Evaluation of the wake around a 22-kW hydrokinetic turbine

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Abstract- The current study presents flow measurements around a hydrokinetic turbine using a Horizontal Acoustic Doppler Current Profiler (HADCP). HADCPs are often used to estimate the water discharge rate and flow velocity however, they can also be used to characterize the near-surface flows; this includes the wake generated by a surface mounted hydrokinetic turbine. Tests are conducted around a 22-kW cross flow hydrokinetic turbine at the Canadian Hydrokinetic Turbine Test Centre located on the Winnipeg River. The goal of the study is to verify the utility of the HADCP for turbine characterization but also to examine the flow around a turbine, especially the inflow and wake regions.

Keywords- Tidal Turbine, Field tests, Wake, Turbine farm, ADCP

I. INTRODUCTION

Marine hydrokinetic turbines are an emerging technology and are currently at the commercialization stage. Marine kinetic energy has a relatively high energy density, when compared to wind and solar, and is a predictable, renewable resource that can be used to address base loads. Hydrokinetic energy from water currents can deliver predictable power to the grid, as water currents are driven primarily by gravity and less impacted by weather than solar or wind. Recent Canadian marine technological roadmaps show a desire to quantify the potential and to commercialise the technology during the next few decades [1]. Therefore, an infield wake study of a turbine is critical to quantify the turbines influence on other turbines and the environment. A hydrokinetic turbine creates a wake proportional to its size, which could affect downstream marine life, as well as the placement of other hydrokinetic turbines. By characterizing the wake, the turbine can be positioned to be efficient with production and preserve the downstream environment.

Horizontal Acoustic Doppler Current Profilers (HADCP) emerged as an innovative technology for measuring river discharge rates by capturing the velocity profile within a horizontal plane across the channel. While HADCP has been used for the near-surface characterization of marine environments, the current work is the first study to use an HADCP to perform field measurements of the flow upstream and downstream of a surface mounted hydrokinetic turbine. While there are numerous studies examining the wakes behind single and multiple hydrokinetic turbines [2] [3], there is limited literature pertaining to actual field measurements. Most studies examining the wake behind hydrokinetic turbines are performed using either numerical simulation with an actuator disc model or scale model turbines in controlled laboratory conditions [4] [5]. Results between the two types of studies are similar, but the scope is limited and full scale field measurements are required for an understanding of the impact of hydrokinetic turbines.

As most numerical simulations are performed using actuator discs, there are concerns as to the accuracy of the results. Some limitations to the actuator disc model include: the disc does not introduce vortices into the flow, the blade tip vortices of the turbine are not generated, and the turbulence modeling techniques typically produce only time-averaged results. Due to the lack of vortices, the predictive accuracy of the model within the near field 2D to 5D, where D is the diameter of the turbine, typically do not match well with laboratory experiments. Furthermore, advanced turbulence modeling techniques, such as large eddy simulation or direct numerical simulation require significant computational resources that cannot match the Reynolds number range of field measurements. These models are compared to experiments with a porous disc which is the closest representation of a turbine, to assess the quality of the model [6].

In comparison to field measurements, laboratory measurements contain lower Reynolds numbers, less turbulence, and smaller vortices. Typically, within a controlled laboratory environment, low-turbulence intensities below 1% are observed. Medium-turbulence, between 1% and 5% are obtainable using grates which generate turbulence artificially, however, there is still a significant difference compared to most riverine measurements. High-turbulence, in deep, wide rivers or low velocity shallow rivers is typically 5% to 20% and the turbulence tends to peak at the free surface and in the boundary layer, creating potential to interact with wakes generated by hydrokinetic turbines [7]. Additionally, the size of the large vortices cannot be reproduced in laboratory conditions.

Based on this range and results of wake measurements behind a wind turbine, the wake is expected to be different from simulations, for any kinetic turbine [8]. The field measurements are an essential part of the development of the industry. When assumptions and conditions are the only options in the laboratory, the data represents the baseline which must be verified by full-scale field measurements. The field measurements in this study demonstrate results that will help further hydrokinetic technology.

