PROGRESS REPORT ON INTEGRATED EXPERIMENTAL AND NUMERICAL STUDIES OF CROSS-FLOW TURBINES

Pete Bachant and Martin Wosnik
Center for Ocean Renewable Energy
University of New Hampshire
Durham, NH, USA

[1]Corresponding author: martin.wosnik@unh.edu

INTRODUCTION

Cross-flow turbines (CFTs), often referred to as vertical-axis turbines, experience fluid dynamic phenomena and exhibit near-wake characteristics quite distinct from axial flow turbines (c.f. [1] for near-wake measurements of a CFT, and [2] for numerical comparison between wakes of CFTs and an axial turbine). Due to their inherent unsteady operating principle, the turbine blades experience large variations in angles of attack as they rotate about the CFT's axis. These variations become larger as the tip speed ratio $\lambda = \omega R / U_\infty$ decreases. The maximum angle of attack excursions are often sufficiently large that the blades operate under dynamic stall, a complex unsteady process that deviates significantly from static foil behavior, during part of their rotation.

There is some evidence that CFTs in close proximity can interact constructively by taking advantage of their unique operating and wake fluid dynamics, thereby improving power output of densely spaced turbines over the sum of their stand-alone power [3, 4, 5]. These turbines have also been shown to allow more closely spaced arrays [6] compared to conventional axial-flow devices, potentially resulting in more efficient tidal/river channel use. To effectively design individual CFTs and CFT arrays it is important to understand the fluid dynamics and near-wake structure to accurately predict interactions between turbine wakes of closely spaced devices.

As turbine designs mature, the research focus is shifting from individual devices towards improving turbine array layouts for maximizing overall power output, i.e., minimizing wake interference for axial-flow turbines, or taking advantage of constructive wake interaction for the aforementioned cross-flow turbines.

Numerical simulations are generally better suited to explore the turbine array design parameter space, as physical model studies of large arrays at (sufficiently) large model scale would be expensive. Lower fidelity models such as those based on simple momentum relations—e.g. double-multiple streamtube (DMST)—or potential flow, i.e., vortex line models, often break down for turbines with high solidity or blade chord to radius ratio. However, modern computing power has made simulating turbines with Navier–Stokes based models feasible.

However, since the computing power available today is not sufficient to conduct simulations of the flow in and around large arrays of turbines with turbulence-resolving direct numerical simulations (DNS) and fully resolved turbine geometries, the turbines' interaction with the kinetic energy resource (water currents or wind) needs to be parameterized, i.e., modeled. The flow field is typically modeled using computational fluid dynamics (CFD) with Reynolds-averaged Navier–Stokes (RANS) turbulence models or large eddy simulation (LES) and the turbines' interaction with the energy resource can be parameterized, or modeled as well, for example with actuator disk (ADM) or line models (ALM) [7, 8]. The simplest and most commonly used model with a CFD framework for turbine arrays is the actuator disk model (ADM), however, it is not able to predict the unique wake structure generated by cross-flow turbines. Alternatives that can capture the important physics of cross-flow turbines in a cost-effective way are sought.

In the literature to date, the ALM has been applied to simulating a very low Reynolds number 2-D CFT case using LES, for which performance predictions were not reported, though the technique showed promise for replicating the unsteady wake characteristics—even in the near-wake region [9]. Therefore, an ALM was developed and validated against a higher Reynolds number case using both RANS and LES.

An integrated experimental and numerical study of cross-flow turbines has been undertaken at the Center of Ocean Renewable Energy at the University of New Hampshire (UNH), and a progress report will be given.

EXPERIMENTS

Experiments were carried out using an automated turbine test bed in a large cross-section tow tank, designed to achieve sufficiently high Reynolds numbers for the results to be Reynolds number independent with respect to turbine performance and wake statistics [10], such that they can be reliably extrapolated to full scale and used for model validation.

