Experimental Test Plan – DOE Tidal And River Reference Turbines

August 2012

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DOCUMENT AVAILABILITY

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TABLE OF CONTENTS

1. INTRODUCTION

Sandia National Laboratory (SNL) developed reference tidal and river turbines illustrated in Fig. 1 to develop and refine design tools, allow accurate estimates of levelized cost of energy (LCOE), and provide testing data that can be made publicly available to the MHK industry. More details on the reference modeling effort are provided in Previsic and Jepsen (2011).

Scaled model studies of the reference tidal (axial-flow) turbine, and the reference river (cross-flow) turbine are needed to provide detailed flow field measurements around the device, while simultaneously collecting information on the MHK machine loading and performance. Dimensional analysis provides scaling laws that are used to upscale model test information into performance and design information for a full-scale prototype turbine. For water turbines, hydrodynamic similitude is achieved when the chord Reynolds number (R_c), Froude number (F), and the tip speed ratio (TSR) of the model and the full-scale device are the same. It is rare to achieve perfect similitude for R_c, but a threshold value should be exceeded. Boundary layer trips or long flumes should be employed to ensure the flow is fully turbulent and simulates the essential physics of flow-machine interaction. Froude number similitude in open channel testing is usually met and is particularly important for upscaling wake flow data. As indicated by Neary and Sale (2010), the inflow characteristics of natural rivers, tidal channels and open channel flumes, including vertical profiles of mean velocity, turbulence intensity and Reynolds normal stresses, are similar, and generally well represented by flat-plate boundary layer theory.

This report provides details of the experimental test plan for scaled model studies in St. Anthony Falls Laboratory (SAFL) Main Channel at the University of Minnesota, including a review of study objectives, descriptions of the turbine models, the experimental set-up, instrumentation details, instrument measurement uncertainty, anticipated experimental test cases, post-processing methods, and data archiving for model developers.

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2. STUDY OBJECTIVES

Our aim is to collect model validation data for turbine design models, e.g. FAST and CACTUS, as well as advanced computational fluid dynamics (CFD) models that can resolve the near- and far-field flow effects of turbines, including wake velocity deficit, wake turbulence and wake recovery. CFD models used for studying near-field hydrodynamic effects of turbines include numerical models developed using STAR CCM+, such as those used to simulate the stresses on the blades of DOE's reference tidal turbine (Lawson and Thresher 2012), and numerical models, such as SNLEFDC, which simulate far-field effects of water turbine arrays, including the effects of energy extraction and wake flow recovery (James et al. 2012). Specific objectives include designing and constructing a scaled model for each reference turbine, measuring performance characteristics, which requires simultaneous measurements of available hydrokinetic power measured at the hub height upstream of each rotor, and the torque and rpm of each rotor, and measuring the near- and far-field instantaneous velocity around each turbine model using ORNL's synchronized three acoustic Doppler velocimeter (ADV) array and SAFL's pulse-coherent acoustic Doppler profiler (ADP). These instantaneous velocity measurements will be post-processed using methods described by Gunawan et al. (2011) and Gunawan and Neary (2011) to extract flow field information that includes the mean velocity, turbulence intensity and Reynolds stresses, turbulent kinetic energy (TKE), velocity spectra, and spectral coherence. Finally, the post-processed data will be archived and disseminated to model developers for model validation.

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3. REFERENCE TURBINE MODELS

Reference turbine model design drawings, specifications and instrument requirements are shown in Figs. 2 and 3. Both models include all the major components of the reference turbines, including the deployment structure, e.g. tower or pontoons, dual rotors, rotor supports and nacelles. The reference tidal turbine model is 1:40 scale, but the rotor nacelles are larger, and not exactly to scale, to accommodate the instrumentation package for collecting instantaneous RPM and torque measurements. This deviation from exact geometric similitude, along with other scaling limitations, needs to be considered when interpreting upscaled results. Also, the model validation step will require that modelers "model the model," and not the prototype. The rotor diameter is 0.5 m. Rotor spacing is 0.7 m, hub height is 0.5 m, and the submerged depth is 0.5 m in a flow depth that will be set to approximately 1 m. The reference river turbine model is 1:15 scale. Rotor shafts, unlike the full-scale prototype will be attached to the channel bed, but the bearing friction will only slightly reduce the torque. Nevertheless, torque measurements will be collected for each bearing to quantify this contribution. The rotor diameter is 0.43 m. Rotor spacing is 0.645 m, hub height is 0.646 m, and the submerged depth is 0.323 m in a flow depth of 1 m. The tidal turbine model will block 14% of the flow in the channel. The river turbine model will block 10% of the flow in the channel. Materials used to construct each model will include a combination of stainless steel, aluminum, and Somos Watershed 11122 reinforced resin. The blades for each turbine will be fabricated with aluminum or Somos Watershed 11122 reinforced resin, or its equivalent, depending on the amount of blade deflection observed. Instrumentation for the model turbines is detailed below.

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4. EXPERIMENTAL SET UP & METHODS

All experiments will be conducted in the SAFL Main Channel, shown in Fig. 4a, which is 2.75 m wide, 1.8 m deep, and 85 m long. The flow rate is monitored using a Massa ultrasonic range sensor mounted upstream of a sharp-crested weir tailgate. The turbine models will be mounted to the floor in the center of the channel approximately 40 m (80 diameters) downstream of flow straighteners. For the experiments, the flow depth will be set at 1.0 m and flow rates will be set to provide a bulk velocity for all tests of 1.0 m/s for performance tests and detailed model validation measurements, including near- and far-field wake measurements at the maximum power coefficient for each turbine. The Froude number will govern upscaling for interpretation of wake flow effects (Froude number similitude). Blade chord Reynolds numbers number (R_c) for each turbine model will be roughly one order of magnitude lower than expected in the field, and well within the turbulent flow regime, 9.1E4 and 1.3E5 for the tidal and river turbine model testing, respectively.

