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Near and far field flow disturbances induced by model hydrokinetic turbine: ADV and ADP comparison

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ABSTRACT

Wake flows downstream of hydrokinetic turbines are characterized by hub and tip vortices, a velocity deficit and an increase in turbulence intensity. Velocity and turbulence recovery in the wakes of individual turbines constrains the density of turbines in an array and limits the amount of energy that can be produced by a turbine farm. However, few hydrokinetic turbine flow recovery studies have been conducted, especially on the far-field flow characteristics. Nor have studies evaluated the accuracy of acoustic Doppler profiler measurements in the wakes of turbines. The present study examines vertical profiles of mean velocity and turbulence, as well as longitudinal profiles of velocity deficit and turbulence levels measured at the symmetry plane of a model three-blade axial flow turbine in a large open channel flow. Mean velocity and turbulence statistics are measured using an acoustic Doppler velocimeter (ADV) and a pulse coherent acoustic Doppler profiler (ADP). ADV and corrected-ADP derived values of mean velocity, turbulence intensity and root-mean-square velocity constitute a well-documented data set that can be used to validate numerical models simulating the effects of hydrokinetic turbine arrays. We found that 80% of the flow recovery occurred about ten diameters downstream from the rotor plane, which suggests that practical values for longitudinal spacing of turbines should be between ten and fifteen diameters. Significant errors observed in mean velocity and turbulence statistics derived from ADP measurements in the near wake region raise concerns on the use of these instruments for such measurements in lab and field studies. Although the cause of some of the errors requires further investigation, we show that errors in turbulence intensity can be successfully corrected with supplemental ADV measurements.

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1. Introduction

Wake flows downstream of hydrokinetic turbines, like wind turbines, are characterized by hub and tip vortices, a velocity deficit and an increase in turbulence intensity, among other flow features. These flow alterations affect the unsteady loading and available hydrokinetic power on downstream turbines in arrays. As a result, wake flow recovery is a major determinant in selecting array layout and spacing in water turbine farms to optimize annual energy production and the cost of energy. Numerical models used to examine the effects of tidal energy extraction and wake flow recovery are reviewed by Yang et al. [1]. These models can be used to evaluate far-field effects, such as flushing time in a tidal bay or to optimize turbine spacing in arrays, but measurements are needed for model validation.

Thus far measurements of wake velocity and turbulence have included scaled model experiments with turbine wake effects simulated with porous actuator disks [2–4] and scaled model turbines [5,6]. Both approaches can provide the measurements required for validating numerical models, but the variables needed to simulate the experimental conditions need to be clearly specified. The longitudinal variation of the centerline (hub height) velocity deficits, which are commonly used to evaluate flow recovery, have been widely reported [2,3,5,6]. Vertical velocity profiles are available [2,4,5]. Turbulence measurements have only been reported in Refs. [3,6], including vertical profiles of Reynolds stress (turbulent shear) and turbulent kinetic energy (TKE) at selected sections [3], and analysis on the flow and structure interactions [6].

Our aim in the present study is to report profiles of streamwise mean velocity, root-mean-square velocity (σ_u), and turbulence intensity ($I_{\overline{u}} = \sigma_u/\overline{u}$) derived from instantaneous velocity

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measurements using an acoustic Doppler velocimeter (ADV) and pulse coherent acoustic Doppler profiler (ADP) in the wake of a 1:10 scale axial flow turbine in a large open channel flume. The comparison of high fidelity ADV measurements with those from the ADP provides a unique opportunity to evaluate ADP measurement error. Although the ADV measurements are reported only for one test case, they provide a comprehensive data set for validating near- and far-field models for simulating the effects of an individual turbine on the flow field. When paired with corrected ADP measurements, they extend flow recovery measurements to $35d_T$ downstream of the turbine.

2. Methods

Measurements were collected in the St. Anthony Falls Laboratory (SAFL) Main Channel at the University of Minnesota, which is 2.75 m wide, 1.8 m deep and 85 m long, has a longitudinal slope of 0.17% and smooth concrete for bed and wall surfaces. As shown in Fig. 1a, a 1:10 scale three-blade axial flow turbine, with a 0.5 m rotor diameter (d_T) and a hub height (z_{hub}) of 0.425 m was mounted to the floor in the center of the channel approximately 40 m (80 d_T) downstream of flow straighteners. The top of the rotor was submerged $1d_T$ below the water surface. Details of the turbine hardware and controls are provided in Ref. [6]. Experimental variables identified as main drivers of wake flow structure and wake recovery [3] were set as follows: For inflow conditions the test flow rate (Q) was 1.265 m^3/s and the flow depth (h) was 1.15 m; resulting in a bulk velocity $\overline{(U)}$ of 0.40 m/s, Reynolds number (R) of 4.6×10^5, and Froude number (F) of 0.12. At the modeled turbine centerline (hub height) $2d_T$ upstream of the rotor plane the mean velocity $\overline{u_h}$ was 0.42 m/s, the root-mean-square velocity (σ_{u_h}) was 0.04 m/s, and turbulence intensity ($I_{u_h} = \sigma_u/\overline{u_h}$) was 0.098.