A number of cross-flow turbines of the O(1m) scale have be tested in the test bed, including a turbine with a simple-geometry, referred to as the UNH Reference Vertical Axis Turbine (RVAT) [1,11], shown in Figure 1. Recently the DOE/Sandia Reference Model 2 turbine [12] was also tested using this turbine test bed, and results were first reported at METS 2015 [13]. These turbine tests have produced several **open data sets [14-17]**, with the intent to make the data available to the marine renewable energy and wind energy communities for model validation. Data sets include performance and wake data, processing code, CAD files.

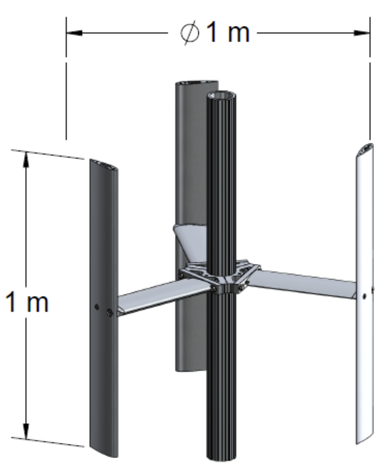

FIGURE 1. UNH REFERENCE VERTICAL AXIS TURBINE (UNH-RVAT) TURBINE MODEL. TURBINE BLADES AND STRUTS ARE NACA 0020 PROFILES WITH 0.14 M CHORD [1, 10].

An example of the performance data for the UNH-RVAT is shown in Figure 2, and the variation of the measured mean power coefficient at $\lambda = 1.9$ with Reynolds number is shown in Figure 3 [10]. These plots indicate that that the performance of this cross-flow turbine becomes essentially Re-independent at a Reynolds number based on the rotor diameter $Re_D \approx 10^6$ or an approximate average Reynolds number based on the blade chord length $Re_c \approx 2 \times 10^5$.

This gives a good indication of what scale experiments should be used for validation of numerical simulations: simulation and models should be validated at Reynolds numbers where the turbine's performance has become Reynolds number independent, or at least varies slowly and close to linearly with Reynolds number.

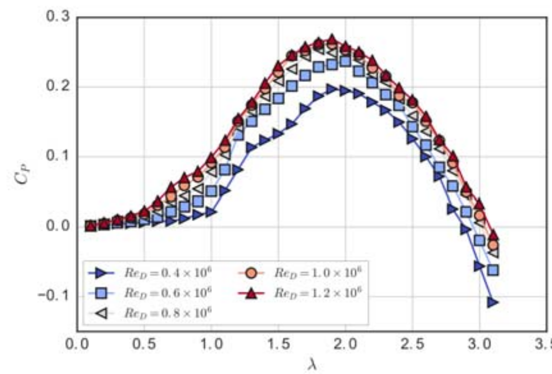

FIGURE 2. UNH-RVAT: PERFORMANCE DATA FOR MULTIPLE REYNOLDS NUMBERS [10].

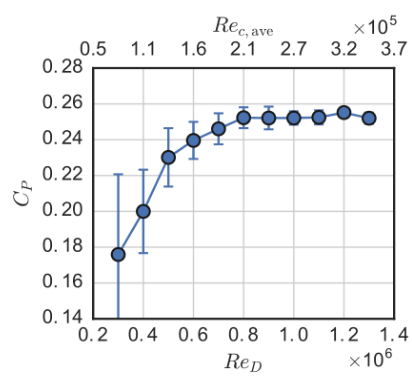

FIGURE 3. UNH-RVAT MEASURED MEAN POWER COEFFICIENT AT $\lambda = 1.9$ PLOTTED VERSUS THE REYNOLDS NUMBER. ERROR BARS INDICATE EXPANDED UNCERTAINTY ESTIMATES FOR 95% CONFIDENCE, WHICH FOR c_P IS DOMINATED BY SYSTEMATIC ERROR ESTIMATES FROM THE TORQUE TRANSDUCER OPERATING AT THE LOWER END OF ITS MEASUREMENT RANGE [10].

