University of New Hampshire
Center for Ocean Renewable Energy (CORE)
Infrastructure Enhancements

Final Report - January 2019

Award Number: DE-EE0003263

Project Title: UNH Center for Ocean Renewable Energy (CORE) Infrastructure Enhancements

Project Period: 07/01/2010 – 09/30/2018

Funding Amount: $750,000

Final Report Submitted: 22 May 2020

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Acknowledgment:
This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Water Power Technologies Office Award Number DE-EE0003623.

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Executive Summary

The objective of this project was to enhance three principal components of the University of New Hampshire (UNH) Center for Ocean Renewable Energy (CORE) research, development and evaluation infrastructure for marine renewable energy (MRE) systems. These three components consisted of

(1) A Tidal Turbine Deployment Platform (TDP) for use at the two UNH tidal energy test sites in Great Bay Estuary/Piscataqua River,
(2) Laboratory Upgrades at Chase Ocean Engineering Laboratory (COEL), and
(3) A Wave/Wind Offshore Test Site Environmental Buoy (for use with WEC testing)

Specifically, for (1) Turbine Deployment Platform, a custom floating platform with nominal dimensions 50 ft x 20 ft (15 m x 6 m) was designed, fabricated and deployed. It uses 42" diameter HDPE pontoons for buoyancy and a galvanized structural steel frame for structural strength. Turbines are deployed through a moon pool via a turbine deployment mechanism. Axial-flow and cross-flow marine hydrokinetic (MHK) turbines with diameters up to approximately 10 ft (3 m) can be deployed. The TDP was designed for use at both the General Sullivan Bridge and Memorial Bridge Tidal Energy Test Sites, both in Great Bay Estuary, NH, both with maximum tidal currents >2.5 m/s. The TDP was first deployed at Memorial Bridge under the NSF-funded "Living Bridge Project" with a 3.2m diameter commercial cross-flow turbine. The mooring system at Memorial Bridge consists of robust custom-designed pile guides which attach to 22-ft tall vertical guide posts on Pier #2, allowing the platform to travel vertically with changing water levels. Various instrumentation components including flow measurement instrumentation, wave measurement instrumentation, and a mobile data acquisition system was acquired to complement the instrumentation already available through the Living Bridge Project.

Specifically, for (2) Laboratory Upgrades at COEL, the towing mechanism of the combined tow/wave tank was fully renovated and upgraded to achieve tow speeds up to 3 m/s and provide highly accurate control of acceleration, velocity and position. A low-drag, 2nd generation hydrokinetic turbine test bed, with a submerged frame made from extruded aluminum NACA 0020 struts enables testing of both cross-flow and axial flow turbines up to nominally 1 m^2 swept rotor area. A High-Speed Cavitation Tunnel (HiCaT), a closed circuit water tunnel with independent control of velocity and pressure, was also renovated. It can achieve test section velocities up to 17 m/s and has a pressure operating envelope from 20-200 kPa. It is equipped with a custom force balance to measure lift and drag on test objects, e.g., hydrofoil sections at various angles of attack. The water quality system for the engineering tank was upgraded.

Specifically, for (3) Wave/Wind Offshore Test Site Environmental Buoy, a custom UNH-built environmental buoy which had previously been deployed for several years at the UNH Offshore Test Site with open Ocean Aquaculture projects required refurbishment to be usable with a wave energy converter (WEC) deployment. Sensors included a radio telemetry link, a lower noise accelerometer for wave measurement, a surface current meter and an acoustic profiling current meter. Upgrades also included various replacement mooring components. The buoy was then used for wave resource measurements during the deployment of a WEC in collaboration with Neptune Wave Power (TX), WEC v3.0 and v3.1.

Towards the end of the project, newly available and comparatively inexpensive, albeit much less capable Spoondrift Spotter wave-rider buoys were acquired which can be used more cost-effectively with future WEC deployments.

