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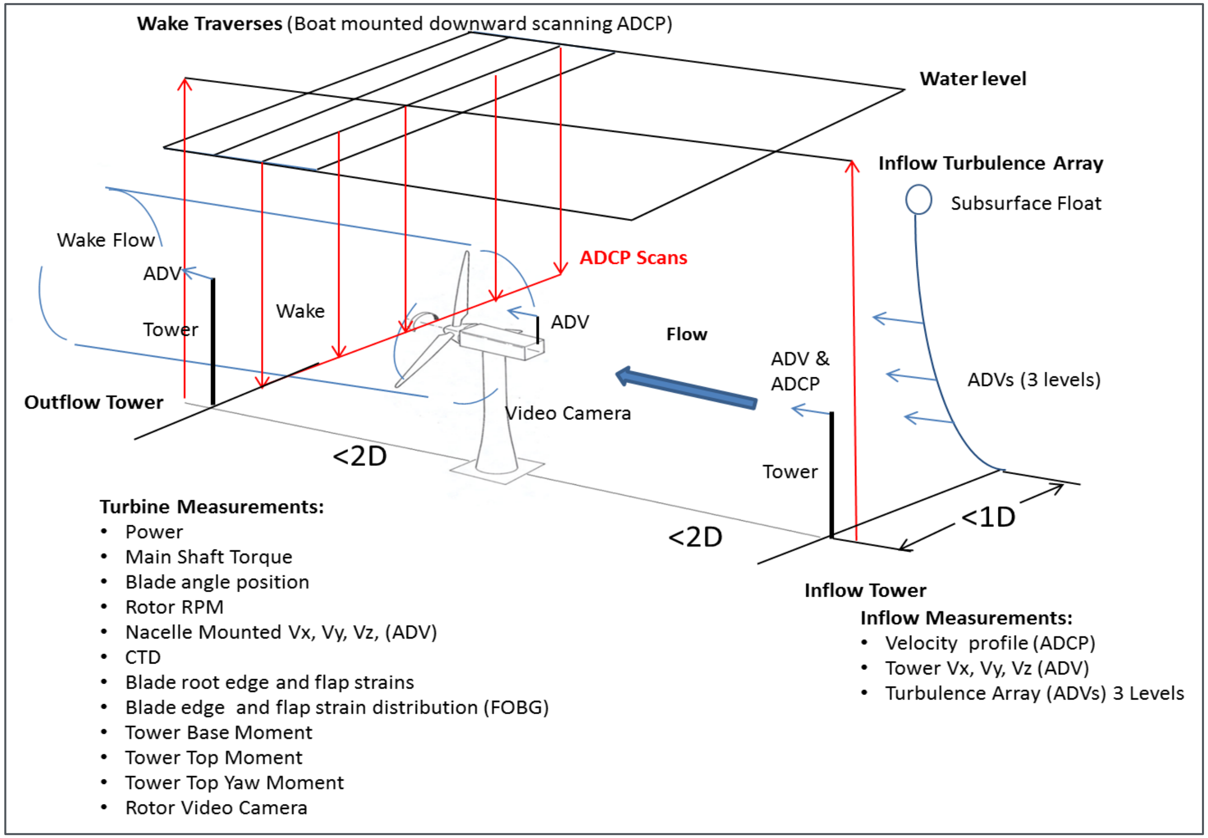

Tidal device field measurement campaign (FMC)

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Project Overview

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Tidal device field measurement campaign: Performance and loads models are critical for predicting the commercial viability, performance, and reliability of marine current turbines. Comprehensive scale-independent measurements of performance, loads, and flow field are needed to validate these models.