Experimental Reynolds numbers based on the inflow velocity and rotor diameters will also be about an order of magnitude lower for the model compared to the full-scale prototype. Given the definition for the full-scale Reynolds number,

$$R_p = \frac{U_p L_p}{\nu}$$

where Up is the full-scale velocity, Lp is the full-scale turbine length scale (in this case, blade chord length), and ν is the kinematic viscosity of water, approximately 1×10^{-6} m^2/s and the model-scale Reynolds number,

$$R_m = \frac{U_m L_m}{\nu}$$

where Um is the model scale velocity, Lm is the model scale turbine length scale; The relationship between the full-scale Reynolds number and the model scale Reynolds number is,

$$\frac{R_m}{R_p} = \frac{U_m L_m}{U_p L_p}$$

For the tidal turbine $Up \approx 2$ m/s at the most efficient operating condition. Given the geometric scaling is 1:40, $Lp = 40$ and $Lm = 1$, a subcritical test velocity of $Um = 1.0$ m/s, we will produce Reynolds numbers up to 1/80th of full-scale Reynolds numbers, Rp. Similar calculations performed for the river turbine using values of Up = 3m/s and Lp = 15 given the proposed 1:15 geometric scaling experiments indicate the ability to produce Reynolds numbers up to 1/45th of the full-scale counterpart.

Reynolds Dependency Study
The Reynolds number is an important parameter for determining the local dynamics on the turbine, such as the device power and thrust. As indicated by Chamorro et al (2011) for wind turbine flows, flow characteristics in the wake of turbines reach Reynolds number independence at relatively low Reynolds numbers (Re, based on the rotor diameter of $9.38E10^4$). The effect of Reynolds number on the mechanical performance of the device, such as power and thrust coefficients, will be systematically investigated

before conducting further experiments. Experiments over a range of Reynolds numbers (up to the maximum allowed in our facility) will be conducted to document the variation of device power and thrust on Reynolds number. SAFL will also leverage the results of ongoing CFD work for the Verdant Power turbine, which include CFD simulations for the complete turbine at full-scale conditions, to examine the sensitivity of device performance on Reynolds number. In a complementary effort, SAFL will examine the dynamic performance of the turbine blade by performing XFOIL simulations to further examine the lift and drag aerodynamic properties with respect to Reynolds number. Therefore, the comprehensive research approach we propose will enable us to systematically investigate Reynolds number effects and extrapolate potential effects at full scale.

Instantaneous Three-component Velocity Measurements

Instantaneous three-component velocity measurements will be collected using ORNL's 3-synchnonized Nortek Vectrino ADV array, and SAFL's Sontek pulse coherent acoustic Doppler profiler (ADP). Both instruments will be mounted from the SAFL Main Channel data acquisition (DAQ) carriage shown in Fig. 4b. The ADVs, shown in Fig. 5, and the ADP, shown in Fig. 6, will be positioned downward-looking. Multiple point and vertical profile instantaneous velocity measurements around the model turbines will be collected as illustrated in Fig. 6a. Mean flow statistics, described below, will be determined along the centerline plane and vertical planes aligned with the rotor hubs at $x/D_t = $ -10, -5, -3, -2, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30, and 35, where $x/D_t = 0$ corresponds with the rotor plane, for the tidal turbine, and the centerline of the vertical shaft of the river turbine rotor. The ADV array will be used to collect high resolution vertical profiles of instantaneous velocity from 1 to 10 rotor diameters downstream of the turbine rotor plane, and from 1 to 3 diameters upstream. Vertical profiles will consist of approximately 30 to 40 sample locations. An additional vertical profile will be collected 5 to 10 diameters upstream to document fully developed flow entering the turbine test section. Lower resolution velocity profiles will be obtained beyond 10 diameters downstream using the ADP as illustrated in Fig. 6b.

ADV and ADP measurements will be collected using practices and protocols detailed in Gunawan et al. (2011) and Gunawan and Neary (2011). Based on previous experience, it is expected measurements will be collected for 300 s at each location with ADV and ADP sampling rates at 200 Hz and 1 Hz, respectively. ADV-1 and ADV-3 will be aligned with the hub centerline of each rotor. ADV-2 will be located at the midpoint between the two rotors. The nominal velocity range for the Nortek Vectrinos will be adjusted based on preliminary measurements around the model turbines. The ADP will be operated with a vertical resolution of 1.6 cm and the centerline of the first cell starting at a depth of 12 cm. The DAQ will allow automated positioning of the ADVs and ADP to sub-cm accuracy. The accuracy of the Nortek Vectrino ADVs is +/- 0.5% of the measured values +/- 1 mm/s (Nortek 2012). The sample bin vertical resolution for the ADP is 1.6cm. The ADP has a velocity accuracy of +/- 1% of the velocity range +/- 1mm/sec (Sontek 2012).