The project "University System of New Hampshire--Center for Ocean Renewable Energy (CORE) Infrastructure Enhancements" (DE-EE0003263) was awarded in 2010 and was a unique project, in the sense that awarded funds in the amount of $750,000 were strictly limited to actual infrastructure (equipment). No funding was provided for researcher time for design, coordination, fabrication or installation. As a result, each infrastructure enhancement had to be gradually funded through cooperation with other symbiotic research projects where these projects could provide the personnel support that was needed. For example, a Ph.D. student was funded on M. Wosnik's UNH startup funds (provided to junior faculty at research universities to help start their research) for two years to rebuild the cavitation tunnel, HiCAT. Another Ph.D. student was funded for two years on M. Wosnik's NSF CAREER award to redesign/rebuild the towing mechanism for the UNH tow/wave tank and build a turbine test bed. The new Tidal Turbine Test Platform was designed and built by graduate students over a period of three years where all students were funded by the NSF Living Bridge Project (E. Bell, M. Wosnik, K. Baldwin), and so on. This, securing the necessary permits, and satisfying NEPA requirements to develop the turbine test platform for the Tidal Energy Test Sites at General Sullivan Bridge and at Memorial Bridge (Living Bridge Project), were the main reasons for the extended period of performance of this project. We highly appreciate the patience and flexibility of the program officers and staff associated with this project.

However, despite the duration of the project, this has been a great opportunity to thoughtfully enhance the UNH-CORE infrastructure to support the nascent MRE and Powering the Blue Economy (PBE) industries. We spent the funds deliberately with the objective of the project in mind.

Overall, the UNH-CORE Infrastructure Enhancement Project can be considered a resounding success. For an investment of $750k, DOE WPTO helped improve and upgrade existing MRE infrastructure and create new MRE infrastructure at UNH. The infrastructure upgrades have already been extensively utilized by MRE industry and will continue to serve the R&D mission in support of MRE and PBE industry. Selected highlights include:

<u>Tidal Turbine Deployment Platform and Instrumentation:</u>

- Deployment of a grid-connected crossflow turbine (D=3.2m) on the DOE-WPTO funded TDP under the NSF-funded Living Bridge Project at Memorial Bridge in Portsmouth, NH;
- This was the only tidal turbine deployed in U.S. waters over the past two years;
- This deployment generated significant interest with the National Laboratories active in marine renewable energy, the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL) and a Pacific Northwest National Laboratory (PNNL) and the MHK industry for using this platform for MHK turbine R&D projects. It provides a very cost-effective open-water testing environment in an energetic tidal estuary at a meaningful physical scale of D~2-3m, i.e., at large enough Reynolds numbers so that performance is independent of Reynolds number.

MHK turbine test bed for the UNH towing tank, renovated tow mechanism and instrumentation:

- Fundamental research with in-house Reference Vertical Axis Turbine (UNH-RVAT), which generated fundamental insights, several public data sets for numerical model validation, and was included in a US-DOE publication on reference model testing;
- UNH-Sandia collaboration on testing of a 1:6 scale (D=1.08m) Reference Model 2 (RM2) turbine, generated public data sets for numerical model validation;
- First successful in-water demonstration of Fiber-Bragg-Grating (FBG) optical strain measurements on an MHK turbine with SNL, using UNH-RVAT;
- Tank testing of a commercial ducted axial turbine under a DOE SBIR Phase 2 project;
- Provided turbine testing capability for research projects of several graduate students from University of Washington (B. Polagye's research group, Pacific Marine Energy Center (PMEC)) over the period 2017-18;
- Test bed is used for an ongoing DOE project on high deformation hydrofoils under FOA 1663 with Ocean Renewable Power Company (ORPC);
- Test bed has been used for single-rotor testing in ORPC ARPA-E project on autonomous turbine generator unit (ATGU);
- Test bed was selected as one of the DOE TEAMER facilities for the first round.

High-speed cavitation tunnel:

- Used for design & testing of novel bi-directional hydrofoil shapes;
- Used for cavitation testing of hydrofoil shape originally specified for RM1 turbine, NACA 63-424.

Wave/Wind Offshore Test Site Environmental Buoy:

- Was used to support MHK industry during wave energy converter (WEC) deployments with Neptune Wave Power (TX), WEC v3.0 and v3.1, at UNH Offshore Test Site South of Isles of Shoals

Acknowledgements

We would like to thank the following people and agencies:

Graduate students Ivo Nedyalkov, Pete Bachant, Matt Rowell, Ian Gagnon, Kaelin Chancey and others, including several undergraduate engineering students working on senior capstone projects (UNH course TECH 797, funded though NH Sea Grant), for helping design, build and commission a unique and very useful set of test facilities and tidal turbine deployment infrastructure for marine renewable energy research and development.