II. METHODOLOGY

Tests are conducted at the Canadian Hydrokinetic Turbine (CHTTC) which is located on the Winnipeg River, Seven Sister Falls, Manitoba Canada. The CHTTC is a Canadian test centre for riverine hydrokinetic turbines and its goal is to reduce the testing and commercialization costs for marine turbine developers through an ideology of shared knowledge and facilities. A list of team members at the CHTTC, along with a list of their activities is available at www.chttc.ca. Highly turbulent and variable flow rates are the main characteristics of this site that attract marine turbine manufacturers and developers for lifecycle project solutions for fully grid integrated systems. The site is located on a 1 km section of river located in the tailrace of the Seven Sisters Generating Station. The tailrace is a manmade channel with rectangular cross section made of granite bedrock. The channel bed is smooth with no considerable roughness or hydraulic jumps. The average width of the channel is about 60 m and the depth varies between 10 m to 12 m in the main test section. The flow in the channel is a function of season, precipitation and load on the Seven Sisters Generating Station, when more electricity is generated from the dam, more water flows through the tailrace. However, on average the CHTTC maintains a flow speed in the range of 1.75 m/s to 3 m/s. Due to the highly energetic flow, the river remains unfrozen even during the winter.

The hydrokinetic turbine used for testing is designed and manufactured by Mavi Innovation Inc. This turbine is a cross flow turbine with 22 kW nominal power output at a current speed of 3 m/s. The unit consists of two main sections: a floating platform and the turbine module. The floating platform is an 8.5 m long by 5 m wide pontoon boat. The turbine module is a three bladed turbine, 2 m in diameter and 3 m wide. The direct drive generator of the turbine converts the kinetic energy of the river currents into electricity. To generate power, the turbine is lowered below the water surface to capture the free-stream flow. The turbine rises above the water for deployment, retrieval, inspection and maintenance. To raise or lower the turbine, the turbine slides up and down on two rails on both sides of the turbine using two winches. The railing system allows the turbine to drop up to 3 m below the water surface. Two composite shrouds on the top and bottom section of the turbine accelerate the flow into the turbine in order to enhance the power output. During the tests, the generated power is dissipated to a heater. Figure 1 shows a previous test of the turbine at the CHTTC site.

Figure 1 - ADCP measurements performed at the CHTTC site upstream of the 22-kW Mavi turbine measure the inflow. The ADCP is connected to the front of the turbine using a custom mounting bracket attached directly to the unit

The HADCP collects the average velocity every 5.6 s and a GPS is used to record the longitude and latitude coordinates of the measurement point. The minimum measurement period is 2 minutes while the longest measurement period is 1 hour. This was done to investigate how the flow in the channel changes with time and dam discharge. Results presented in this report are the averaged values over the measurement period.

In this experiment, the HADCP is an RD Instruments CM 600, a 2-beam 600 kHz at 20° angles which measures up to 128 cells. The cell size varies between 0.5 m and 4 m, and the horizontal range is 200 m.

While the HADCP can be deployed from a measurement arm located on the shore, several issues prevent such a test from being feasible. First the distance from the shoreline to the turbine is relatively large in comparison to the measurement range of the device. However, the orientation and the inclination of the HADCP must be checked to confirm the reliability of data. By considering the vertical spread angle 1.5°, the distance where beams hit the surface for the first time can be estimated as listed in Table 1, and if there is a gap between the two beams the roll can be calculated. This procedure is explained in the technical report by Birjandi *et al* [9]. Figure 2 shows a representation of axes when the HADCP is in position, then a positive roll involves that Beam 2 will be in contact with the surface first and for a negative roll it will be Beam 1 first. Secondly, the HADCP bin size increases due to the beam spread as the distance increases causing the results to be measured over a larger area reducing the accuracy of the results. Measurements are conducted using an HADCP and pontoon measurement platform, referred to as the blue pontoon.

The experimental set-up requires three people, one watercraft operator, one computer operator and one measurement arm operator to raise and lower the HADCP. Once a measurement location is selected, the HADCP is lowered into the water by rotating the measurement arm to a vertical position and locking the arm in position using a stopper built onto the side of the blue pontoon. The watercraft operator holds the watercraft stationary for the duration of the measurement. The measurements used in this study and their configurations are listed in Table 1.

Table 1 - HADCP measurement details

Month	Run	HADCP Depth	Streamwise Distance (m)	Spanwise Distance (m)	Coordinates Lat (N) / Long (W)
July	5	1.75	30	35	50°07.5820 / 96°01.6657
	6	1.75	35	30	50°07.5800 / 96°01.6760
	7	1.75	50	15	50°07.5749 / 96°01.6941
	10	1.01	26	32.5	50’07.5796 / 96’01.6667
	21	1.37	-18	9	50°07.5553 / 96°01.6593
	22	1.37	-4	3	50°07.5592 / 96°01.6712
	23	1.37	4	3	50°07.5626 / 96°01.6803
	24	1.37	20	9	50°07.5729 / 96°01.6706
September	1	1.6	-16	4.5	50°07.5544 / 96°01.6639
	2	1.6			50°07.5544 / 96°1.6639
	3	1.6			50°07.5544 / 96°01.6639
	4	1.6			50°07.5544 / 96°01.6639
	5	1.6	16		50°07.5692 / 96°01.6852

HADCP is fixed to a metallic arm on the blue pontoon. Measurements are performed over two periods: July and September. For July, the turbine is stopped and for September, the turbine is operating at varying RPM: 50, 60, 70 and 75, and different deployment depths.