NUMERICAL SIMULATIONS

To improve parameterization in array simulations, an actuator line model (ALM) was developed to provide a computationally feasible method for simulating full turbine arrays inside Navier--Stokes models. The ALM predicts turbine loading with the blade element method combined with sub-models for dynamic stall [18], flow curvature, added mass, and blade end effects. The open-source software, named *turbinesFoam*[1], is written as an extension library for the *OpenFOAM* CFD package, which allows the ALM body force to be applied to their standard RANS and LES solvers. Turbine forcing is also applied to volume of fluid (VOF) models, e.g., for predicting free surface effects on submerged MHK devices. Results are presented for the simulation of performance and wake dynamics of axial- and cross-flow turbines and compared with experiments and body-fitted mesh, blade-resolving CFD.

Note that the ALM simulations reduce computational effort over that required with blade-resolving simulations by several orders-of-magnitude). Using the ALM, high-fidelity array modeling with LES becomes feasible.

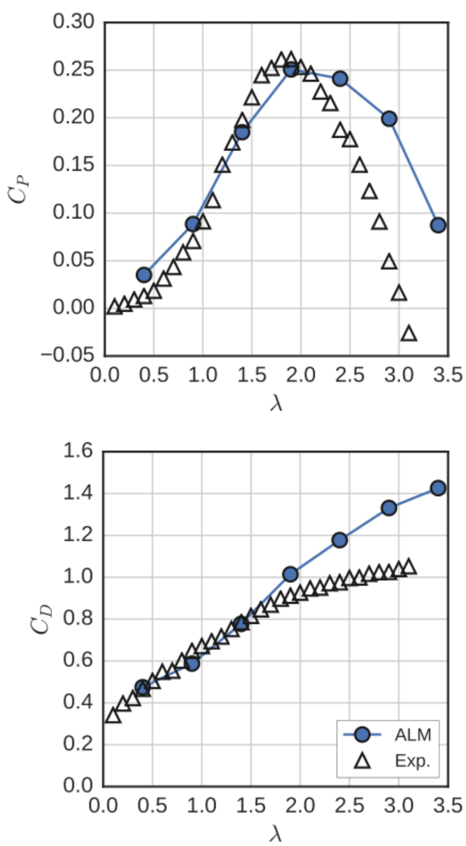

FIGURE 4. PRELIMINARY RESULTS OF ACTUATOR LINE MODEL FOR CROSS-FLOW TURBINE, COMPARED TO EXPERIMENTAL DATA (UNH-RVAT). TOP: POWER COEFFICIENT CURVE, BOTTOM: ROTOR DRAG (OR THRUST) COEFFICIENT.

An example of preliminary results with actuator line model implementation for cross turbines is shown in Figure 4 with comparisons to the experimental data from the UNH-RVAT (RANS, k–ϵ model). An example of preliminary results of the actuator line model implemented in a large eddy simulation (LES) is shown in Figure 5. The LES is able to capture the vertical advection of blade tip vortices, which contribute to the strong vertical transport in the near wake [1].

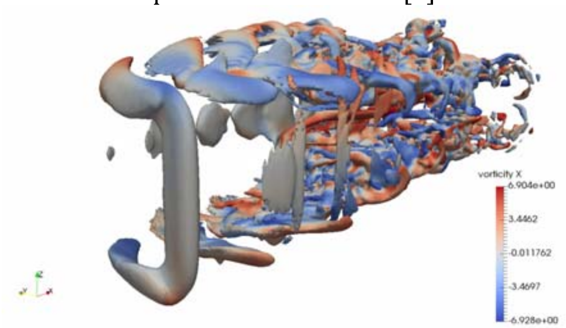

FIGURE 5. SNAPSHOT OF UNH-RVAT VORTICITY ISOSURFACES SIMULATED WITH ACTUATOR LINE MODEL IN LES.

A progress report on the numerical modeling work with validation against large-scale tow tank experiments will be given.

Acknowledgements: Supported by NSF-CBET grant 1150797.

REFERENCES

[1] Bachant P; Wosnik M. (2015) Characterizing the near-wake of a cross-flow turbine. Journal of Turbulence, Vol. 16, No. 4, 392–410, http://dx.doi.org/10.1080/14685248.2014.1001852

[2] Boudreau M; Dumas G (2015) Wake Analysis of Various Hydrokinetic Turbine Technologies through Numerical Simulations. 62nd Canadian Aeronautics and Space Institute (CASI) Aeronautics Conference, Montreal, QC, Canada, 19th - 21st May 2015.