Collaborators: Erin Bell, P.I. for Living Bridge Project (NSF-PFI, NH-DOT, FHWA).

Funding agencies that paid for graduate students, UNH, NSF-CAREER, NSF-PFI, and supported undergraduate research projects, NSF-REU and NH Sea Grant.

Sheri Millette in the Business Services Center of the UNH College of Engineering and Physical Sciences for processing a never-ending stream of receipts for parts.

Vince Neary at Sandia National Laboratories for recognizing the quality of the turbine performance data that can be acquired with the new turbine test bed in the UNH towing tank, and for collaborating on the DOE Reference Model 2 (RM2) project with us.

US Department of Energy Water Power Technology Office.

At the US Department of Energy Water Power Technology Office: DOE Project Monitor Michael Carella for his thoughtful guidance and infinite patience, DOE Field Project Officer Tim Ramsey, DOE HQ Program Manager Alejandro Moreno, DOE Environmental Protection Specialist Roak Parker, and everybody in DOE Contracting for their patience and understanding, and allowing us an unusually large number of No-Cost Extensions.

Introduction

The United States, like most countries, faces significant challenges in energy sustainability and security, which motivates research into renewable energy technologies. Marine Renewable Energy (MRE), including tidal, ocean current and wave energy, has significant energy resources in the United States, but has proven challenging to be converted to usable forms of energy in a cost-effective way.

The Center for Ocean Renewable Energy at the University of New Hampshire (UNH-CORE) was founded in the Spring of 2008, with founding members with a broad range of relevant expertise in Ocean Engineering, Mechanical Engineering, Civil and Environmental Engineering and Electrical Engineering.

UNH-CORE provides research and technology evaluation for Ocean/Marine Renewable Energy systems at multiple scales. Cost-effective open water test sites for tidal energy and wave and offshore wind energy are available in close proximity to extensive support infrastructure. CORE is a synergistic, interdisciplinary center for research, development and evaluation for MRE systems, from the laboratory scale to open water large or full scale deployments. CORE provides innovation and commercialization support for developers as they evolve tidal, ocean current and wave energy systems – collectively known as “marine hydrokinetic (MHK)” energy systems, and offshore wind platforms. CORE helps train the next generation of engineers, scientists and policy makers for advancing this new industry.

The physical infrastructure available at UNH-CORE is unique in terms of proximity, ease of access, and favorable test site characteristics. It consists of the Chase Ocean Engineering Laboratory (COEL) with wave/tow tank, engineering tank and water/wind tunnels, two tidal energy test sites in Great Bay Estuary, the UNH Pier and the AMAC/wave and offshore wind energy test site. The layout of the UNH open water test sites and marine support infrastructure is shown in shown in Figure 1.

The UNH-CORE Tidal Energy Test Site at General Sullivan Bridge is a sheltered “Nursery Site”, where tidal turbines can be deployed off a floating platform, with turbine diameters up to ~3m (cross flow/axial flow). The peak currents are typically > 2 m/s during each tidal cycle, with maximum currents >2.5 m/s. The nominal depth is about 10 m, with a tidal range of ~2.5m. UNH-CORE has operated the site with local and state permits, and has recently completed a full Environmental Assessment (EA) through the US Department of Energy under NEPA in 2014. The site is not grid-connected. The test location has a flat bottom, and there is easy access to the site from the UNH Pier and nearby marinas and docks. Marine Hydrokinetic Turbines are deployed from the surface via floating platforms for DoE Technology Readiness Levels (TRL) 5-6 for MRE devices, and for the full range of TRLs for PBE applications [1,2].