The Challenge: Scale independent tidal device performance measurements are limited, especially for cross-flow turbines

Partners: National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Pacific Northwest National Laboratory (PNNL; planning, instrumentation and measurements); University of New Hampshire (UNH; test facility and measurements)

Program Strategic Priorities

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Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- Conduct R&D for Innovative MHK systems & components
- **Develop tools to optimize device and array performance and reliability**
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- **Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets**
- Exchange of data information and expertise

Project Strategic Alignment

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Target: CACTUS, open-source tool for predicting performance of hydrokinetic turbines of arbitrary geometry, including crossflow turbines

Impact: Turbine developers need accurate modeling tool for design and optimization

Endpoint and Final Products: (1) Assessment of present capabilities & limitations of CACTUS; (2) Published model validation data set from scale-independent turbine performance experiments; (3) Github sites to facilitate open-source CACTUS model development; (4) Demonstrated first-ever application of fiber Bragg grating (FBG) sensor system for measuring blade loads

Technical Approach

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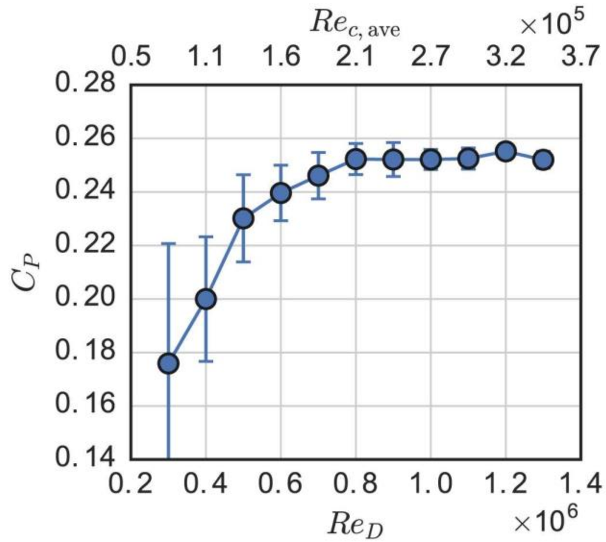
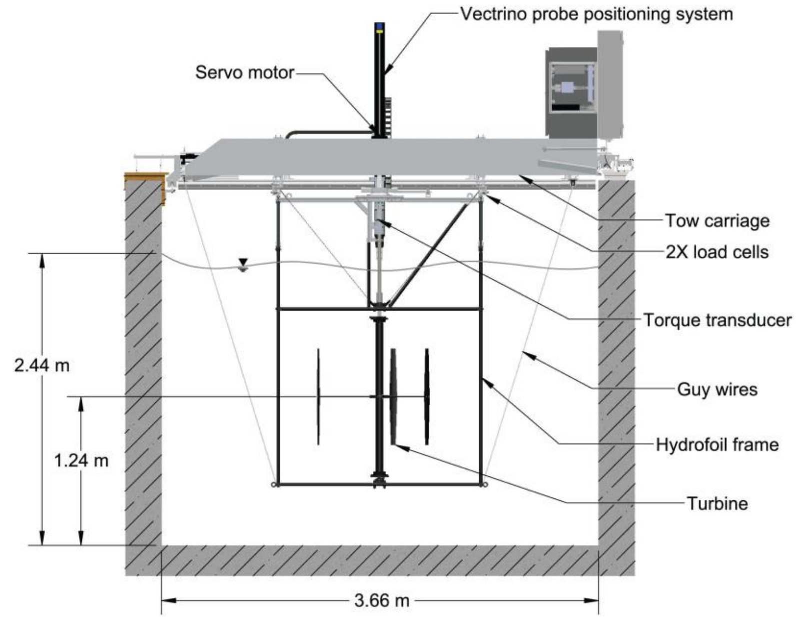
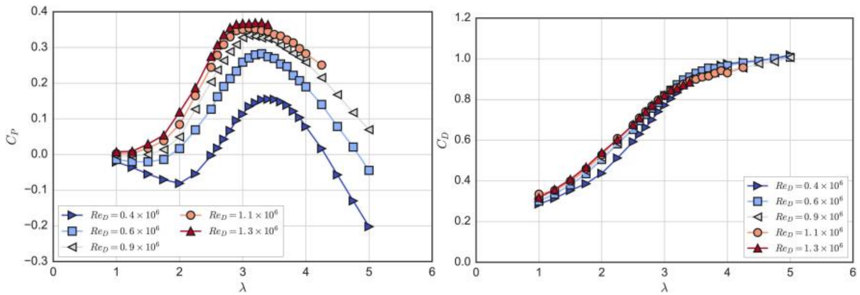