III. VELOCITY RESULTS

Horizontal profiles are used to characterize the impact of a turbine on the flow due to wake created. Typically, tests are carried out at the CHTTC at different locations and depths. In these experiments, the turbulence of the river is between 5 and 20%, varying with depth and mean velocity of the flow ahead of the turbine, which is approximately 2.3 m/s. This is denoted as Uref or U_∞, which is the maximum free-stream velocity observed upstream of the turbine. Figure 3 shows the results of the HADCP measurements upstream and downstream of the turbine.

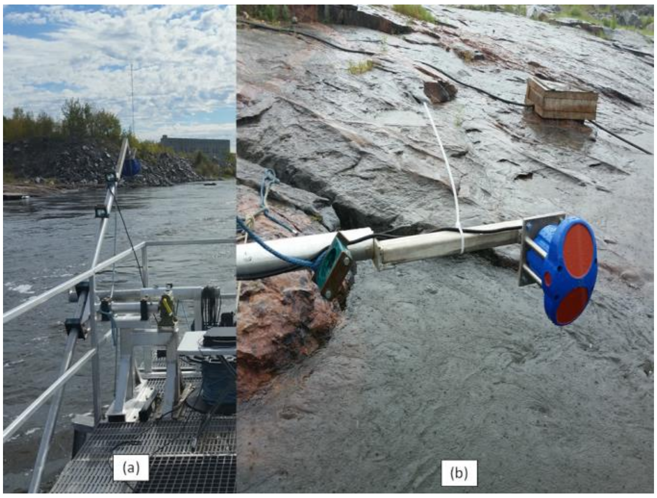

Figure 2 - (a) HADCP and custom mounting bracket designed by the CHTTC used to attach the device to the measurement arm on the blue pontoon, and (b) photo of the measurement arm on the blue pontoon taken during the testing

