EMPIRICALLY DERIVED VELOCITY SCALES TO CHARACTERIZE NON-UNIFORM INLET FLOW TO A MARINE HYDROKINETIC TURBINE

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INTRODUCTION

This article addresses the question: to what degree is there a practical basis for comparison of marine hydrokinetic turbine performance when a turbine operates in a non-uniform flow? In other words, what is the basis for relating the off-design behavior to on-design behavior due to non-uniform inflow?

Performance comparisons typically use non-dimensional parameters such as power coefficient. These parameters require scales which characterize the flow speed and geometry in a meaningful manner. Can a single scale be developed which captures the effect of inflow non-uniformity on turbine behavior? A previous study [1], has used computer simulations to show that, for tidal turbines operating in a non-uniform flow, a meaningful comparison can be made between performance in uniform and non-uniform flows if the volume-averaged velocity across the face of the turbine is used as a scale. Additionally in the experimental portion of the previous study, a depth averaged velocity across the vertical diameter of the turbine was shown to yield meaningful comparisons, when the inflow variation was significant only in the vertical direction. Often, in large turbine arrays, inflow to a particular turbine is affected in a far more complex manner when the turbine operates in the wakes of turbines upstream. Similar study on cross-flow turbines, demonstrated that reference velocity representative of the flow across the turbine can be calculated by using a spatial average across the turbine swept area assuming that vertical shear is negligible, [2]. This paper focuses on the definition of a single velocity scale that best captures the effect of a non-uniform inflow on a turbine. To study the effect of a non-uniform flow on the performance of a turbine, a laboratory experiment using two identical turbines in tandem configuration was conducted, with one turbine operating in the wake of a second, upstream turbine. The degree of inflow non-uniformity is varied with separation distance between the two turbines. In previous studies [1, 2], a wake generating device was not present. With a wake generating device (ex. rotating turbine) the assumption that the velocities do not change in the horizontal direction, is invalid. For this case, a better approach for determining the reference velocity was proposed by McNaughton [3], in which the integral of the velocity of the rotor swept area is considered.

Wake velocity measurements characterize the non-uniform inflow to the downstream turbine. Several schemes for developing a single inflow velocity scale are explored.

Characterizing non-uniform velocity distribution with a single scale

Based on wake velocity measurements four different velocity scales were identified and defined as follow:

Freestream

This velocity scale uses incoming freestream velocity upstream of the turbine to represent the flow that the turbine sees. This velocity scale is not a good representation because it does not take into account the non-uniformity.

Channel-Width-Averaged

This velocity scale is calculated by averaging measured velocity points across channel width in which the turbine was placed. This velocity scale only uses transverse velocity profiles. Comparing to the freestream velocity scale, channel width averaged is a better option because it takes into account the non-uniform flow but it also takes into account some velocity points that are outside the swept area of the turbine. Due to flow acceleration around the turbine the average velocity was shown to be higher than freestream which makes this velocity scale not a good representation of the flow that the turbine sees.

Actuator Disk Averaged

This velocity scale is similar to the previously explained velocity scale but the length across which the velocities are averaged is smaller. This velocity scale is calculated by averaging measured velocity points across rotor diameter and it only uses transverse velocity profiles. This velocity scale better represents the flow that turbine sees because it only takes into account velocity points located inside the rotor area. It was shown that this average tends to increase as separation distance increases. This behavior can be explained by saying that the velocity deficit is higher closer to the wake generating device. As the velocity deficit decreases the average velocity across the blades increases.

Average Tip Speed

This velocity scale is calculated by averaging four velocity points located at the tip of the blades. Two points are taken from a transverse profile while two points were taken from a vertical profile. The motivation behind this velocity scale is that it uses velocity points from both transverse and vertical profiles but it is also driven by an assumption that most of the turbine torque is developed at the blade tips. Finally, due to smaller number of velocity measurements, time required to develop this velocity scale is much lower than for previous scales.

A graphical representation of these four velocity scales is shown in figure below.