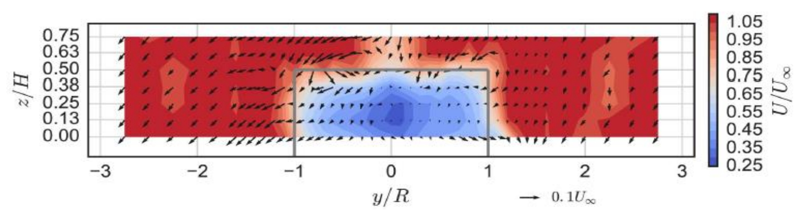
Reynolds dependency study



Experimental setup: RM2 crossflow turbine.

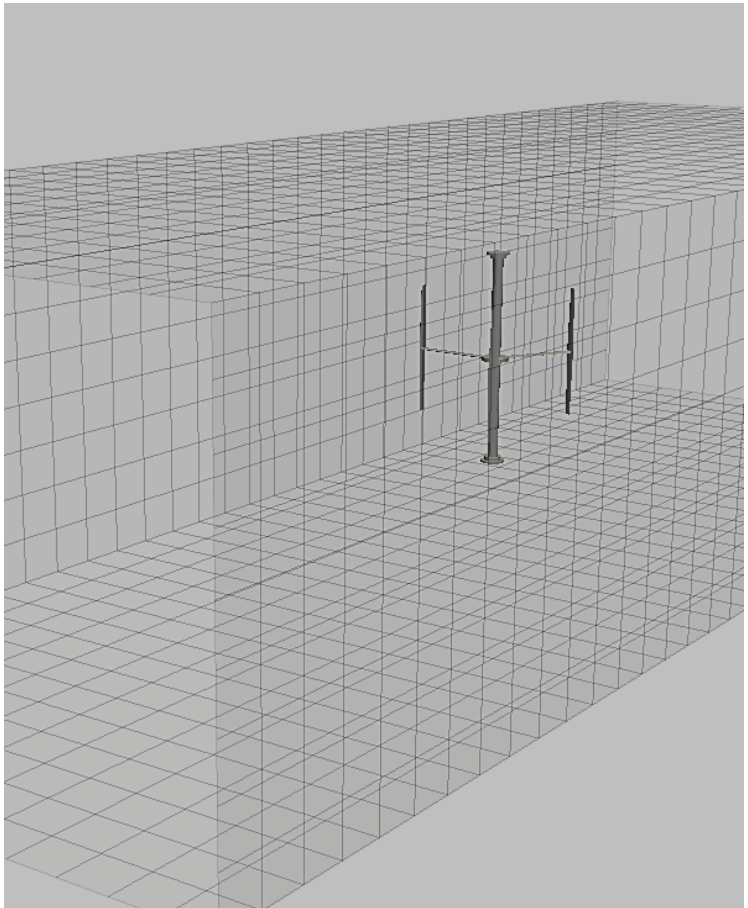


Turbine performance measurements, power and drag coefficients

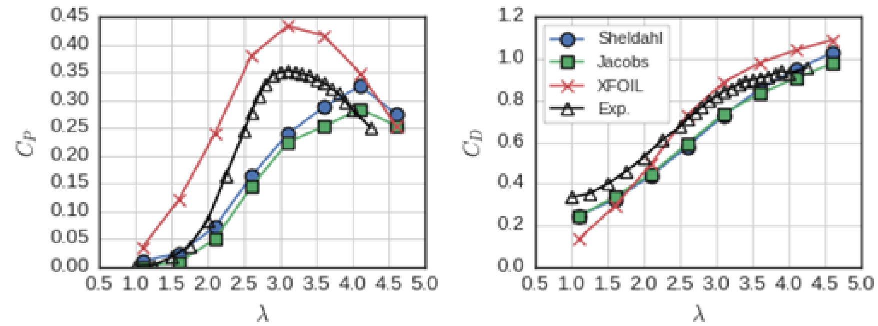


Wake flow field measurements