The scaled model turbine was set to operate at 90 RPM and a tip speed ratio (TSR) of 5.8, which generated a measured torque of 0.346 N-m and resulted in the maximum power coefficient (C_p) of 0.48. The value for the thrust coefficient (C_t) was 0.52 and was estimated indirectly by calculating the axial induction factor (a) from the power coefficient, where $C_p = 4a(1-a)^2$, and then substituting into the expression $C_t = 4a(1-a)$ [7]. The ratio of the turbine diameter to flow depth (d_T/h) was 0.43, the ratio of hub depth to flow depth (submergence ratio) (h_{hub}/h) was 0.63, and the ratio of hub height to flow depth (z_{hub}/h) was 0.37. The blockage ratio, defined as the ratio of the projected area of the disk or turbine to the flow section area, (A_d/A) was only 0.062. The ratio of the rotor diameter to the channel width (d_T/b) was only 0.18. Therefore, blockage and wall effects were negligible.

The flow rate was monitored using a Massa ultrasonic range sensor mounted upstream of a sharp-crested weir tailgate that was used to control flow depth. All three components of the instantaneous velocity were measured using a Nortek Vectrino ADV and a three-beam Sontek pulse coherent ADP. Both instruments were mounted downward-looking from the SAFL Main Channel data acquisition (DAQ) carriage to collect vertical velocity profile measurements along the turbine centerline (Fig. 1). Mean flow statistics along the centerline plane from upstream to downstream of the turbine were collected between $x/d_T = (-2, 15)$ at a spacing of $1d_T$ for the ADV profiles. For the ADP profiles, measurements upstream of the turbine were collected at $x/d_T = -10, -5, -3$ and -1. ADP measurements downstream were collected between $x/d_T = (1, 20)$ at a spacing of $1d_T$, and at $x/d_T = 25$, 30, and 35. Data were collected for 240 s at each location with the ADV sampling rate set at 200 Hz and at least 300 s for each profile with the ADP sampling rate set at 1 Hz. The ADP was operated with a vertical resolution of 1.6 cm and the centerline of the first cell starting at a depth of 12 cm below the water surface. The DAQ allowed automated positioning of the ADV and ADP along longitudinal axis with sub-cm accuracy. Instantaneous velocity measurements collected with the ADV and ADP were post-processed using methods described in Refs. [8,9], including despiking and replacement.

3. Results

3.1. Centerline vertical profiles

Vertical profiles along the rotor centerline of streamwise mean velocity ($\overline{u}$), streamwise root-mean-square velocity, or standard deviation, (σ_u), and streamwise turbulence intensity ($I_{\overline{u}} = \sigma_u/\overline{u}$),

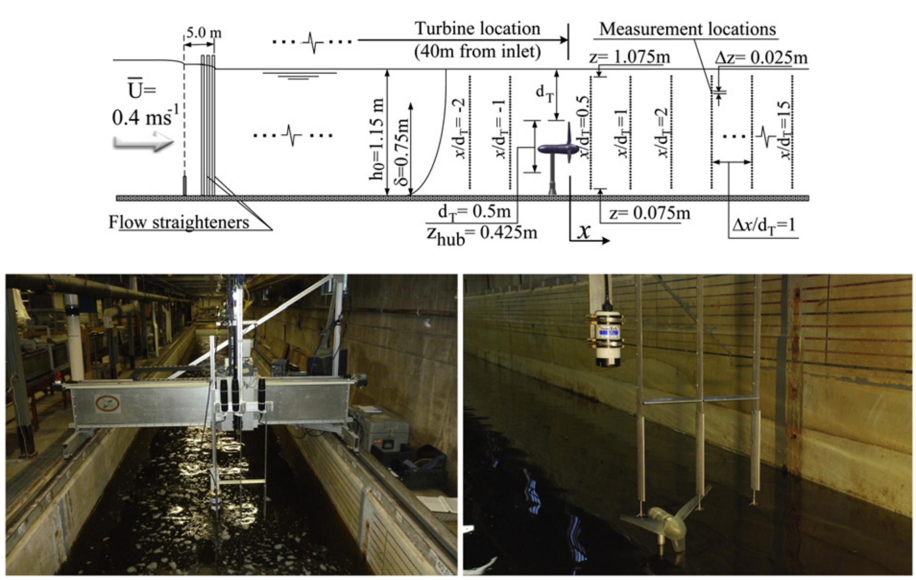

Fig. 1. Clockwise from top to bottom: Experimental set up and measurement locations [6]; Photo looking upstream showing model turbine, three-ADV array and ADP; and Photo looking upstream showing instruments mounted to traverse.