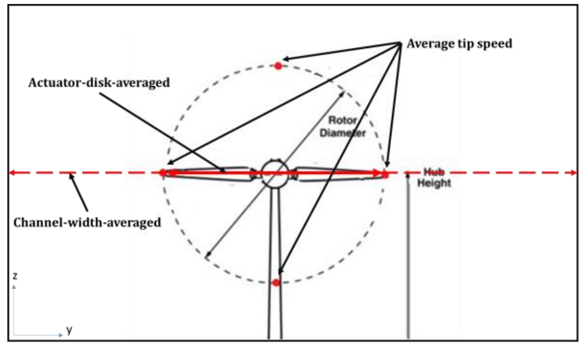

FIGURE 1. SCHEMATIC DIAGRAM OF FOUR VELOCITY SCALES

Methodology

Laboratory-scale Turbine

All experimental testing is performed using scaled model MHK turbines. The blades of the horizontal axis model turbine are taken directly from the Structural and Hydrodynamic Design Optimization Enhancements with Application to Marine Hydrokinetic Turbine Blades study [4]. The diameter, *D,* of the turbine blades is 102 mm. The turbine blade is unique and shaped after the National Renewable Energy laboratory (NREL) and Delft University family of foils. Specifically, the blade is created using three different foils: a DU91-W2-250, a NREL-S816, and a NREL-S817 airfoil. The optimized bounds for the foil locations were defined to be the Delft DU91-W2-250 at the root, the NREL-S816 at 70 to 80% span, and the NREL-S817 at the tip [4].

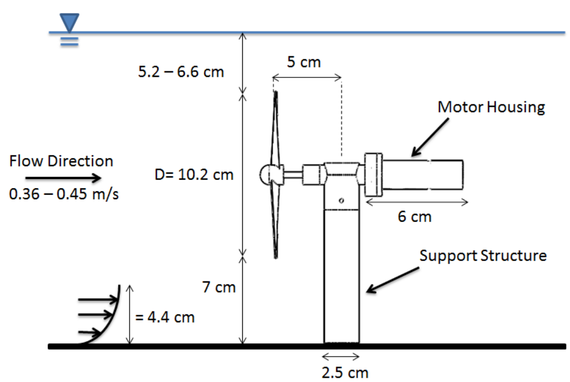

FIGURE 2. SIDE VIEW SCHEMATIC OF THE MARINE TURBINE ASSEMBLY INSTALLED IN THE TEST SECTION. DIAGRAM IS NOT TO SCALE

The turbine assembly is shown in Figure 2. The rotor shaft is connected to a DC motor with a flexible coupling system. The DC motor is held in a casing (referred to as the motor housing) which is co-stream-wisely aligned to the shaft to provide support and minimize friction. The turbine and all other components are supported by a cylindrical support structure and anchored to the bottom of