Turbine Performance Measurements

The model turbine rotors will be equipped with an instrumentation package developed by SAFL engineers to measure turbine power output via measurements of angular velocity and torque at 200 Hz (See Chamorro et al. 2012). This instrumentation package is illustrated in Fig. 7 for a 1:10 axial flow turbine tested in 2011 (Gunawan et al. 2012a, 2012b). For the reference model turbines in this study, an Interface 20-Nm MRT miniature reaction torque transducer will be mounted in the nose cone of each nacelle. By having the torque sensor mounted directly to the rotor, this minimizes any potential loss of torque measurement sensitivity through the system. Measurements from the sensor will be transferred into the nacelle, through a slip-ring, and out to the surface via vinyl tubing mounted flush with the turbine support structure. Angular velocity of each rotor will be precisely defined and maintained using a Pacific Scientific NEMA 42 multi-stack stepper motor coupled with a Zeta 6108 indexer drive. A series of gearboxes and shafts transmits the rotation from the above-surface stepper motor to the individual nacelles and rotors. Additionally, suction lines will be routed to the nacelle chambers to remove any

potential leakage, thereby protecting the instruments. The configuration of the reference river turbine allows for the sensors and angular velocity control motors to remain above the water surface. Similar torque sensors and motors will be used for this model.

Software developed by SAFL Engineers will allow precise control of angular velocity for the turbine by setting the rotational speed of the stepper motor (Fig. 8). The software records torque measurements; typically at 200 Hz. Temperature is recorded at the beginning and end of each data file to monitor drift in the operating temperature. The turbine control software also allows for synchronous measurements of instantaneous velocity and torque from the three ADVs and two torque sensors. This operation can either be controlled manually by using a push-button, or a 5-volt TTL signal can be sent from the SAFL Main Channel Data Acquisition Carriage to initiate data collection.

Torque time series data at 200 Hz, as illustrated in Fig. 9, will be collected at each angular velocity setting for 5 minutes. The high-resolution torque measurements allow for time-resolved fluctuations of turbine power output, and for a detailed examination of the turbine response to approach flow turbulence characteristics. Instantaneous turbine power output will be calculated as,

$$P_t = \omega \cdot \tau$$

where P_t is instantaneous turbine power, ω is the instantaneous angular velocity, and τ is the instantaneous torque at each tip speed ratio. Using these computed turbine power outputs at each tip speed ratio, we will calculate the instantaneous power coefficient (C_p) as,

$$C_p = \frac{P_t}{P_a} = \frac{2P_t}{\rho A u^3}$$

Where P_a is the available hydrokinetic power of the approach flow, ρ is the fluid density, A is the blade swept area or area of the energy extraction plane (EEP), and u is the instantaneous free stream velocity of the approach flow measured at the hub centerline of each tidal turbine rotor, and the centroid of the EEP for each river turbine rotor. The mean values for P_t, P_a, and C_p, will be calculated for each test case, and recorded and archived as described below.

Thrust Measurements
Approximate estimates for turbine thrust coefficients will be calculated using cross-sectional velocity measurements upstream and downstream of the turbine and applying momentum conservation across the turbine rotor plane (e.g. Gunawan et al. 2012a). This will require measurement of the velocity distribution within a cross-section using the ADP, which will be deployed approximately 1 to 2 rotor diameters upstream of the turbine as well as one rotor diameter downstream of the turbine. A set of each cross-sectional velocity measurements will be collected for a range of tip-speed ratios, thereby allowing an estimate of the relationship between the turbine thrust coefficient (C_t) and *TSR*. With these data, we will use the force equation to estimate C_t as,

$$C_t = \frac{F_t}{F_a} = \frac{\rho \iint u_2 \left(u_{2(y,z)} - u_{1(y,z)} \right) dydz}{0.5 \rho A u^2}$$

Where F_t is the thrust on the rotor and F_a is the hydrodynamic force of the approach flow. The results from this analysis will provide estimates of how C_t changes with respect to *TSR*.

Test Matrices

The anticipated test cases for the tidal and river turbine model performance experiments are shown in Tables 1 through 3. Tables 1 and 2 show the experimental settings for the turbine model performance measurements, including the *RPM*, resulting *TSR*, and the corresponding values for torque estimated assuming a power coefficient C_p=0.45, where

$$\tau = \frac{P_t}{2\pi\omega} = \frac{0.5\rho C_p A u^3}{2\pi\omega}$$

The averaged measured values for torque (τ), thrust (F_t), hydrodynamic force (F_a), power (P_t), power available (P_a), three-quarter span blade chord Reynolds number (R_c), thrust coefficient (C_t), and power coefficient (C_p) will be reported for each test case. Six test cases roughly corresponding to *TSR* values of approximately 3-8 will be conducted for the tidal turbine model performance curve. *TSR* values will likely range from 1-6 for the river turbine model. Average inflow characteristics at "hub height," calculated from instantaneous values and to be reported in Table 3, will include the mean velocity ($\bar{u}$), the standard deviation of the velocity (σ_u), the turbulence intensity ($TI = \sigma_u / \bar{u}$), all six Reynolds stresses ($-\overline{u_i u_j}$), and the turbulent kinetic energy (*TKE*).

Upon completion of the performance testing, and plotting of the performance curves for each turbine model, e.g. those collected previously and reported in Fig. 10, detailed instantaneous velocity measurements around the model turbines will be collected as described above for the test case at the optimal or near-optimal power coefficient. At each measurement point the mean flow statistics summarized in Table 3 will be calculated, reported, and archived.

Table 1: Matrix for Performance Testing, Tidal Turbine Model. Note that the estimated value for torque will be replaced by the measured value.