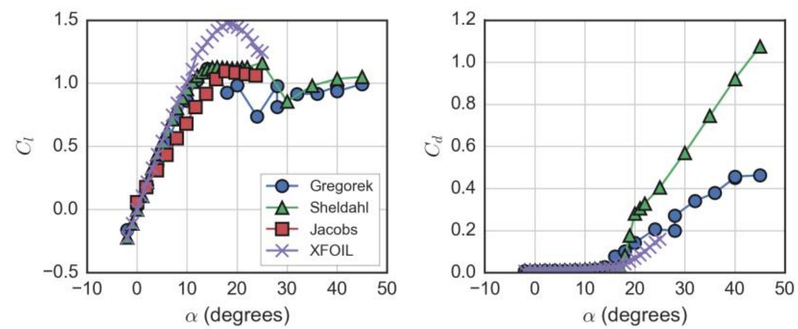
Technical Approach



CACTUS model computational domain and wall geometry



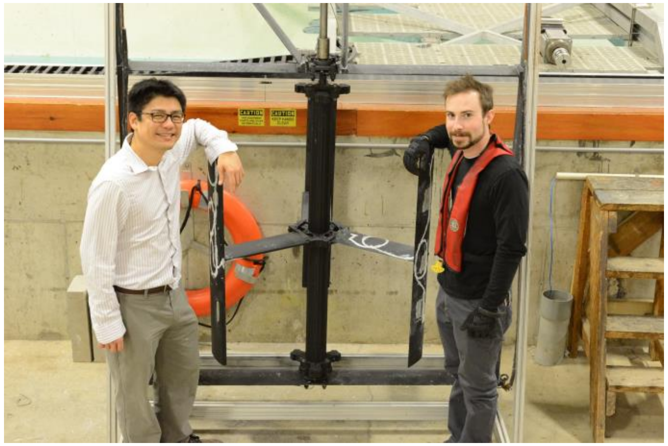
Power coefficient C_P and rotor drag (thrust) coefficient C_D CACTUS with Leishman-Beddoes (LB) Dynamic Stall (DS) model, compared to UNH RM2 physical model data.

