbine. Q-criterion with Q = 2.

The situation appears different in the wake of the third turbine. As illustrated in Fig. 10, which shows the tip vortices at two instants of time, the vortices appear to loss their stability consistently at a distance of 0.5 rotor diameter behind the turbine. As mentioned before, increased levels of turbulence may play a critical role in the destabilization of these coherent structures.
Fig. 10 Propagation of the tip vortices within the first rotor diameter behind the third turbine. Q-criterion with Q = 1.2

Figure 11 shows phase-averaged data of both tip and hub vortical structures with isosurfaces of Q-criterion shown and color representing distance from the hub axis. It is apparent from the plots that the wake of the first turbine is fairly stable (Fig. 11a), but subsequent turbines lose wake stability. See for example Fig. 11c, where both the hub and tip vortices appear less coherent, more diffuse, and with smaller length scales that correspond to increased disorder and higher turbulence levels. Note that the interaction between the hub and tip vortices appears to be minimal for all cases.

Fig. 11 Propagation of the tip and hub vortices within the first rotor diameter behind the first (a), second (b) and third (c) turbine. Isosurfaces are Q-criterion with Q = 4.7, 2 and 1.2, respectively. For clarity, colour levels indicate the distance from the turbine axis.

4. Conclusions

Turbine wakes were studied by examining mean and turbulence statistics, instantaneous captures, as well as phase-averaged data of volumetric velocity fields downstream of one, two, and three turbines spaced by seven turbine diameters. The current data, only a portion of which is shown here, indicate that increased disorder and higher turbulence intensity occurs downstream of a turbine within a turbulent boundary layer. In addition, turbines placed in series serve to increase
turbulence values and induce earlier breakup of the wake in subsequent turbines downstream.

The data revealed significant new details of the tip vortex interactions with adjacent vortices due to the operation within a boundary layer which exhibits a velocity gradient. A principle of vortex interaction was discussed in which drag associated with the boundary layer slowed the downstream progress of one helical tip vortex to the point where the next tip vortex overtook it and precipitated a merging and intertwining process between the two adjacent tip vortices. Additional analysis revealed little interaction between the hub and tip vortices.

The V3V technique was useful for studying this flow for two reasons. The first is that the resolution of the entire 3D field allows us to place individual structures and events within the context and framework of the rest of the overall flow environment. The second is that the phase-averaged data allows us to track the evolution of dominant and secondary structures. In particular, V3V is valuable for use in flows which exhibit highly complex 3D structures as it elucidates behavior that is difficult to resolve or understand from 2D data. The vortical interactions discussed here are much easier to track and understand by viewing movies of the events from multiple viewing angles, as will be shown at the conference.

5. References