RPM	TSR	ω	F_t	F_a	P_t	P_a	R_c	C_t	C_p
RPM	-	N-m	N	N	N-m/s	N-m/s	-	-	-
120	3.1	3.52	TBD	TBD	TBD	TBD	TBD	TBD	TBD
150	3.9	2.81	TBD	TBD	TBD	TBD	TBD	TBD	TBD
192	5.0	2.20	TBD	TBD	TBD	TBD	TBD	TBD	TBD
228	6.0	1.85	TBD	TBD	TBD	TBD	TBD	TBD	TBD
270	7.1	1.56	TBD	TBD	TBD	TBD	TBD	TBD	TBD
300	7.9	1.41	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Table 2: Matrix for Performance Testing, River Turbine Model. Note that the estimated value for torque will be replaced by the measured value.

RPM	TSR	ω	F_t	F_a	P_t	P_a	R_c	C_t	C_p
RPM	-	N-m	N	N	N-m/s	N-m/s	-	-	-
48	1.1	6.22	TBD	TBD	TBD	TBD	TBD	TBD	TBD
90	2.0	3.32	TBD	TBD	TBD	TBD	TBD	TBD	TBD
132	3.0	2.26	TBD	TBD	TBD	TBD	TBD	TBD	TBD
180	4.1	1.66	TBD	TBD	TBD	TBD	TBD	TBD	TBD
222	5.0	1.34	TBD	TBD	TBD	TBD	TBD	TBD	TBD
264	5.9	1.13	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Table 3: Measured inflow characteristics for each test case.

u	σ_u	TI	$-\overline{uu}$	$-\overline{vv}$	$-\overline{ww}$	$-\overline{uv}$	$-\overline{vw}$	$-\overline{uw}$	TKE
m/s	m/s	%	m²/s²	m²/s²	m²/s²	m²/s²	m²/s²	m²/s²	m²/s²
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

5. POST-PROCESSING METHODS FOR INSTANTANEOUS VELOCITY DATA

All instantaneous velocity measurements will be post-processed using methods described in Gunawan et al. (2011) and Gunawan and Neary (2011). This includes correction methods for eliminating and replacing spikes (e.g. Goring and Nikora 2002), Doppler noise (e.g. Voulgaris and Trowbridge 1998), and filtering effects (Garcia et al. 2005).

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6. RESEARCH DELIVERABLES

Research deliverables will include the following: Geometrically scaled horizontal axis (1:40) and vertical axis (1:10) turbine model testing; Mean U,V, and W velocity statistics upstream and downstream of each model; Detailed turbulence intensity, turbulent kinetic energy (TKE), spectral energy densities, and Reynolds stresses; Multi-point space-time correlation of inflow and wake-flow velocity measurements; Synchronous blade azimuth and turbulence/torque data; Instantaneous and time-averaged power and torque of the each turbine; Turbine performance curves; Extensive dataset for future computational model validation study.

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7. ARCHIVING EXPERIMENTAL DATA

The raw and post-processed data, including turbine torque measurement files, ADP profile measurements and synchronized ADV measurements, will be archived at an Oak Ridge National Laboratory (ORNL) server with designated data formats, filename descriptions, and tabular formats detailed in the Appendix, Data Descriptions. The data will be made available to model developers as validation data sets upon signing of a nondisclosure agreement (NDA) that restricts publication of these model data sets for model validation by "the modelers" until ORNL-SAFL, "the data-collectors" publish these data sets in peer-reviewed journal articles. The NDA will not delay the early dissemination of these data sets to modelers for model validation, only the publication of model validation results.

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8. PROJECT MILESTONES

A. Complete design and fabrication of model turbines (October 1, 2012, Q1)
B. Complete Reynolds dependency experiments (November 15, 2012, Q1)
C. Complete performance curve measurements for tidal reference turbine (November 30, 2012, Q1)
D. Complete flow field measurements around tidal turbine (December 15, 2012, Q1)
E. Complete performance curve measurements for river reference turbine (January 30, 2013, Q2)
F. Complete flow field measurements around river turbine (March 30, 2013, Q2)
G. Complete analysis of performance data and flow field measurements (June 30, 2013, Q3)
H. Complete technical report and archiving of experimental data (September 30, 2013, Q4).