[3] Li Y; Calisal SM (2010) Modeling of twin turbine systems with vertical axis tidal current turbines: Part I, power output. *Ocean Engineering,* 37, pp. 627–67.

[4] Goude A; Ågren O (2010) Numerical Simulation of a Farm of Vertical Axis Marine Current Turbines. Proc. ASME 2010 29th Int'l Conference Ocean, Offshore and Arctic

[1] https://github.com/turbinesFoam/turbinesFoam

Engineering (OMAE 2010), June 6-11, 2010, Shanghai, China, OMAE2010-20160.

[5] Antheaume S, Maître T, Achard J-L (2008) Hydraulic Darrieus turbines efficiency for free fluid flow conditions versus power farms conditions, *Renewable Energy*, 2008, vol. 33, issue 10, pages 2186-2198

[6] Dabiri J (2011) Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays. *Journal of Renewable and Sustainable Energy*, 3-043104.

[7] Sørensen JN; Mikkelsen RF; Henningson DS; Ivanell S; Sarmast S; Andersen SJ (2015) Simulation of wind turbine wakes using the actuator line technique. Phil Trans Ser A, 373-2035

[8] Martínez-Tossas LA; Churchfield MJ; Leonardi S (2015) Large eddy simulations of the flow past wind turbines: actuator line and disk modeling. *Wind Energy*. 18-6: 1047-1060

[9] Shamsoddin S; Porte-Agel F (2014) Large Eddy Simulation of Vertical Axis Wind Turbine Wakes. *Energies* 2014, 7, 890–912

[10] Bachant P; Wosnik M (2016) Effects of Reynolds Number on the Energy Conversion and Near-Wake Dynamics of a High-Solidity Vertical Axis Cross-Flow Turbine. *Energies* 2016, 9, 73; doi:10.3390/en9020073

[11] Neary VS; Fontaine AA; Bachant P; Wosnik M; Michelen C; Meyer RJ; Gunawan B; Straka WA (2013) US Department of Energy (DOE) National Lab Activities in Marine Hydrokinetics: Scaled Model Testing of DOE Reference Turbines. In Proceedings of 10th European Wave and Tidal Energy Conference - EWTEC 2013, Aalborg, Denmark, 2-5 September 2013.

[12] Neary VS; Previsic M; Jepsen RA; Lawson MJ; Yu YH; Copping AE; et al. Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies. Albuquerque, NM, USA: Sandia National Laboratories; 2014. SAND2014-9040.

[13] Bachant P; Wosnik M; Gunawan B; Murphy A; Neary VS (2015) Performance Measurements for a 1:6 Scale Model of the DOE Reference Model 2 (RM2) Cross-Flow Hydrokinetic Turbine. Proceedings of the 3rd Marine Energy Technology Symposium, METS2015, April 27-29, 2015, Washington, DC.

[14] Bachant P; Wosnik M (2014) UNH-RVAT baseline performance and near-wake measurements: Reduced dataset and processing code. figshare. DOI: 10.6084/m9.figshare.1080781

[15] Bachant P; Wosnik M (2015b) UNH-RVAT Reynolds number dependence experiment: Reduced dataset and processing code. figshare. DOI: 10.6084/m9.figshare.1286960

[16] Bachant P; Wosnik M; Gunawan B; Neary V (2015b) 1:6 scale RM2 cross-flow turbine CAD package. figshare, DOI10.6084/m9.figshare.1373870

[17] Bachant P; Wosnik M; Gunawan B; Neary VS (2015a) UNH RM2 tow tank experiment: Reduced dataset and processing code. figshare. DOI: 10.6084/m9.figshare.1373899

[18] Sheng W; Galbraith R A M; Coton F N (2008) A Modified Dynamic Stall Model for Low Mach Numbers. *Journal of Solar Energy Engineering* 2008, 130