ORPC RivGen Wake Characterization

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ABSTRACT

Baseline and post-deployment flow conditions were measured at the ORPC RivGen turbine site on the Kvichak river in the vicinity of Igiugig village, Alaska. Mean surface flow and turbulence measurements were collected from a drifting platform equipped with a Nortek Signature 1000Hz five beam AD2CP. Baseline measurements indicate a maximum flow of 2.5 m/s and a 10% turbulent intensity in the turbine vicinity. Measurements after turbine deployment and grid connection show a significant decrease in surface velocity up to 200 m downstream from the turbine and an increase in turbulence intensity up to 20% that extends about 75 m downstream of the turbine. The turbulent kinetic energy dissipation rate is also increased immediately downstream of the turbine.

1. INTRODUCTION

The extraction of hydrokinetic energy from rivers and tidal currents requires the installation of marine hydrokinetic turbines facing the flow field, as for any perturbation in the river medium, environmental effects are expected to occur [1, 2, 3]. Such environmental effects pose a challenge to the development of hydrokinetic energy extraction projects at all scales and must be carefully analyzed.

The study of the wake behind a turbine is essential in the characterization of hydrodynamic effects. Wake analysis reveals changes to the mean flow and mixing behind the turbine, as well as how long it takes to return to the natural flow conditions. The length of the wake and its features also affect the downstream distribution of additional devices and their performance [4].

Much of the research on hydrokinetic turbine wakes has been carried out numerically [5, 6, 7], and at the laboratory scale under controlled conditions [8, 4, 9], differing mainly on how detailed the turbine and the energy extraction are represented [10]. At the field scale, towing experiments of a vertical crossflow turbine were conducted in an unconfined environment in [11]. In general, the wake of the turbine is characterized by: i) a deficit in the mean flow that might persist beyond several turbine diameters downstream [12]; ii) an increase in turbulence due to eddies shed by turbine blades; and iii) complex interactions between natural and turbine induced turbulent structures [6].

In this investigation we assess the wake formed behind a horizontal cross-flow turbine installed on the Kvichak river in southwest Alaska, USA, just downstream of the village of Igiugig. The small village is home to 70 people and its electricity source currently depends on an isolated power grid fed by diesel generators. The Ocean Renewable Power Company (ORPC) has set a pilot hydrokinetic energy project on the Kvichak river stream to provide Igiugig with a renewable and locally produced source of energy.

ORPCs RivGen turbine was successfully deployed, tested and connected to the local power grid during the summers of 2014 and 2015. During each deployment a team from the University of Washington Applied Physics Laboratory performed several measurements of pre and post-deployment river flow conditions. Here, analysis focuses on the turbine wake observed during deployment in summer 2015.

The characterization of the wake requires the ability to capture, in space and time, the complex three dimensional nature of the flow in the vicinity of the turbine [12]. In this case, the turbine's wake was captured using a drifting approach. A freely drifting platform instrumented to measure flow velocity at high frequency through the water column was released at different locations along a cross-section upstream the turbine location and let flow along river streamlines. This repetitive process allowed us to cover a large portion of the river in the turbine vicinity before and after turbine deployment without interfering with turbine operations and without deploying an array of instruments on the riverbed.

The use of repeated drifts is only possible because the river flow has strong stationarity, and thus drifts from different times can be merged to get a complete picture of the river flow state. Data from before and after turbine deployment can then be organized into horizontal grids in order to obtain a map of river flow conditions and further elucidate the turbine effects in the flow. As noted in [12], the mean flow and turbulence do not recover at the same rate in a turbine wake, thus the wake extension and recovery to an undisturbed state are analyzed using both mean flow and turbulence statistics.

Figure 1: Kvichak river near Igiugig, Alaska, and local coordinate system. X-axis corresponds to main flow direction. Basemap was taken from Google Earth.

2. DATA COLLECTION

Surface velocity and velocity variations along the water column were collected from a moving platform around the turbine deployment site on the Kvichak river. Figure 1 shows a plan view of the river and turbine location. Measurements took place prior to and after the deployment (and grid connection) of ORPC's RivGen hydrokinetic turbine in order to analyze the effects of turbine rotation and energy extraction in the river flow conditions.

Site and Turbine Description

The ORPC deployment site is on the Kvichak River, just downstream of the village of Igiugig in southwest Alaska. The Kvichak river flows southwest from Iliamna Lake to Bristol Bay. At the deployment site, the river is approximately 5 m deep and 150 m wide. The flow is at is maximum, $u \sim 2.5$ m/s, in the center of the river.

