Interactions between turbulent open channel flow, power and the wake of an axial-flow marine turbine

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I. Introduction

Until recently, an understanding of the range of scales of turbulent flow and its dynamic interaction with the performance and wake characteristics of axial-flow marine hydrokinetic turbines was lacking. Advancing this area of knowledge within the field of marine and hydrokinetic energy research, development, and deployment will lead to more efficient turbine operations and reduced cost of energy. Laboratory experiments were carried out at St. Anthony Falls Laboratory (SAFL) at the University of Minnesota (UMN) to a) investigate the performance and wake characteristics in a nearly fully developed turbulent open-channel flow, and b) study the effect of energetic coherent motions on the performance and wake characteristics of a model axial-flow hydrokinetic turbine. The measurements provide novel insights into the interaction of the surrounding turbulent environment and turbine power characteristics, details on near- and far-field wake characteristics, and the role of strong energetic coherent motions on turbine power fluctuations, tip vortex stability, and mean flow recovery in the turbine wake. Implications of these findings can be directly applied towards the efficient operation of hydrokinetic turbines in natural waterways.

II. Experimental setup

The SAFL open-channel test facility was used to evaluate the performance and wake characteristics of a scaled model hydrokinetic turbine. The channel is approximately 2.75m wide, 1.8m deep, and 85m long with a constant longitudinal slope of 0.17% and draws water directly from the Mississippi River allowing for prolonged measurement campaigns at relatively high and constant velocities. A computer-controlled three-axis automated data acquisition (DAQ) carriage spans the channel and is used to position a variety of instruments throughout the channel. A 1:10 scale axial-flow hydrokinetic turbine model instrumented to provide high-resolution measurements of turbine power was positioned in the center of the flume (Figures 1 and 2). The model turbine has a rotor diameter, d_T = 0.5m, and hub height of 0.85d_T. Two complementary in-depth experiments were performed. The first one provided performance measurements of the turbine at a range of tip-speed ratios (λ) in fully-developed turbulent open-channel flow. Additionally, high spatially resolved velocity measurements both upstream and downstream of the turbine provided insights into turbine wake characteristics, as well as a robust dataset for computational model validation. A Nortek Vectrino velocimeter collected vertical velocity profile measurements at 200Hz from -2d_T to 15d_T at 1d_T spacing. Vertical sampling spatial resolution was 0.025m. Both experiments were completed with a flow depth of 1.15m, a cross-sectional flow rate of 1.265m^3s^{-1}, resulting in a Froude number of Fr = 0.12 and a Reynolds number of Re = 1.7 x 10^5 based on the turbine diameter. During the detailed velocity measurements, the turbine operated at its maximum efficiency, $C_P \approx 0.47$.

The second experiment investigated further the effects of energetic coherent motions on turbine power and wake characteristics. For these experiments, a series of cylindrical piers were placed at several locations upstream of the turbine (Fig. 2). Synchronous velocity and power measurements provide insight into the complex interactions occurring between scales of turbulent motions in the approach flow and turbine power characteristics. Cylinder diameters were chosen to specifically introduce von Karman-like vortices that would impact the model turbine in different ways. For example, the largest cylinder impacted the entire energy extraction plane of the turbine, while the smallest cylinder introduced turbulent frequencies nearly coincident with the rotational frequency of the turbine (f_T = 1.5Hz). During this experiment, synchronous velocity measurements were collected at hub height at $1d_T$ spacing up to $10d_T$ downstream of the turbine. These measurements provided a representative look into wake recovery characteristics under various turbulent approach environments.

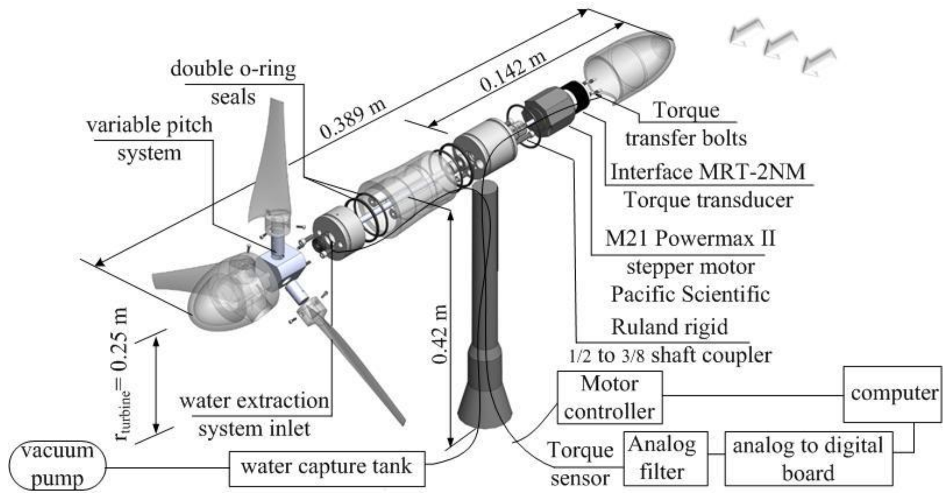

Figure 1: The 1:10 scale axial-flow model turbine.