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9. ACKNOWLEDGEMENTS

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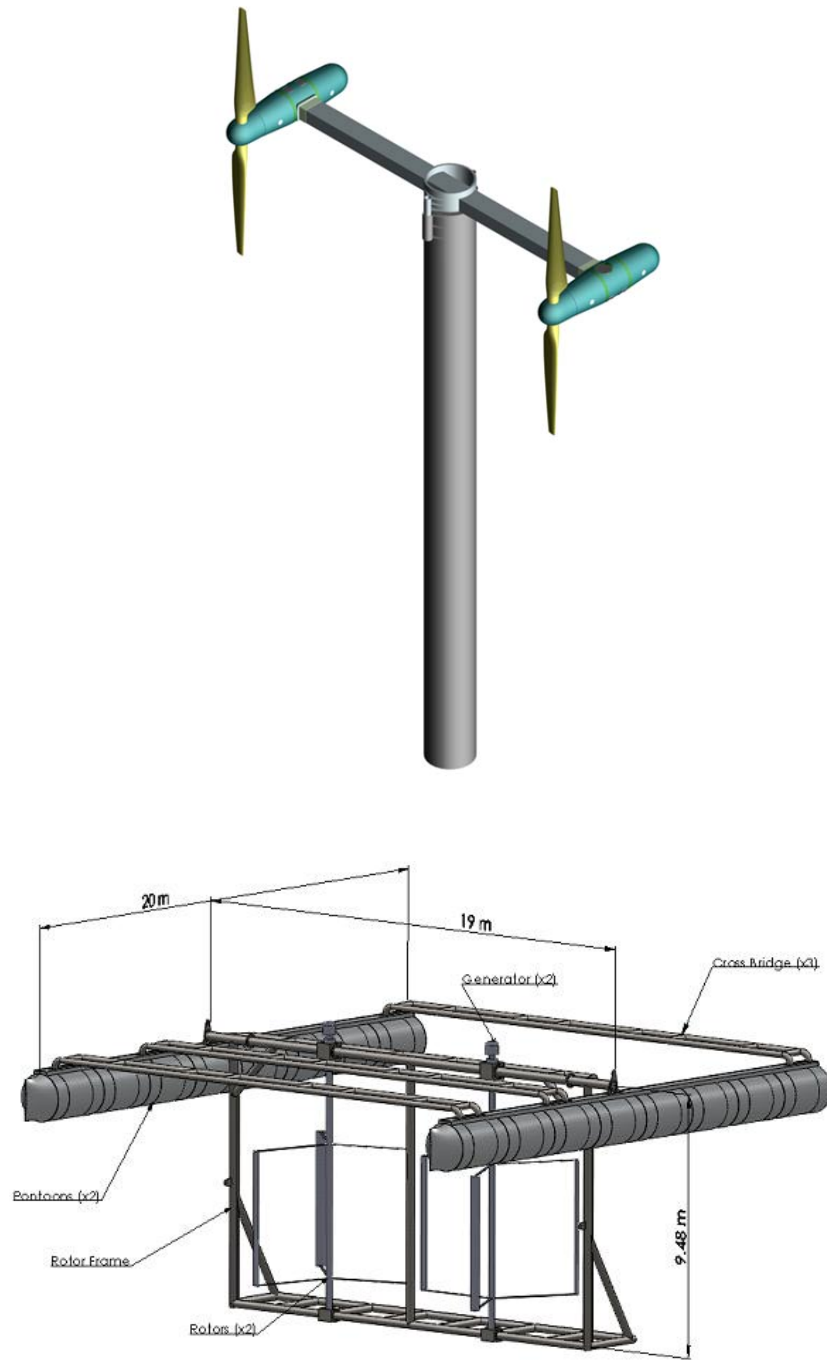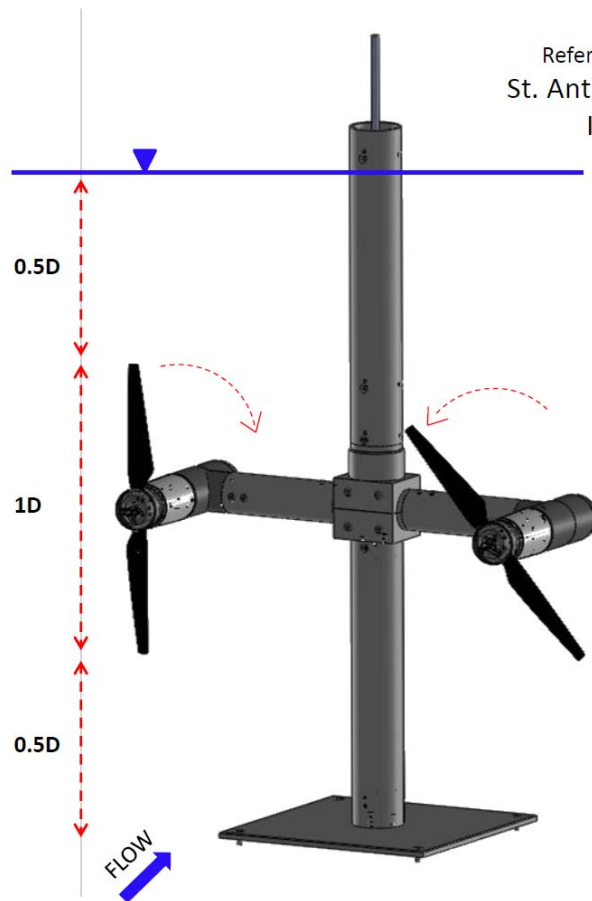[THIS PAGE LEFT BLANK INTENTIONALLY]

11. FIGURES

Figure 1. DOE's reference tidal (axial-flow) and river (cross-flow) turbines.