RivGen is a crossflow horizontal turbine, approximately 12 m wide and 1.5 m in diameter. Turbine hub-height is approximately 2.5 m below the river free surface when the turbine is submerged and resting on the riverbed. Turbine blockage in the Kvichak river was estimated to be 10% when considering the turbine swept area plus the turbine's support structure area over the area of the river cross-section at the turbine location (obtained from a previous bathymetric survey conducted by ORPC).

2.1 Drifting Platform Description

Flow velocities throughout the water column were collected using a drifting Nortek Signature 1000Hz five beam AD2CP. The Signature was mounted looking downward on a disk buoy equipped with two Qstarz GPS data receivers measuring geographic position and drifting velocity at 10 Hz with a 5 m accuracy in position and 0.05 m/s in drifting velocity (using a phase-resolving GPS antenna). The platform is shown in Figure 2.

The Signature was set up to measure velocities in its 5 BEAM coordinates at an 8 Hz sampling rate (continuous). The blanking size was set to 0.5 m and cell size to 0.5 m, with a 7.5 range to cover the entire water column.

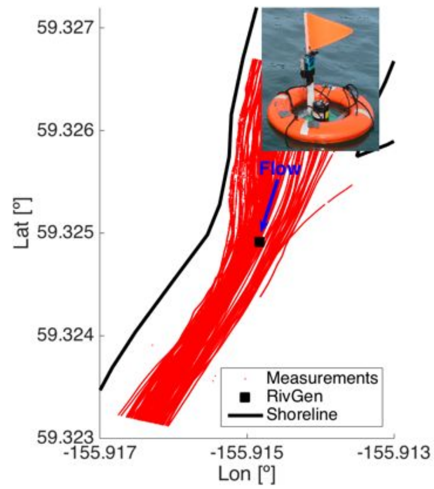

Figure 2: Instrumented drifting platform and drifts path in red. Black lines represent the river shoreline and black square defines turbine location

2.2 Measurement Procedure

Drifts began $\sim$ 200 m upstream of the turbine position by directly dropping the drifter buoy from a small vessel. The cross-sectional river span was covered by releasing the drifter at seven different (estimated) positions across the river. Each drift was recovered $\sim$ 200 m downstream of the turbine. Figure 2 shows location and direction of drifts.

Two sets of drifts were conducted: before and after turbine deployment. The first set was conducted in order to characterize the river in its natural state and the inflow conditions for the turbine. This data set consisted of $\sim$ 150 drifts between July 8th and July 13th, 2015. A portion of the drifts (15) were set-up to measure altimetry (bathymetry) and due to an instrument restriction, could only measure along beam velocities at 4 Hz (instead of 8 Hz).

The second set of drifts took place after turbine deployment, from July 19th to July 21st, 2015. This data set consisted of $\sim$ 190 drifts covering the same longitudinal river span, but concentrated over and next to the turbine to evaluate the turbine wake. As for the first set, 25 drifts were taken in altimeter mode, measuring 5 beam velocities at 4 Hz.

3. ANALYSIS

3.1 Data organization

A local coordinate system was defined for all flow measurements, with positive x downstream (u component of velocity), positive y cross-river towards the village (v component of velocity), and positive z upwards (w com-

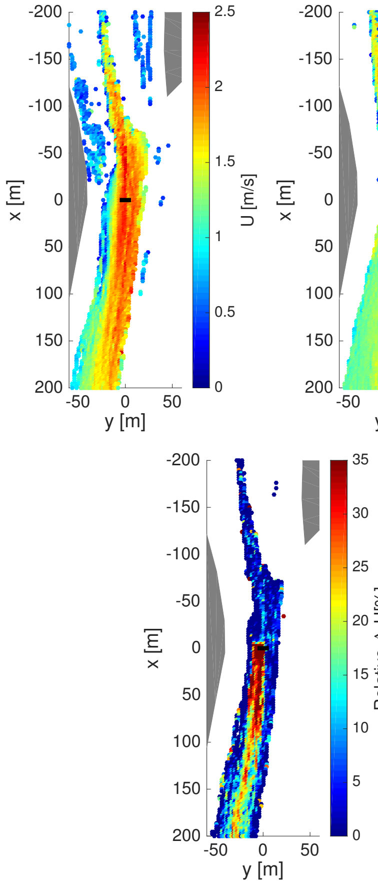

Figure 3: Hub-height velocity measurements maps: baseline (top left), post-deployment (top right) and relative difference (lower). Grey areas represent river banks and black square defines turbine location.