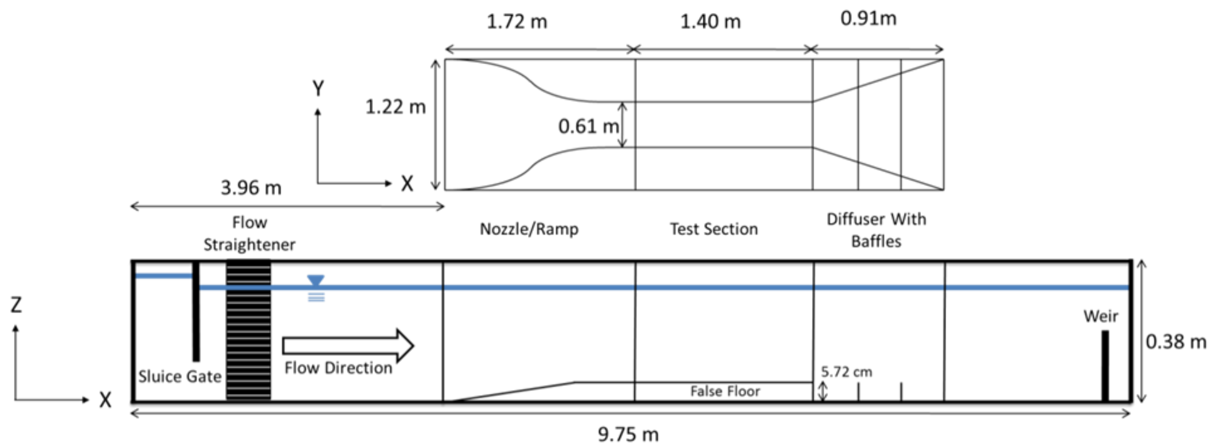

FIGURE 3. SCHEMATIC OF THE PLAN AND SIDE VIEW OF THE HYDRAULIC FLUME FACILITY [5]. THE X, Y AND Z DIRECTIONS REFER TO THE STREAM-WISE, TRANSVERSE, AND VERTICAL DIRECTION, RESPECTIVELY [7].

the channel. The motor housing has a diameter of 2 cm and is 6 cm long. The aspect ratio of the motor housing diameter to the rotor diameter is similar to other laboratory studies [5, 6]. The horizontal axis of the turbine shaft is held approximately 12 cm from the channel floor. The diameter and height of the support structure is maintained at 2.54 cm and 12.7 cm, respectively. The cylindrical support structure alone creates an estimated blockage ratio (occupied/flow area) of approximately 2.5%. The blockage ratio of the scaled model turbine assembly is approximately 7 % which lies within the accepted range for scaled laboratory studies.

Facility Description

All experiments were conducted in the small-scale testing platform in the Hydraulics Laboratory at Bucknell University. Flow control systems, such as the sluice gate and flow straightener are illustrated in Figure 2. The overall dimensions of the flume are 9.75 m long, 1.22m wide, and 0.38 m deep. These systems provide uniform and constant velocity profiles through the flume length which are necessary to ensure the repeatability of the experiments. The weir is located at the end of the flume and provides a suitable average flow depth of 22-24 cm, approximately 2.5 rotor diameters deep. The available testing area, shown in Figure 2, is 0.61 m wide and 1.40 m long. The flow is accelerated upstream using a nozzle insert that decreases the channel width from 1.22 m to 0.61 m. Flow rate in the flume is determined using a dial connected to the orifice plate and the instantaneous flow rate is displayed on a control panel. The pump has the capacity to operate between flow rates of 0 and 3.41 m^3/min, which correspond to a flow velocity range in the test section from 0 to 0.45 m/s. Previous experimental studies have determined that the transverse flow profile is uniform throughout the bare test section. The vertical boundary layer thickness ranges from 4.0 to 4.4 cm. Finally, the channel is kept level at all times to avoid a gravity driven flow.

Measured Quantities

The study focuses on characterizing the inflow velocity distribution to a turbine operating in a non-uniform flow. The flow velocity is measured using a laser-doppler velocimeter (LDV) which is mounted vertically above the free surface to a traverse system and positioned to measure the stream-wise velocity component of the flow. Velocity data is collected using a profile type acquisition mode. The precision for these measurements is ± 0.002 m/s which is equivalent to 0.5% of the free-stream velocity. The fringe separation for this specific probe is 5.08 μm while probe volume distance is 500 mm. Probe volume length is 1.2 mm.

Hydraulic Flume Experiments

When placed in a uniform flow, a power extracting device will alter the flow and create a 3-dimensional wake behind the rotor. It is essential to understand the behavior of the wake since this wake flow will be incident on the downstream turbine. The wake velocity of a single MHK device was measured using a uniform free-stream velocity of 0.42 m/s. This velocity is kept constant for all studies unless otherwise specified. Using the LDV setup, hub height, horizontal and vertical velocity profiles are measured downstream of the device. Specifically these profiles were measured at stream-wise locations ranging from x/D = -1 to x/D = 11 in constant increments of 1D. A total of 33 velocity points are taken from y/D = -2 to y/D = 2 at each stream-wise location. The hub-height location at which the transverse velocity profiles were measured is shown in Figure 4.