U.S. Department of Energy
Reference Horizontal Axis Turbine (RHAT) - Tidal Turbine
St. Anthony Falls Laboratory (SAFL) model testing
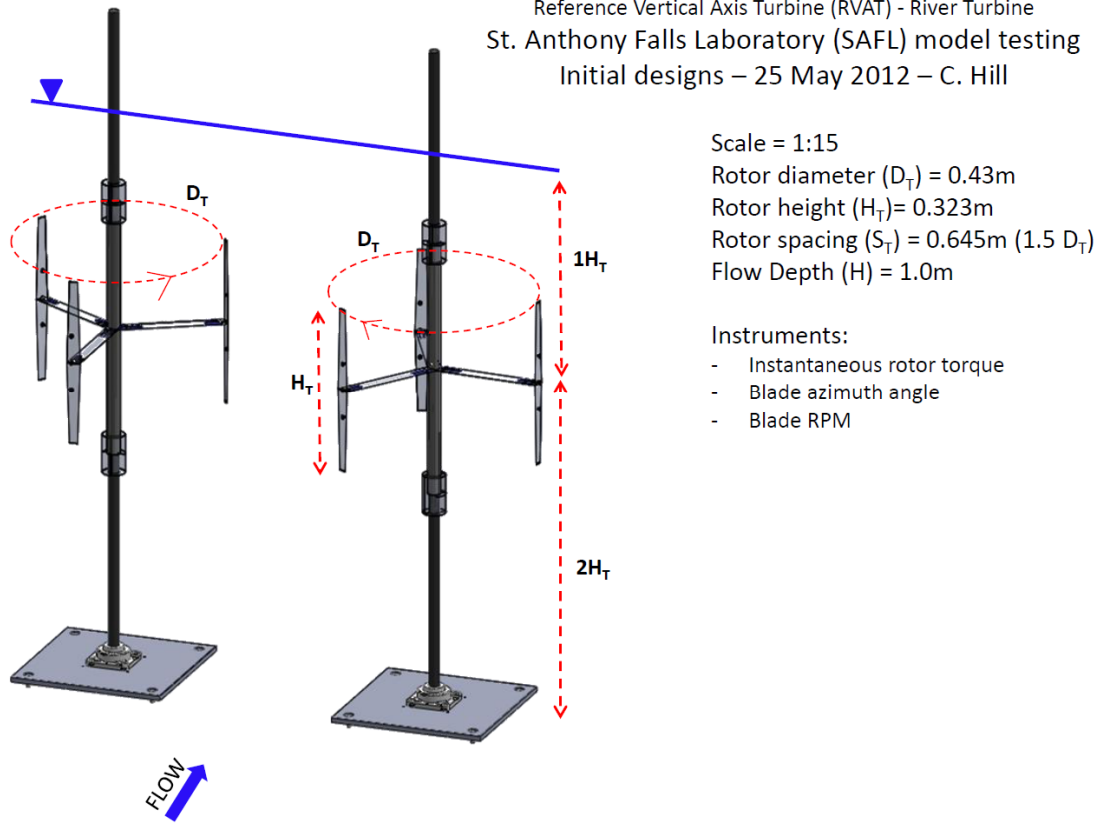Initial designs – 25 May 2012 – C.Hill

Scale = 1:40
Rotor diameter (D_T) = 0.5m
Rotor spacing (S_T) = 0.7m
Hub height (H_{hub}) = 0.5m
Flow Depth (H) = 1.0m

Instruments:
- Instantaneous rotor torque
- Blade azimuth angle
- Blade RPM

0.5D

1D

0.5D

FLOW

Figure 2. Reference tidal turbine model, design specifications, and instruments.

Figure 3. Reference river turbine model, design specifications, and instruments.

Figure 4a: The SAFL Main Channel (looking upstream).

Figure 4b: The SAFL Main Channel DAQ Carriage.
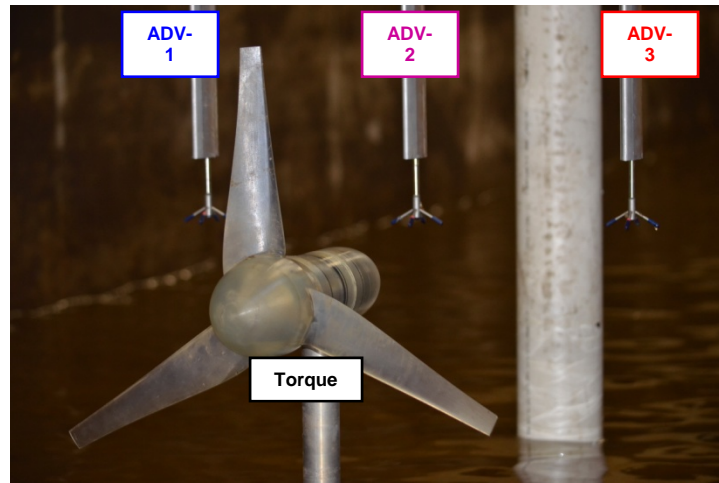
Figure 5: ORNL's 3 synchronized ADV array positioned to sample upstream of 1:10 scale axial flow turbine (Not tidal reference turbine to be tested) at hub height simultaneously with turbine torque measurements. The cylinder upstream of the turbine was used to study the effects of large vortex shedding on the turbine performance.
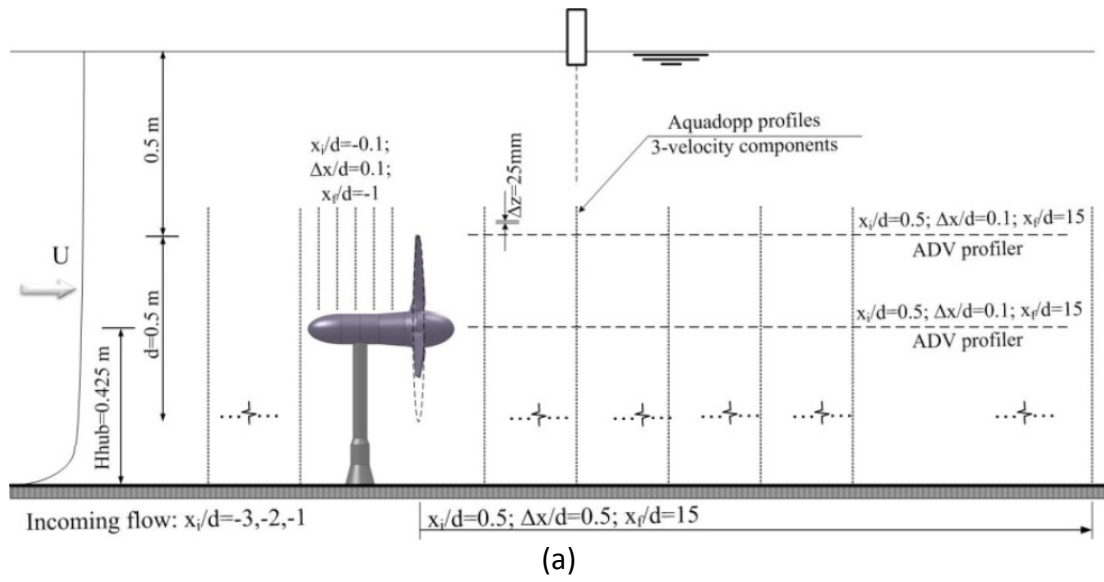
(a)