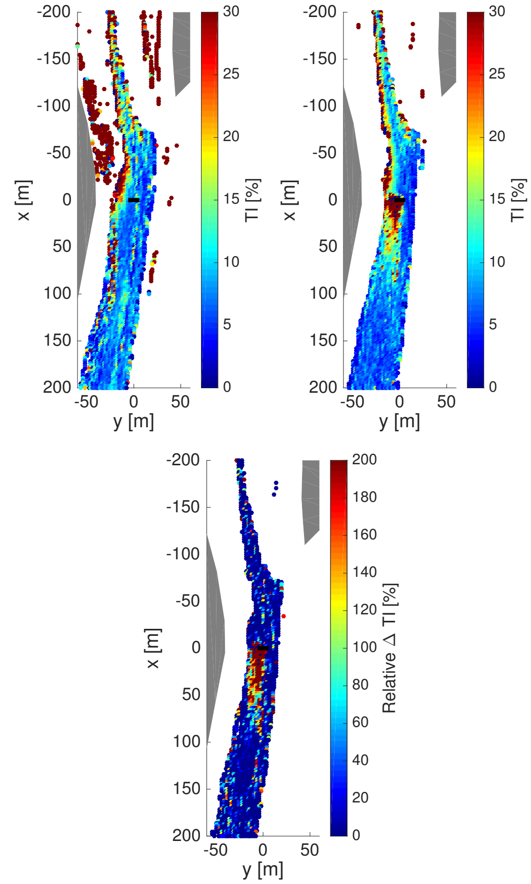

Figure 4: Pseudo-Turbulence intensity measurements maps: baseline (top left), post-deployment (top right) and relative difference (lower). Grey areas represent river banks and black square defines turbine location.

ponent of velocity). The origin is at the nominal center of the turbine (59.324916 °N; 155.914828 °W) and the rotation from an east-north-up (true) coordinate system is 107° clockwise. The system is shown in Figure 1.

Collected data was organized into a $2x2$ m^2 horizontal grid defined in the local coordinate system which covers 400 m in the along river direction and 60 m in the cross-river direction; the center of the grid is at the center of the turbine. The grid organization results in a map of surface velocities and a set of velocity variations at different depths where significant differences can be observed between before and after turbine deployment.

3.2 Horizontal Velocity

Surface flow velocity was obtained from platform drifting velocities recorded by the GPS receivers. Horizontal velocity magnitude profiles through the water column were estimated from the surface flow velocity and the horizontal velocity measured by the drifting Nortek Signature as:

$$U(x, y, z, t) = U_d(x, y, t) - U_{ad2cp}(x, y, z, t) \qquad (1)$$

where U_d is the drifting horizontal velocity and U_{ad2cp} represents the horizontal velocity magnitude estimated from the Nortek Signature measurements.

Grid averaged hub-height velocity magnitude maps are shown in Figure 3. Maximum hub-height velocity is at the main channel center, reaching ~ 2 m/s just upstream of the turbine; the velocity magnitude distribution agrees with the shape and bathymetry of the river. Post-deployment measurements show a decrease in hub-height flow velocity magnitude towards mid-river, observable immediately downstream of the turbine. The velocity decrease was also observed in the surface flow velocity, beginning about 25 m downstream the turbine (not shown). This distance indicates how long it takes for the water column to mix behind the turbine for the wake effects to be observable at the free surface.

The relative velocity change map, shown in the lower panel of Figure 3, indicates a strong hub-height velocity change beginning right downstream the turbine location. The velocity change reaches a maximum of 35% and extends for more than 200 m downstream the turbine. The persistence of the wake in terms of mean flow velocity is an indicator of energy extraction.

3.3 Turbulence

Flow turbulence is spatially characterized by two parameters: turbulence intensity and the rate of turbulent kinetic energy (TKE) dissipation. These two parameters provide key information on the turbine's turbulent wake, describing how much river turbulence is increasing, and how does the river flow recovers downstream the turbine.

A pseudo-turbulence intensity (TI) is estimated using the 5 beam raw velocity measurements from the Signature relative to the mean surface velocity of the flow. This pseudo-TI is defined as:

$$TI(x,y,z,t) = \frac{\sqrt{\frac{1}{5}\sum_{i=1}^{5} u_i^2(x,y,z,t) - \Delta u_n^2}}{U_{ad2cp}(x,y,z,t)} \quad (2)$$

where u_i represents each along beam velocity from the Nortek Signature, u_n is the along beam velocity error and $U_a d2cp$ is the horizontal velocity magnitude. This assumes that the platform is drifting with the mean flow and that the fluctuations are all independent realizations of the turbulent field, though there are only three independent components of velocity. The along-beam measurements have independent noise errors, u_n, and thus the use of all 5 beams is preferred to estimate the velocity variations at each point along a drift track. By only using the along beam velocities, pseudo-TI only captures the turbulent length scales similar to the beam separations. This spatial definition is uniformly biased low compared to the usual temporal definition of turbulent intensity $\sigma_u/\bar{u}$, where σ_u is the standard deviation of along channel velocity and $\bar{u}$ corresponds to the mean flow.