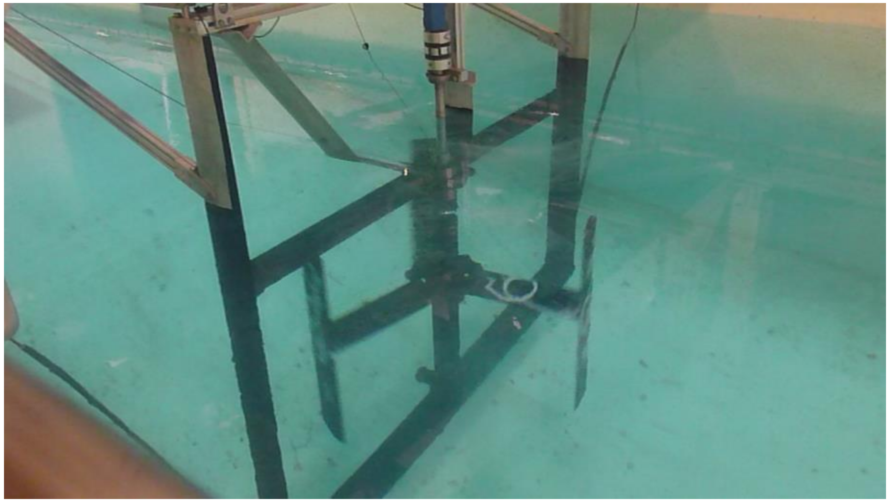


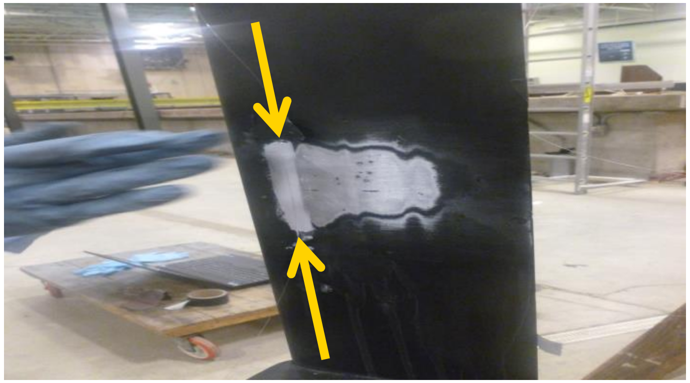
Static foil section lift and drag coefficients from various sources at chord Reynolds number of 1.5E6.

Technical Approach

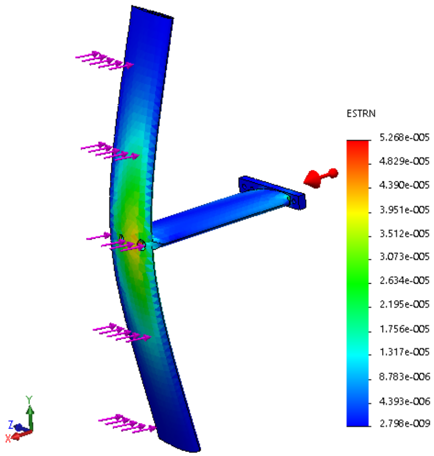
1. Design a customized FBG instrumentation system (bare fiber sensor)
2. System integration
   - FBG system integration with turbine
   - Dry testing
3. Wet measurements for various rotor tip - speed ratio at UNH tow tank