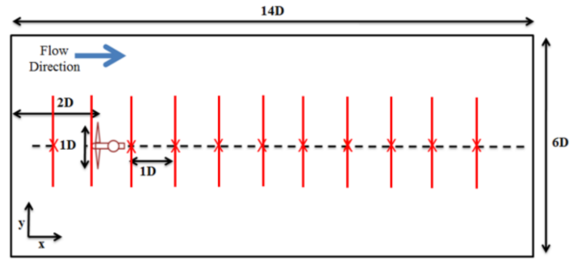

FIGURE 4. TRANSVERSE VELOCITY PROFILES TAKEN AT VARIOUS X/D LOCATIONS. ALL THE VALUES ARE NON-DIMENSIONALIZED BY THE TURBINE DIAMETER.

In vertical direction, the datum is situated along the false floor of the test section. This can be better visualized in Figure 5. A total of 28 points are taken for each vertical profile ranging from z/D = 0 to z/D = 1.85.

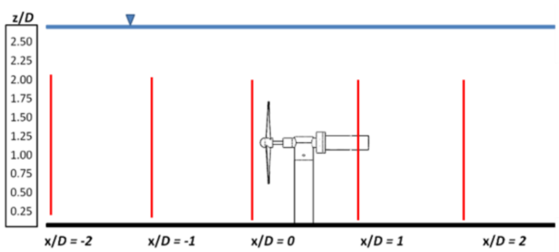

FIGURE 5. VERTICAL VELOCITY PROFILES TAKEN AT VARIOUS X/D LOCATIONS.

Results

At each stream-wise location, transverse wake profiles were divided into near wake and far wake velocity profiles for better representation. Figures 6-7 show these velocity profiles. Velocity profile of an incoming flow, upstream of the device is shown as well for comparison. All velocity values are time-averaged values and they were not normalized with freestream velocity of 0.42 m/s. Average velocity uncertainty was calculated to be ± 3.2%.

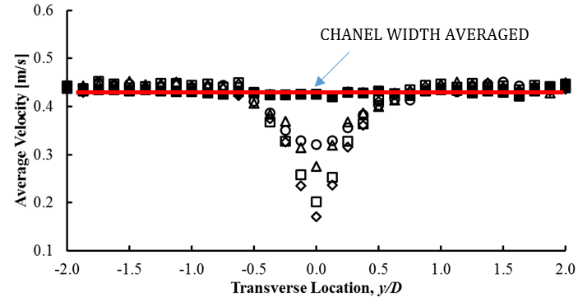

FIGURE 6. INCOMING AND NEAR WAKE TRANSVERSE VELOCITY PROFILES AT VARIOUS SPAN-WISE LOCATIONS (X/D): X/D = -2 (♦); X/D = -1 (■); X/D = 1 (◊); X/D = 2 (□); X/D = 3 (Δ); X/D = 4 (○)

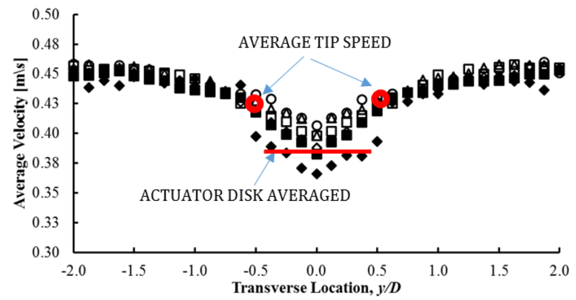

FIGURE 7. FAR WAKE TRANSVERSE VELOCITY PROFILES AT VARIOUS SPAN-WISE LOCATIONS (X/D): X/D = 5 (♦); X/D = 6 (■); X/D = 7 (◊); X/D = 8 (□); X/D = 9 (Δ); X/D = 10 (○)

Vertical velocity profiles were taken at the same stream-wise location as transverse profiles and presented in the similar fashion, Figures 8-9. All velocity values are time-averaged values and they were not normalized with freestream velocity 0.42 m/s. Average velocity uncertainty was calculated to be ± 3.1%.