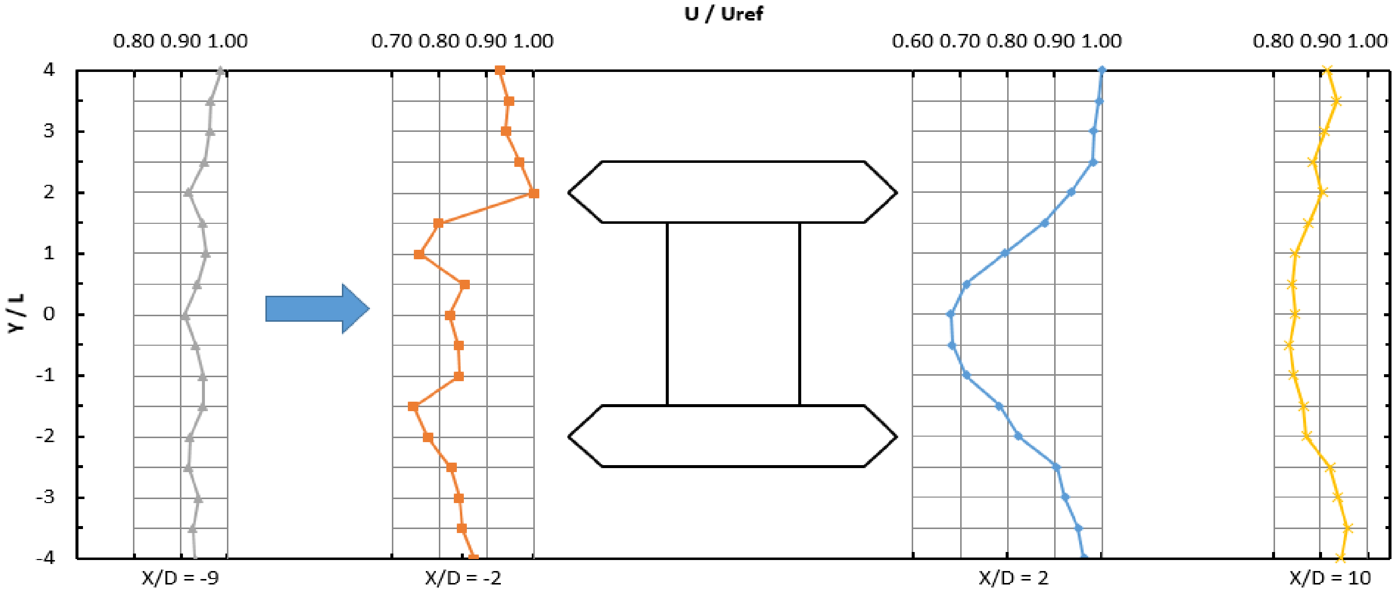

Figure 3 - Top down view of streamwise velocity profile across the turbine area

Around the turbine, the H-ADCP measures the velocity through 128 cells of size 0.5 m. For the farthest point (Run 10), the size is 0.75 m. This allows the HADCP to record valid data across the span of the river. As can be seen by examining Figure 3, the results around the turbine are divided into two parts: upstream and downstream. Distances are relative to the centre of the turbine, specified in number of diameters (X/D) away from the turbine, negative for upstream and positive for downstream. The flow upstream, X/D = -9, is impacted by the mooring system creating a decrease of 9% when compared to the free-stream velocity. This surface velocity defect can be attributed to the lines and buoys used to moor the turbine. Close to the turbine, for X/D = -2, a decrease in velocity varying between 15% and 25% is observed, however, the profile of the velocity defect resembles the outline of the pontoon structure, indicating the defect could be caused by the boundary layer formation around the turbine's pontoons.

Moving to downstream results, at X/D = 2, a decrease in velocity of 32% is recorded within the wake region, however, as the downstream distance increases the wake merges and mixes with the turbine river flow causing a diminution of the velocity defect. Finally, at X=D = 10, the velocity is still affected by the wake of the turbine, and reduced by 15% compared to the free stream velocity.

Erreur ! Source du renvoi introuvable. shows the evolution of the velocity profile behind the turbine at three depths, which are given in Table 1. At X/D = 2, the wake aligns with the center of the rotor, but as the distance from the center increases, the velocity begins to recover. This is explained by the fact that for Run 6, the HADCP is closer to the wake than for Run 5, which has an impact on the beam and the size of the cell is different which reduces the resolution. Table 2 shows a summary of the velocities surrounding the turbine.

Table 2 - Wake velocities around the turbine

Streamwise distance from turbine	U/U_∞
X/D = -9	0.91
X/D = -2	0.82
X/D = 2	0.68
X/D = 10	0.83
X/D = 13	0.95
X/D = 15	0.92
X/D = 17.5	0.91
X/D = 25	0.97

Figure 6 shows the flow measurements around the turbine taken during the month of September. Runs 1 to 4 are measured at X/D = -8 while the turbine is operating at varying Revolutions Per Minute (RPM). The upstream profiles are relatively stable, varying between 94% and 100% of the free-stream velocity. Any losses are explained by the mooring system. Run 5 is measured at X/D = 8 downstream of the turbine when the rotor is deployed 0.8 m below the surface and is operating at 50 RPM. The profile behind the turbine is expected and in agreement with expected results. The graph shows a velocity decrease of 43% at a distance of X/D = 8, and by comparing with data measured in July, it is increased from measurements at X/D = 2 (32% decrease in velocity) and X/D = 10 (17% decrease in velocity).

IV. CONCLUSION

Results show that flow measurements done with HADCP around the turbine are can be performed using the procedures developed at the CHTTC. The wake is