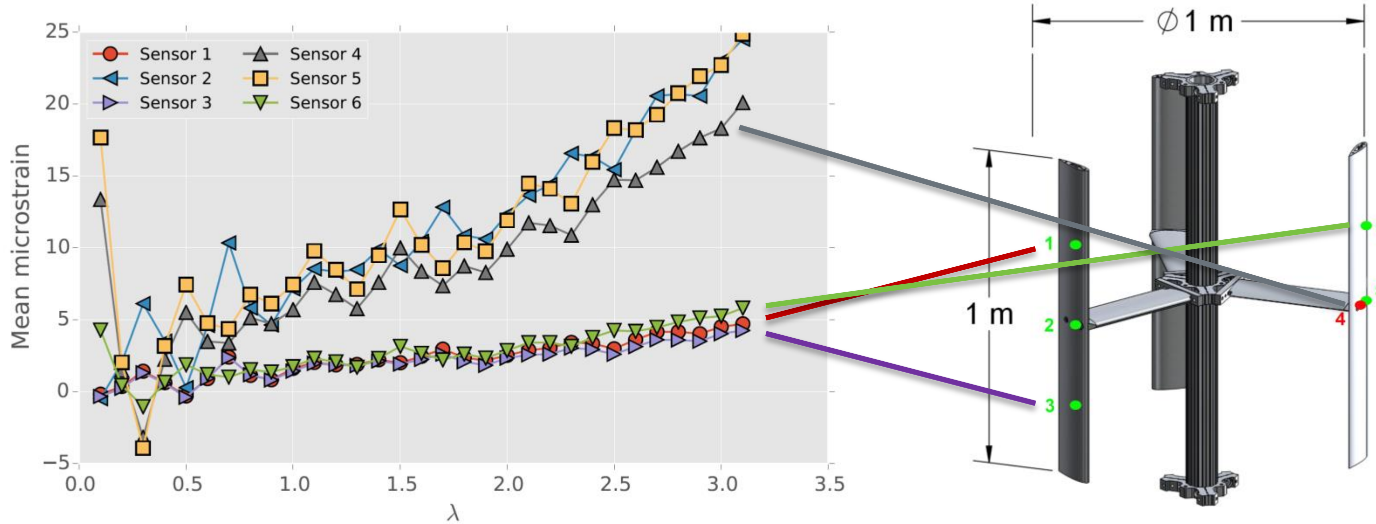






Technical Approach





- FBG instrumentation survived a one-week wet testing at UNH tow tank
- Results are encouraging:
  - Very low noise data, compared to conventional strain gauges
  - Measurements are repeatable for sensors located at the same blade span
  - Good agreement with Finite Element Analysis model

Accomplishments and Progress

- Identified main limitation of mid-fidelity models used for predicting crossflow turbine performance –empirical foil characteristics
- Demonstrated novel application of FBG sensor strain measurements for foils of a vertical axis hydrokinetic turbine
- Published non-proprietary CAD drawings of model turbine, first scale-independent validation dataset, and CACTUS simulation case files

Project Publications:

1. Wosnik, M., Bachant, P., Gunawan, B., Murphy, A.W. and Neary, V.S. (2015) Performance Measurements for a 1:6 Scale Model of the DOE Reference Model 2 (RM2) Cross-Flow Hydrokinetic Turbine. Marine Energy Technology Symposium 2015 (METS2015), Washington, DC, April 27-29.
2. Gunawan, B., Bachant, P., Neary, V.S., and Wosnik, M. (2016) Fiber optic instrumentation for measuring rotor strain. Proceedings of the 4rd Marine Energy Technology Symposium METS2016 April 25-27, 2016, Washington, D.C.
3. P. Bachant, A. Murphy, M. Wosnik and V. S. Neary (2016c) 1:6 scale RM2 cross-flow turbine CAD package, https://dx.doi.org/10.6084/m9.figshare.1373870 [DOI: 10.6084/m9.figshare.1373870]
4. P. Bachant, A. Murphy, M. Wosnik and V. S. Neary (2016d) UNH RM2 tow tank experiment: Reduced dataset and processing code, https://github.com/UNH-CORE/RM2-tow-tank [DOI: 10.6084/m9.figshare.1373899]
5. P. Bachant, A. Murphy, M. Wosnik and V. S. Neary (2016e) RM2 CACTUS simulation case files and data: https://github.com/UNH-CORE/RM2-CACTUS [DOI: 10.5281/zenodo.61027]
6. Bachant P, Wosnik M, Gunawan B, Neary VS (2016) Experimental Study of a Reference Model Vertical-Axis Cross-Flow Turbine. *PLOS ONE* 11(9): e0163799. doi: 10.1371/journal.pone.0163799
7. Wosnik, M., Bachant, P., Neary, V.S. and Murphy, A.W. (2016) Evaluation of Design & Analysis Code, CACTUS, for Predicting Cross-flow hydrokinetic Turbine Performance. SAND2016-9787, September 2016. 35 pages.

Program Strategic Priorities

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- **Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets**
- Exchange of data information and expertise

Target: The Flow Measurement Campaign facilitated field measurements of a wide variety of flow conditions and environments

Impact: Improved understanding of flow conditions improve design inputs for MHK technologies, reduce deployment risks, and improve performance during operation

Endpoint & Final Products: Published non-proprietary flow field data

Technical Approach

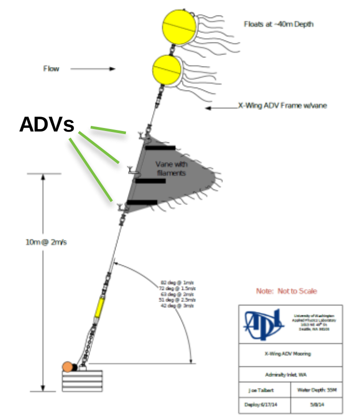
In lieu of an industrial partner to facilitate flow measurements around an MHK installation, several numerical and experimental studies were performed to fulfil the project objectives.