(b)
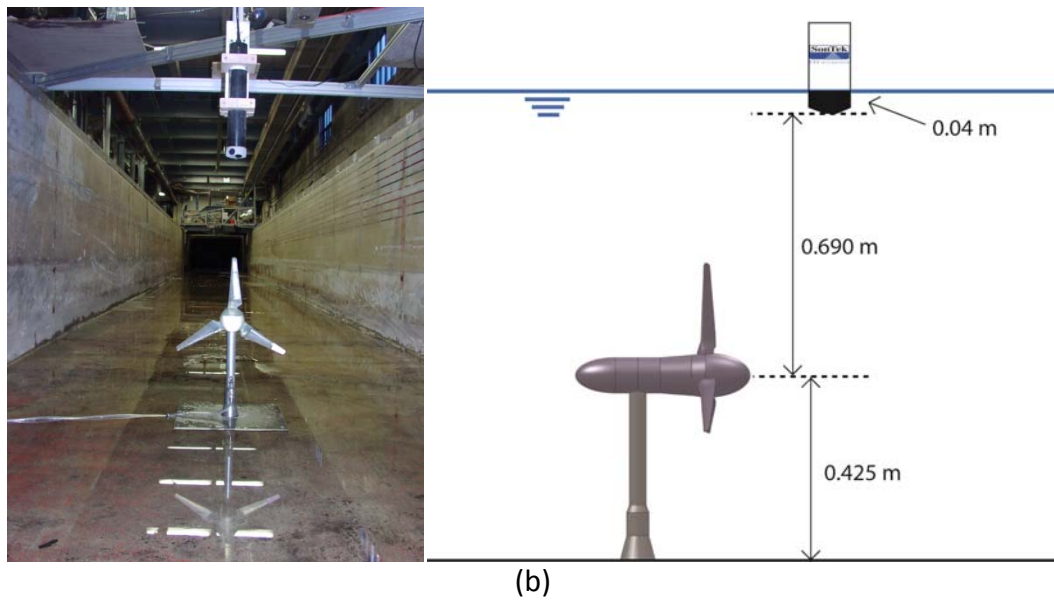
Figure 6: (a) ADV and ADP measurement grid; (b) Sontek ADP Setup. Photo looking upstream, and vertical location of PC-ADP with respect to 1:10 scale axial flow turbine hub and channel bed.
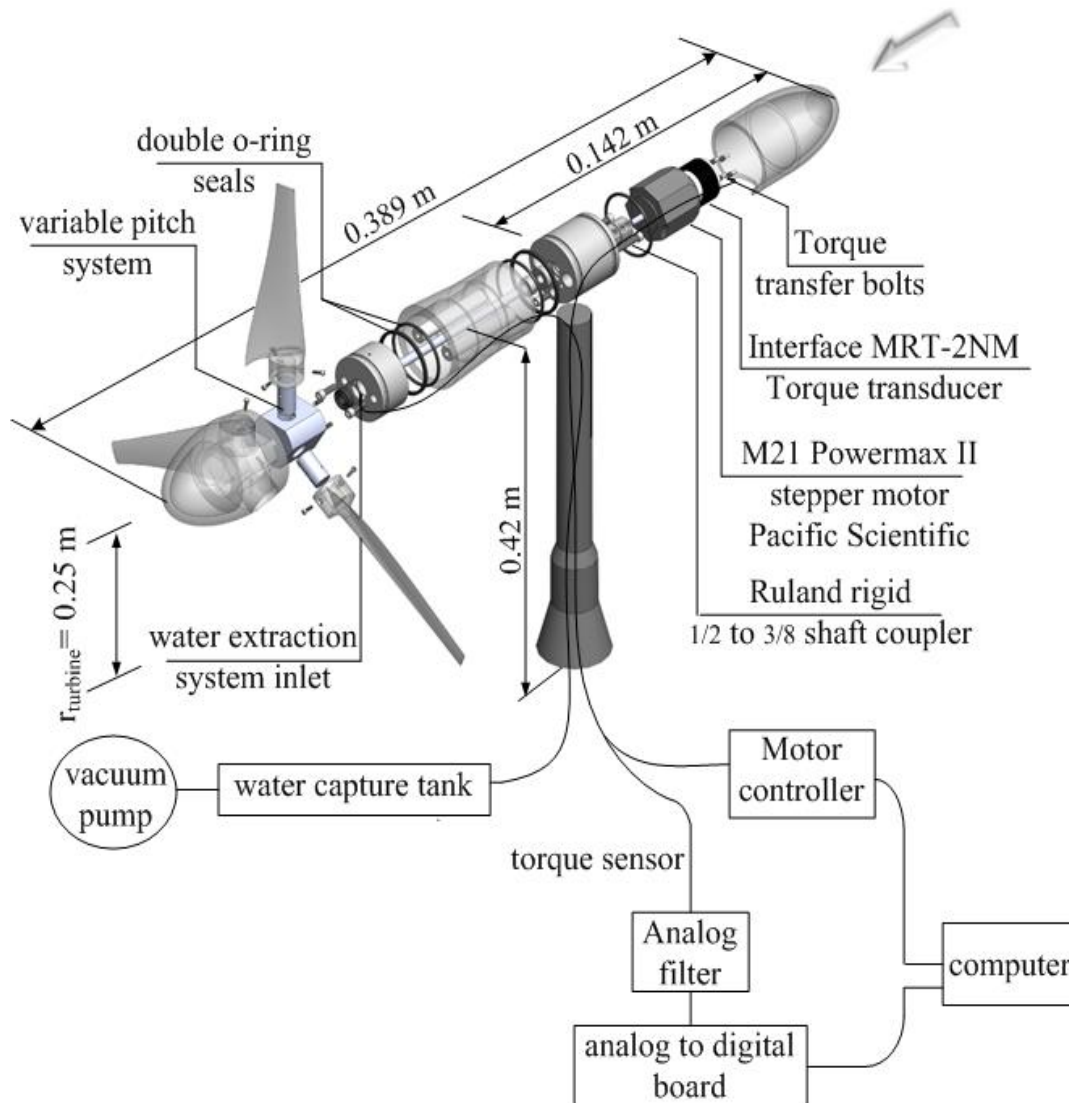
30