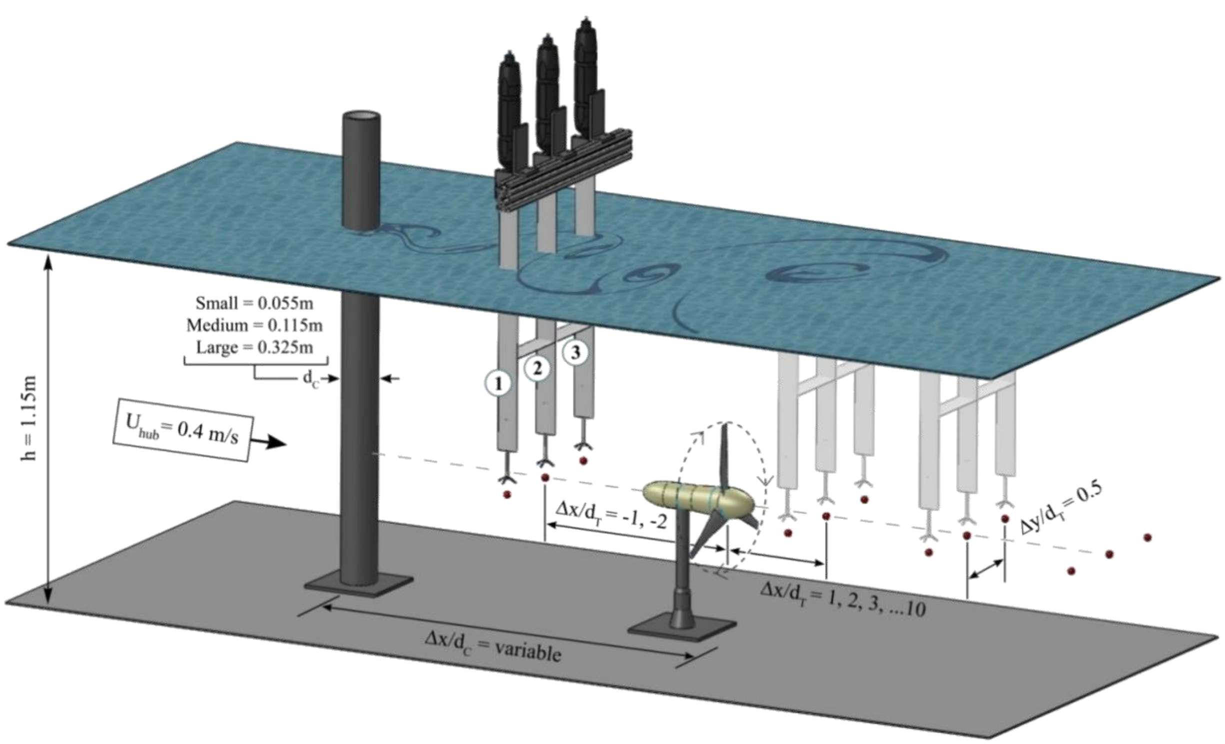

Figure 2: Experimental setup in the SAFL Main Channel. The cylinder upstream of the turbine was only used in the study on effects of energetic coherent motions (experiment 2). ADV measurements were collected upstream and downstream of the turbine and synchronized with turbine power measurements. Flow is left to right.

III. Results

Results from these two experiments provided significant insights on the effects of the flow turbulence on the turbine and its wake, which can be summarized as follows: a) the smallest scales of the turbulence affecting the power output depend on the turbine operation, b) turbine power is strongly modulated by turbulence scales in the approach flow environment, c) energetic coherent motions are able to destabilize the tip vortices, and d) based on these three previous findings, site specific turbulence scale characterization plays a central role in understanding the short and long term turbine performance.

Detailed vertical velocity profile measurements throughout the wake of the turbine illustrate the complex and energetic regions in the near- and far-field environments (Figure 3). Wake rotation persists for a few rotor diameters downstream before the highly turbulent and coherent tip vortex structures destabilize and allow for wake mixing with the surrounding ambient flow environment. Despite rapid near-field velocity deficit recovery, downstream flow conditions remain altered by the presence of the turbine beyond $15d_T$. This has direct implications for device spacing in arrays of similar devices.

Additionally, results from the second experiment focusing on investigating the impacts of energetic coherent motions on the power and wake dynamics provide important findings that are applicable to turbine development. Depending on the size of the perturbations introduced upstream of the turbine, a range of scales of turbulence and corresponding range of scales of power fluctuations in the turbine were modified. The large cylinder impacted a broad range (Fig. 4), whereas the smallest cylinder had only local, yet still persistent, modulation on the turbine power characteristics. Given that these devices are inherently installed in environments where a range of energetic turbulent scales are present, understanding and providing proper pre-installation site assessment is an important consideration and result of this work.