The UNH “Living Bridge” turbine deployment site was developed under the NSF “Living Bridge Project” (PFI IIP-1430260) and NH-DOT funding, and is located on the south-facing side of Pier 2 of the Memorial Bridge in Portsmouth, NH. The nominal depth is 18 m, with maximum currents on the ebb tide of > 2.5 m/s, and a tidal range of ~3.5m. The test site is permitted under the US Army Corps of Engineers. The test site is connected to the bridge grid. There is easy access to the site from the UNH Pier and nearby docks, with platform egress/transport in emergency situations to the NH Port Authority or the NH Sate Fishing Pier. Marine Hydrokinetic Turbines are deployed from the surface via a floating platform moored to vertical guide posts mounted on Pier 2, for testing at DoE TRL 5-6 for MRE devices, and for the full range of TRLs for PBE applications. The turbine deployment location can be viewed from a new deck built by the City of Portsmouth at the foot of Memorial Bridge and provides an excellent opportunity for STEM outreach [3,4].

The UNH Offshore Test Site for Wave and Wind Energy is research-permitted 36 acre site in NH state waters (permits through Army Corps of Engineers, NH-DES). The site is located 6 miles off-shore, 1 mile south of Isles of Shoals, NH in state waters, and is 52m deep. The site was originally developed as the Atlantic Marine Aquaculture Center (AMAC) test site [5,6], and extensive environmental and survey data is available. The site is supported by research vessels (R/V Gulf Challenger, others) and diving crews. It provides a typical Northeast wave climate, and can be considered a scaled wave energy site for MRE devices (TRL 5-6) and full scale test site for all TRLs for PBE applications.

The main staging area for UNH tidal estuary, near-shore and offshore work is the UNH Pier at the Judd Gregg Marine Research Complex, located 1 hr north of Boston about 8 km from Interstate I-95. The Pier Support Facility has offices, specialized fabrication and repair areas, and storage space. The UNH Pier has a crane and offers drive-on access for boom trucks.

Faculty and staff of CORE have a long history of solving complex ocean problems and have depth of experience relevant to ocean energy in Mechanical, Ocean and Civil Engineering. Beyond engineering, other UNH faculty involved with CORE are experts in environmental and ocean sciences, policy, community engagement and regulatory issues and business and finance.