Figure 7: Exploded diagram of the model hydrokinetic turbine construction including the instrumentation package installed in the nacelle of the turbine (Chamorro et al. 2012).
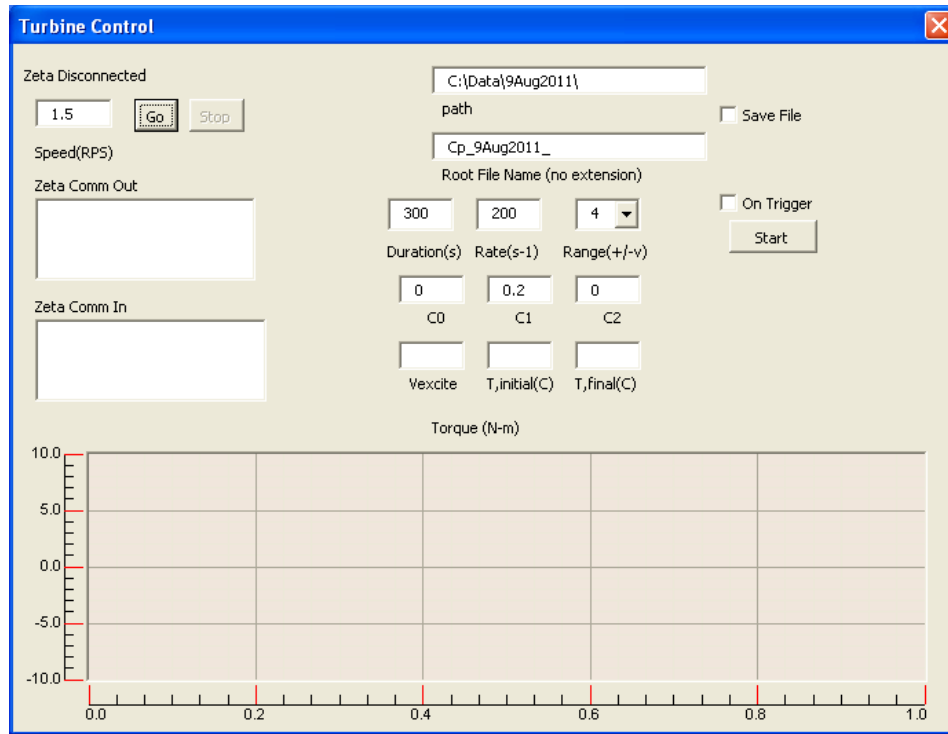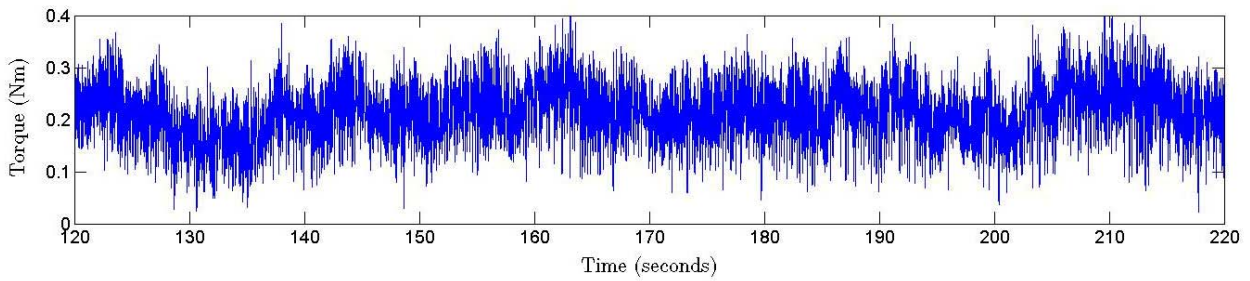
Figure 8: SAFL Turbine Control software window.

Figure 9: Sample time-series plot of 200-Hz torque measurements from previous model studies performed at SAFL in conjunction with Oak Ridge National Lab in 2011.