Multi-scale Coherent Turbulence at Tidal Energy Sites

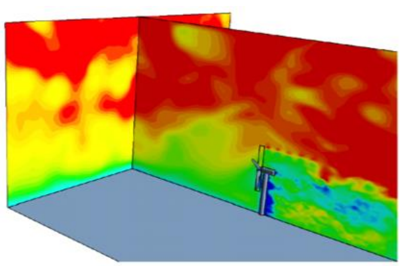
Collaboration with NREL and the University of Washington (UW); deployment of velocimetry equipment in the Puget Sound. This work focuses on the coherence of turbulence at this energetic tidal site, and how this could be measured with available Acoustic Doppler Velocimetry (ADV) and Acoustic Doppler Profiler (ADP) instrumentation.

Virtual ADCP Simulations

The flow measurement algorithms of conventional acoustic Doppler current profilers (ADCPs) were modelled in the flow field of an MHK wake generated using eddy-resolving computational fluid dynamics (CFD) simulations. This location represents an area of non-homogeneous flow which invalidates the assumption of diverging beam ADCP devices. The resulting errors were quantified with this technique.



Deployment of multiple ADVs on tethered mooring to measure coherence



CFD velocity field showing wake of horizontal axis MHK

Technical Approach

Convergent-beam Acoustic Doppler Velocimetry (ADV)

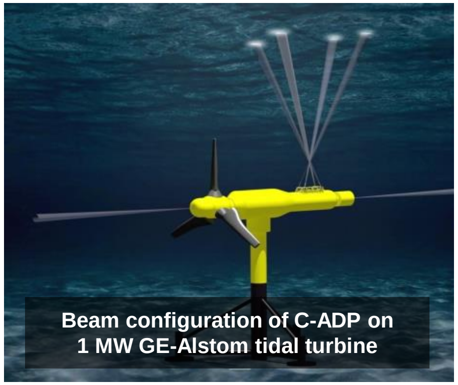
In collaboration with the University of Edinburgh (UK), analysis and validation of novel convergent configuration of acoustic Doppler profilers (C-ADP) performed using data collected from turbine-mounted sensor platform installed at European Marine Energy Centre.

Motion Analyses of Compliant Moorings

In a collaboration with NREL and UW, motion characterization of tethered sensor platforms performed using range of platform geometries (shown to the right) [5,6].

Flow Measurements on the Kvichak River, AK

PNNL assisted NREL and UW in collaborative project with Ocean Renewable Power Company during installation of RivGen® in Kvichak River, Igiugig, AK. Specifically, PNNL and NREL staff involved with field characterization of turbulent velocity at turbine site prior to installation of device using range of acoustic velocimetry techniques.



Beam configuration of C-ADP on 1 MW GE-Alstom tidal turbine

Turbulence (ADV) measurements using StableMoor platform

Aquadopp measurements using towed DoppCats in Kvichak river

- Developed capabilities to estimate tidal turbulence and coherence using mooring-deployed, inertial measurement unit (IMU)-equipped ADVs in energetic tidal flow.
- Improved understanding of ADCP use and processing algorithms in near wake of full-scale MHK devices using CFD simulations
- Demonstrated potential to improve spatial resolution of flow measurements using novel convergent beam ADP
- Improved/developed methods for velocimetry using tethered sensor platforms
- Supported industry partner with field measurements for inflow characterization

Project Publications:

1. Thomson, J., L.F. Kilcher and **S Harding**. 2014. Multi-scale coherent turbulence at tidal energy sites, *Proceedings of the 5th International Conference on Ocean Energy* (ICOE2014), November 4-6, Halifax, Nova Scotia
2. **Richmond, M.**, **S. Harding** and **P. Romero-Gomez**. 2015. Numerical performance analysis of acoustic Doppler velocity profilers in the wake of an axial-flow marine hydrokinetic turbine, *International Journal of Marine Energy*, 11, 50-70.
3. Sellar, B., **S. Harding** and **M. Richmond**. 2015. High-resolution velocimetry in energetic tidal currents using a convergent-beam acoustic Doppler profiler, *Measurement Science and Technology*, 26 (8), 1-10. *Outstanding Paper Award in the field of Measurement Science*
4. **Harding, S.**, B. Sellar and **M. Richmond**. 2016. Field testing of a convergent array of acoustic Doppler profilers for high-resolution velocimetry in energetic tidal currents, *Proceedings of the 4th Marine Energy Technology Symposium* (METS), April 25-27, 2016, Washington, DC.
5. **Harding, S.**, L. Kilcher and J. Thomson. 2016. Turbulence measurements from compliant moorings - Part 1: motion characterization, Journal of Atmospheric and Oceanic Technology, In Review.
6. L. Kilcher, J. Thomson, **S. Harding** and S. Nylund. 2016. Turbulence measurements from compliant moorings - Part 2: motion correction, Journal of Atmospheric and Oceanic Technology, In Review.

Project Plan & Schedule

- Project original initiation date: October 1, 2013 (FY14 start)
- Failure to identify industry partner with test article and test site in FY14 and FY15
- SNL redirected efforts to crossflow turbine experiment at UNH towing tank Q2 FY15
- Experiments completed on time and budget, June 30, 2015
- CACTUS model evaluation delayed one year due to staff shortage. Completed September 30, 2016.
- Deployment of acoustic velocity instrumentation in Puget Sound for multi-scale coherent turbulence studies Q3 FY14
- Deployment of compliant moorings with velocity instrumentation in Puget Sound Q3 FY15
- Field measurements of Kvichak River at ORPC site in collaboration with NREL and UW Q4 FY15
- Completion of final mooring data analysis and submission of journal articles Q4 FY16

Project Budget

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Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NREL $573k PNNL $150k SNL $425k	N/A	NREL $0k PNNL $0k SNL $0k	N/A	NREL $0k PNNL $0k SNL $0k	N/A

- The above table only includes budget authority allocations for each fiscal year, and does not show carryover from FY13.
- Total SNL cost was $728k for project planning, crossflow turbine performance testing, CACTUS model evaluation, and FBG sensor system testing. Remaining funds reallocated to FOA 1310 for supporting industry projects, and Wave Energy Prize project.
- Total PNNL cost was $110k for project experimental planning, field instrumentation and techniques for flow and motion measurements. Remaining funds reallocated to MHK program technical support.
- Total NREL cost was $44k for project experiment planning, instrumentation, and test article selection. Remaining funds reallocated to FOA 1310 for supporting industry projects.

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- University of New Hampshire: Dr. Martin Wosnik
- University of Washington: Dr. Jim Thomson
- University of Edinburgh: Dr. Brian Sellar
- Ocean Renewable Power Company: Jarlath McEntee

Communications and Technology Transfer:

- Three conference presentations: International Conference on Ocean Energy (ICOE) 2014, Marine Energy Technology Symposium (METS) 2015, METS 2016
- Three conference publications: ICOE 2014, METS 2015, METS 2016
- Five peer-reviewed journal publications: *PLOS ONE, Intnl. J. Mar. Enrgy, Msrmt. Sc. & Tech., J. Atm. & Oc. Tech.*
- One technical report
- Three Github sites

Next Steps and Future Research

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FY17/Current research: None

Proposed future research: Accurate data sets on foil characteristics needed over wide range of chord Reynolds number (10^4 to 10^5), and angles of attack up to 30 degrees.