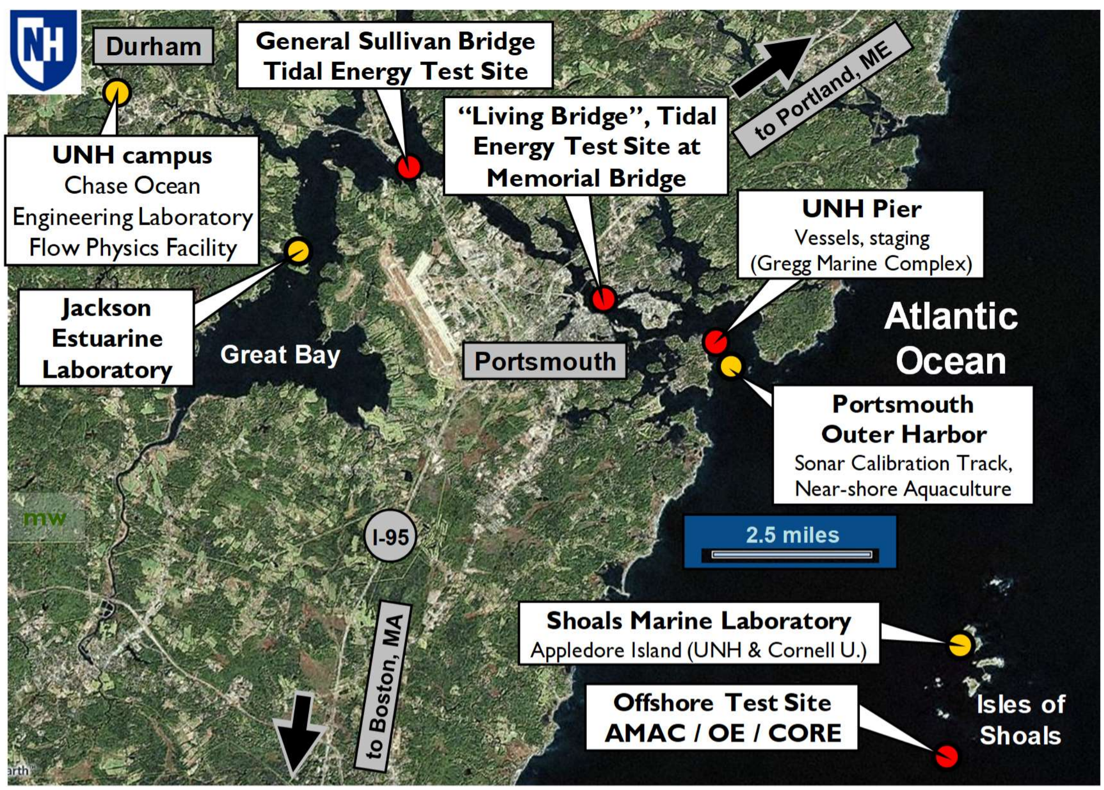


Figure 1. Map of Great Bay Estuary, New Hampshire, with locations of UNH-CORE marine renewable energy test sites and UNH marine support infrastructure.

Statement of Work

This final report follows a revised Statement of Project Objectives (SOPO) from March 2018, approved by the US Department of Energy. The main difference between the SOPO from March 2018 and the original SOPO from 2010 was an acknowledgement that the Tidal Turbine Deployment Platform should be designed to be deployable at both Tidal Energy Test Sites developed by UNH-CORE, at General Sullivan Bridge and Memorial Bridge. Where applicable, distinctions between the two sites were made.

The Statement of Work is briefly summarized here, and in the following section of the report it will be described what was accomplished under each project task.

The objective of this project was to enhance three principal components of the University of New Hampshire (UNH) Center for Ocean Renewable Energy (CORE) research, development and evaluation infrastructure for marine renewable energy (MRE) systems. These three components consisted of a Tidal Turbine Deployment Platform (TDP) for use at the two UNH tidal energy test sites in Great Bay Estuary/Piscataqua River, Laboratory Upgrades for Chase Ocean Engineering Laboratory (COEL), and an environmental monitoring buoy for use with WEC testing at the UNH Offshore Test Site.

Statement of Project Objectives (SOPO) --- Summary

Task 1 Tidal Turbine Deployment Platform (TDP)

- **1.1** Turbine Deployment Platform Design and Fabrication (for use at General Sullivan Bridge and at Memorial Bridge)
- **1.2** TDP Mooring System Design and Acquisition
    - ***1.2.1*** TDP Mooring System Design and Acquisition (General Sullivan Bridge)
    - ***1.2.2*** TDP Mooring System Design and Fabrication (Memorial Bridge)
- **1.3** TDP Instrumentation
    - ***1.3.1*** TDP Instrumentation (General Sullivan Bridge)
    - ***1.3.2*** TDP Instrumentation (Memorial Bridge)
- **1.4** Turbine Deployment Structure

Task 2 Chase Lab Upgrades[1]

- **2.1** Tow System Upgrade
- **2.2** Wave and Tow Tank Instrumentation
- **2.3** Water Quality System
- **2.4** High Speed Water Tunnel

Task 3 Offshore Wave/Wind Test Site Environmental Buoy

- **3.1** Environmental Buoy Water Column Sensors
- **3.2** Environmental Buoy Mooring Components

[1] Subtasks 2.1 and 2.2 are reported in reverse order compared to how they were listed in the original SOPO, because it makes more sense to report the instrumentation in reference to the tow system.

Task 1 Tidal Turbine Deployment Platform (TDP)

The Great Bay Estuary (GBE) system in New Hampshire, shown in Figure 1, is a tidally driven estuary that is one of the most energetic on the East Coast of the United States [7]. The tidal range is on the order of up to 4 m at the Gulf of Maine mouth and decreases to about 2 m in the upper estuarine locations. The Gulf of Maine connects to the upper estuary by way of the Lower Piscataqua River, whose channel depth is on the order of 15-20 m with maximum currents ranging between 0.5 m/s and 2.0 m/s, with faster currents at constrictions (which mostly coincide with bridge locations) during spring tides. The tidal sea level excursions cause almost half of the volume of Great Bay to be exchanged during each tidal cycle. Several freshwater tributaries exist in this section, but their overall input to the system is low, representing only 1% or less of the tidal prism under normal conditions. This makes the Great Bay Estuary a tidally dominated, well-mixed system with near ocean salinity.