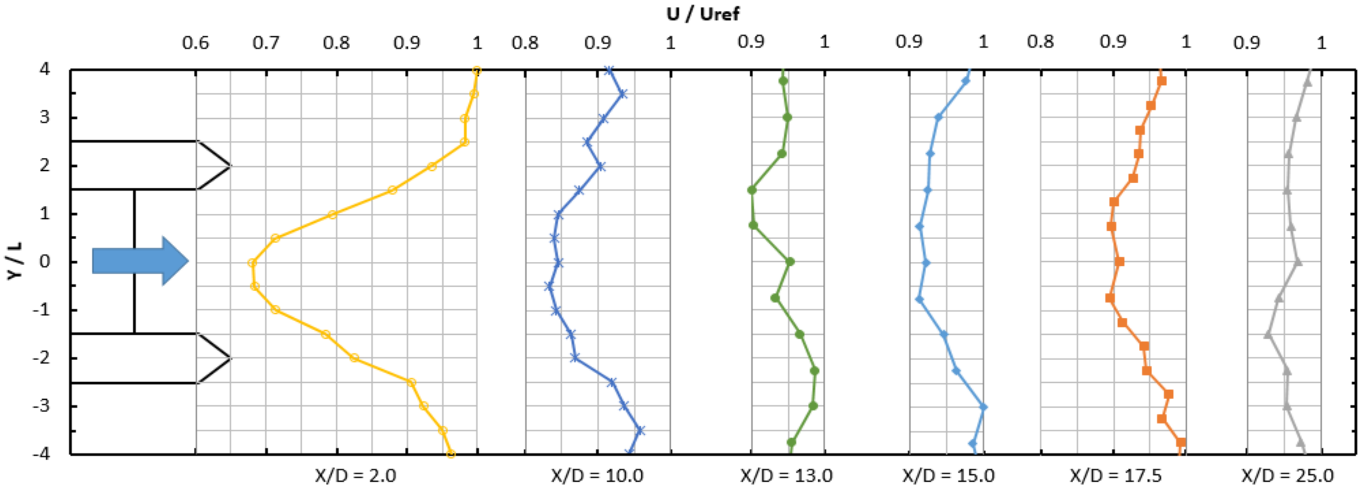

Figure 4 - Downstream measurements of the wake of a hydrokinetic turbine taken in July 2015

characterized for different configurations of the turbine, deployment depth and RPM. However, results can be less reliable if the inclination is significantly greater than 0°, which can be solved initially by ensuring the HADCP is mounted properly. Results confirm some hypotheses made for numerical and laboratory tests but also improve the parameters and conditions for the next numerical and laboratory simulations. Results show that the operating turbine can create a velocity deficit downstream, down to a minimum of 58%, while the turbine structure produces a minimum velocity of 68% of the free-stream velocity. The velocity defect is still observed at 10D downstream, however wakes are observed to recover to 90% of the free-stream velocity 13D downstream

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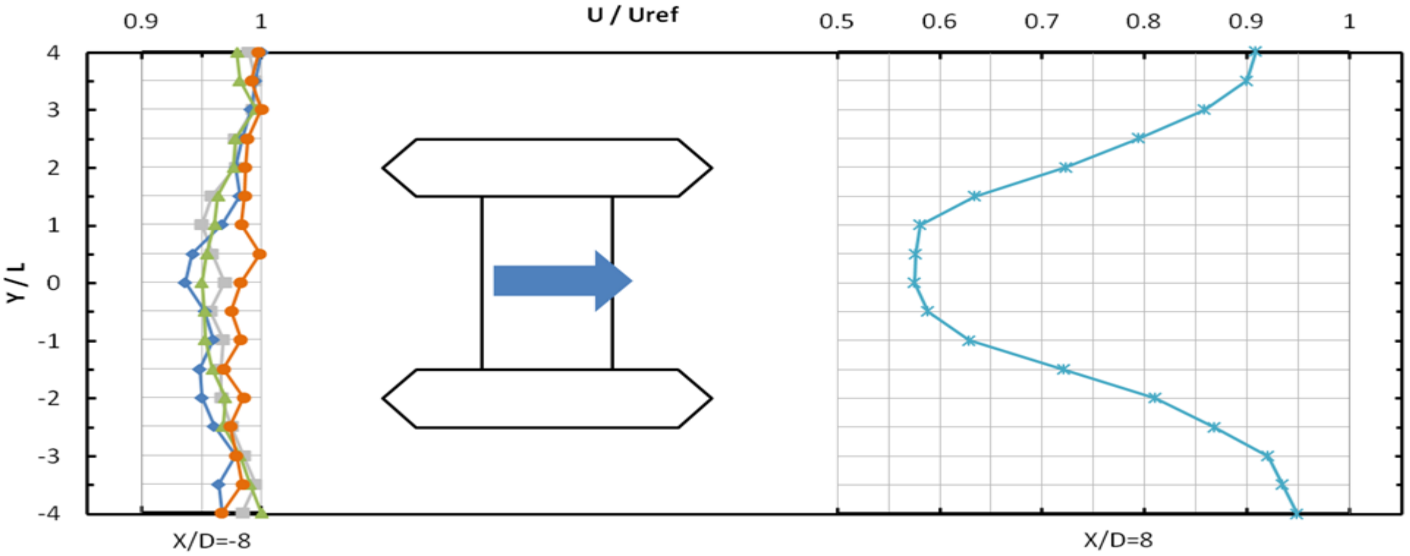

Figure 5 - Upstream and downstream profiles around the operating 22kW turbine taken in September

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