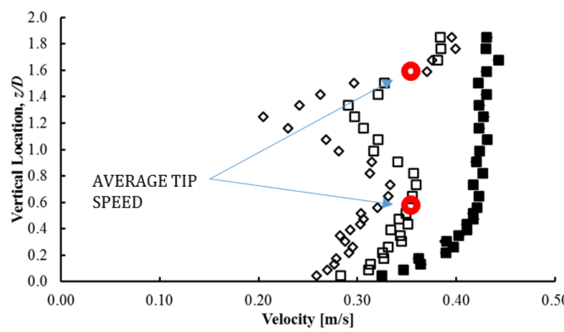

FIGURE 8. INCOMING AND NEAR WAKE VERTICAL VELOCITY PROFILES AT VARIOUS STREAM-WISE LOCATIONS (X/D): X/D = -2 (♦); X/D = -1 (■); X/D = 1 (◊); X/D = 2 (□)

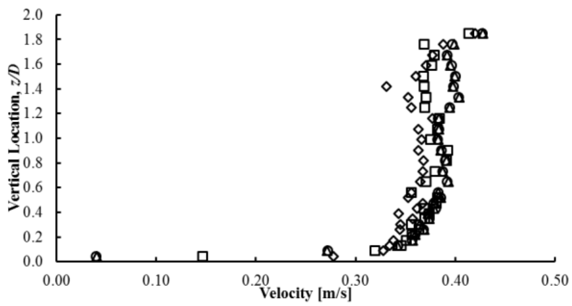

FIGURE 9. FAR WAKE VERTICAL VELOCITY PROFILES AT DIFFERENT STREAM-WISE LOCATIONS (X/D): X/D = 3 (◊); X/D = 4 (□); X/D = 5 (Δ); X/D = 6 (○). NOTE: PROFILES FOR STREAM-WISE LOCATIONS OF X/D=7, 8, 9 AND 10 ARE NOT SHOWN ON THIS PLOT

Figures 6 through 8 identify three different velocity scales. The fourth velocity scale is not shown on these plots.

Each velocity scale was calculated as a function of separation distance between two turbines, Figure 10.

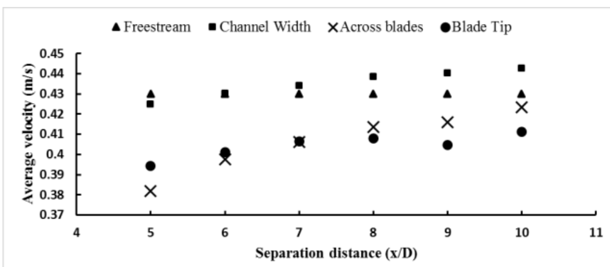

FIGURE 10. FOUR DIFFERENT VELOCITY SCALES FROM WAKE FLOW AS A FUNCTION OF SEPARATION DISTANCE.

SUMMARY

In order to determine to what degree is there a practical basis for comparison of a turbine performance when a turbine operates in a non-uniform flow, several velocity scales were defined and examined.

Four different velocity scales were defined as:

- Freestream
- Channel Width Averaged
- Actuator Disk Averaged
- Average Tip Speed

To study a non-uniform flow effects on a turbine, two identical turbines were used in tandem configuration, with a turbine operating in the wake of a turbine located directly upstream. Flow non-uniformity was varied by changing separation distance between two turbines.

A good representation of the non-uniform inflow to the turbine can be achieved using a channel width averaged velocity. However, the problems arises when the average velocity across channel width shows a higher value than freestream velocity due to flow acceleration around the turbine. Both actuator disk averaged and average tip speed scales provide a much better representation of the flow that the turbine sees. The question here is which one of these velocity scales is actually better? Comparing these two velocity scales we can see that actuator disk averaged does not take into account vertical velocity profiles while average tip speed uses both transverse and vertical velocity points. An assumption made earlier that says that most of the shaft torque is located at the tips of the blade, supports the statements that average tip speed velocity scale can be used as a good representative of the non-uniform flow that the turbine sees. Additionally, the time required to collect velocity measurements across the horizontal diameter of the turbine is much greater than the time needed to measure the velocities at the tip of the blades.
The next steps in this study is to analyze the effects these velocity scales will have on the performance curves of the device operating in the wake flow.

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