Stationary measurements of turbulence using Accoustic Doppler Velocimeters at the turbine site show the existence of a cascade of isotropic turbulence in the Kvichak river [13, 14], which allows for the estimation of the rate at which turbulent kinetic energy is dissipated.

Here, we instead use a spatial method for the TKE dissipation rate. Dissipation rates of TKE are calculated using the spatial structure functions of the along-beam turbulent fluctuations $D(z,r)$ [15, 16], defined as:

$$D_i(z,r) = \langle (u_i(z) - u_i(z+r))^2 \rangle \quad (3)$$

where u_i corresponds to each along beam velocity, z is the along beam measurement location, and r the distance between velocity measurements; the angle brackets denote a time average. It is important to note that the spatial structure function captures a wider range of turbulent length scales than the pseudo-TI, as it incorporates the velocity fluctuations differences along the entire water column. At the inertial subrange of isotropic turbulence, the dissipation rate ϵ is obtained from the following relation [16]:

$$D_i(z,r) = C_v^2 \epsilon^{2/3} r^{2/3} \quad (4)$$

where C_v^2 is a constant equal to 2.1.

The structure function was estimated using all instantaneous profiles within each grid cell (about 8 instantaneous profiles for each drift that passed through a grid cell). TKE dissipation rate was estimated from the time averaged structure function estimate at different depths by linearly fitting $D_i(z,r)$ to $r^{2/3}$ as:

$$D_i(z,r) = A(z) r^{2/3} + N(z) \quad (5)$$

where $A(z)$ is the slope of the linear fitting defined as $A(z) = C_v^2 \epsilon(z)^{2/3}$ and $N(z)$ represents uncertainties related to Doppler noise [15]. TKE dissipation rate at each depth of each grid cell is estimated from $A(z)$. For the calculations, r values ranged between 1 m and 2.5 m.

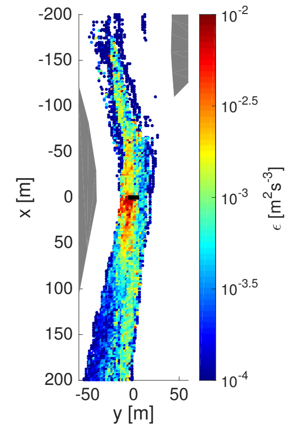

Figure 5: Turbulent kinetic energy dissipation rate map from turbulent structure function along vertical beam after turbine deployment and grid connection. Grey areas represent river banks and black square defines turbine location.

Baseline, post-deployment, and relative change of pseudo-turbulence intensity maps are shown in Figure 4. All maps correspond to hub-height measurements, 2.5 m below free surface. Baseline ambient turbulence at hub height is about 10% around the turbine location, increasing near the river boundaries as the water depth decreases. This value is consistent with stationary measurements using ADVs at the site. When the turbine is operational, at hub height, there is approximately a doubling of pseudo-TI, extending from just upstream of the turbine to ~ 75 m downstream the turbine.

A plan view of TKE dissipation rate for a fully operational turbine is shown in Figure 5. A region of higher TKE dissipation rate is observed immediately downstream of the turbine extending about 50 m downstream, consistent with the increase in turbulence intensity and its recovery extension.

4. CONCLUSIONS AND FUTURE WORK

Spatial measurements of mean flow and turbulence in the vicinity of the ORPC RivGen power system site in the Kvichak river in Alaska reveal the impact of a hydrokinetic turbine on flow conditions. The repetitive drifting approach at a high sampling rate has proven to be effective in capturing the natural flow conditions and the averaged effects of turbine rotation and energy extraction in the flow, showing a turbulent wake that extends more than 50 m downstream of the turbine location and a larger effect in the mean flow extending more than 200 m downstream.

Future work includes the study of turbine operation and wake relation, the analysis of free surface variations upstream and downstream of the turbine from a longitudinal array of pressure gages installed under the turbine, the analysis of the spatial scales of the turbulence, and the analysis of momentum balance measured upstream and downstream of the turbine.

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