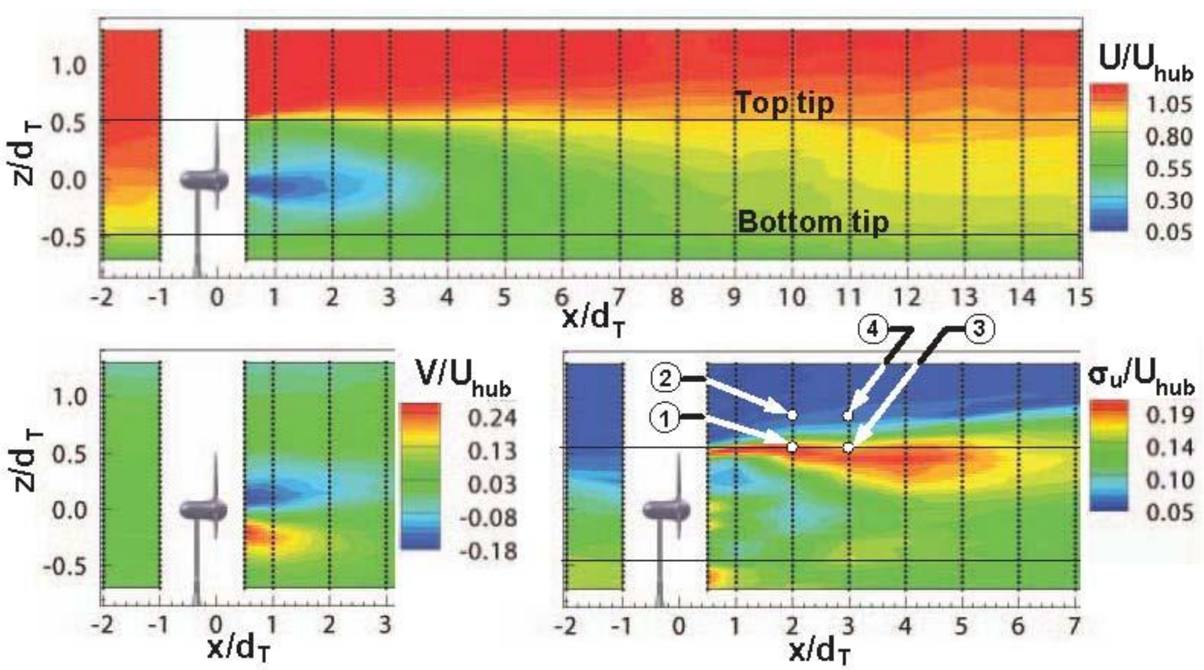

Figure 3: Streamwise (top), and spanwise (bottom left) velocities and turbulence intensity in the symmetry plane for $\lambda = 5.8$. For clarity, the vertical scale is distorted by a factor of two. Vertical lines identify the locations of measurements. Horizontal lines mark the location of the turbine top and bottom tips.

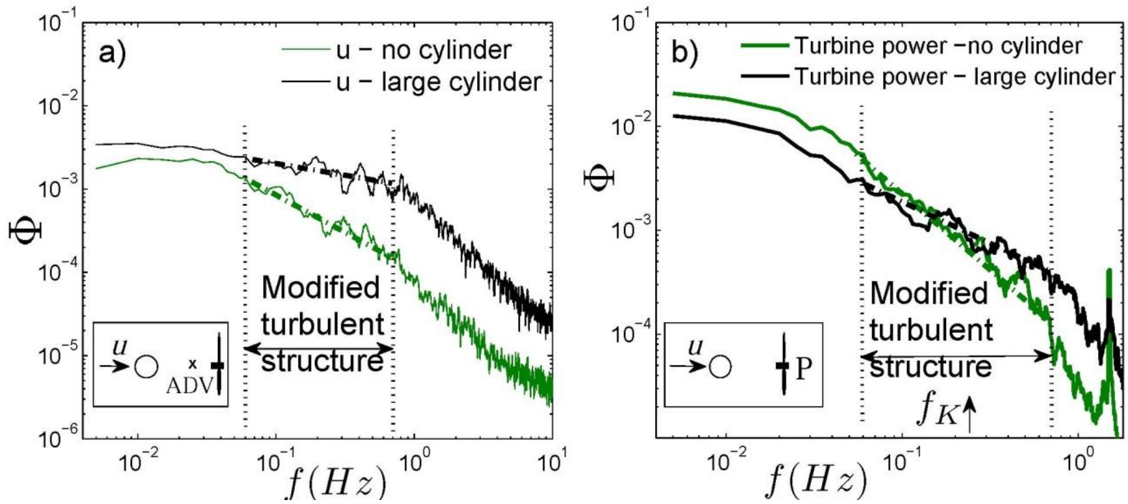

Figure 4: Influence of large-scale energetic coherent motions on approach flow turbulence and turbine power characteristics. a) Spectrum of the approach flow (*u*-velocity) at one rotor diameter, d_T, upstream of the turbine; b) Spectrum of the turbine power.

IV. References

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