The GBE is well studied and surveyed (1976, 2007) and has been modeled numerically to understand its dynamics and circulation. The first order dynamics of this system and tidal analysis results were discussed by [8]. In the Great Bay Estuary, the M2 tidal constituent is dominant by more than an order of magnitude over the two other semidiurnal constituents N2 and S2. The two important diurnal tidal constituents K1 and O1 are also of lower order compared to M2. More recent numerical modeling was reported by [9], [7] and [10] (in order of publication).

A new test platform, or Turbine Deployment Platform (TDP), was designed and fabricated for deploying intermediate scale tidal energy conversion devices at tidal energy test sites in Great Bay Estuary, NH, including the UNH-CORE **Tidal Energy Test Site at General Sullivan Bridge (GSB)** and the **Tidal Energy Test Site at Memorial Bridge in Portsmouth, NH**. The test platform has a decked, twin-hulled configuration, based on our previous field experience with a smaller test platform. Tow tank testing of a 1:13 scale physical model indicated that the design is very stable in high currents, both longitudinally and transversely, and that there is ample reserve buoyancy. The test platform was equipped with instrumentation to evaluate the tidal flow upstream and downstream of the device under test throughout the water column, in situ loads on the mooring system, detailed flow measurements, platform motion, and mechanical and electrical outputs of the device under test.

1.1 Turbine Deployment Platform Design and Fabrication (for use at General Sullivan Bridge and at Memorial Bridge)

The University of New Hampshire Center for Ocean Renewable Energy (UNH-CORE) utilized U.S. Department of Energy (DoE) funding for ocean renewable energy infrastructure to design and fabricate a hydrokinetic (tidal) Turbine Deployment Platform (TDP). The TDP is a floating platform with nominal dimensions of 50 ft x 20 ft (15 m x 6 m), c.f. Figure 2 (CAD rendering) and Figure 3 (built and deployed at UNH Pier, prior to first turbine installation). The TDP uses 42-inch (1.07 m) diameter HDPE foam-filled pontoons for buoyancy and a galvanized steel frame for structural strength. Turbines are deployed through a moon pool (with dimensions 11 ft x 18 ft, or 3.3 m x 5.7 m) via a turbine pitching mechanism. The orientation of the moon pool was chosen so that turbines can be rotated out of the water under load during the stronger ebb tide flow at the Memorial Bridge location. Axial-flow or Cross-flow marine hydrokinetic (MHK) turbines with diameters up to approximately 10 ft (3 m) can be deployed. Detailed

TDP specifications are given in [11, 12]. Ultimately the design was tailored for the Memorial Bridge location, since this was the first deployment location for the TDP. During the design process for the TDP, the support and environmental condition of the Memorial Bridge and General Sullivan Bridge locations were considered. Throughout the design and fabrication process, the broader needs of the MRE industry for MHK turbine testing at this scale were considered. The TDP maintains the functionality anticipated for the original General Sullivan Bridge platform (original SOPO). The TDP can be deployed at the General Sullivan Bridge Tidal Energy Test Site using site-appropriate moorings, discussed below.

Predicted structural demand on the TDP due to gravity, wind, waves, and tidal currents were determined based on expected worse case environmental conditions with a tidal turbine deployment. To design the TDP steel frame against wave loads DNV-GL specified wave load cases were used [16, 17]. Once these demands were accepted by the design team, a SAP2000® finite element analysis (FEA) model was created for the vertical guide posts (VGPs) and the TDP steel frame, Figure 4.

These FEA models were used to ensure the anchorage of the VGPs could withstand the TDP mooring forces due to wind, wave, and currents without causing damage to the concrete bridge pier. The FEA models were also used to ensure the VGPs could withstand vortex induced vibrations. The TDP mooring forces due to waves on the VGPs were determined using empirically derived results [13-15]. The VGPs are instrumented with uniaxial strain transducers to measure loads and compare those loads to input forces measured by a suite of estuarine sensors. The design analysis and fabrication constraints were used to determine the final specifications of the hydrokinetic turbine deployment structure.

The structure was designed to enable the deployment of a hydrokinetic turbine at a bridge location, and thereby demonstrate the feasibility of deploying turbines at similar bridge sites. Additional information with regards to the structural design and the operation of the tidal energy conversion system can be found in [18] and [19]. The details of all the design calculations are given in [12].

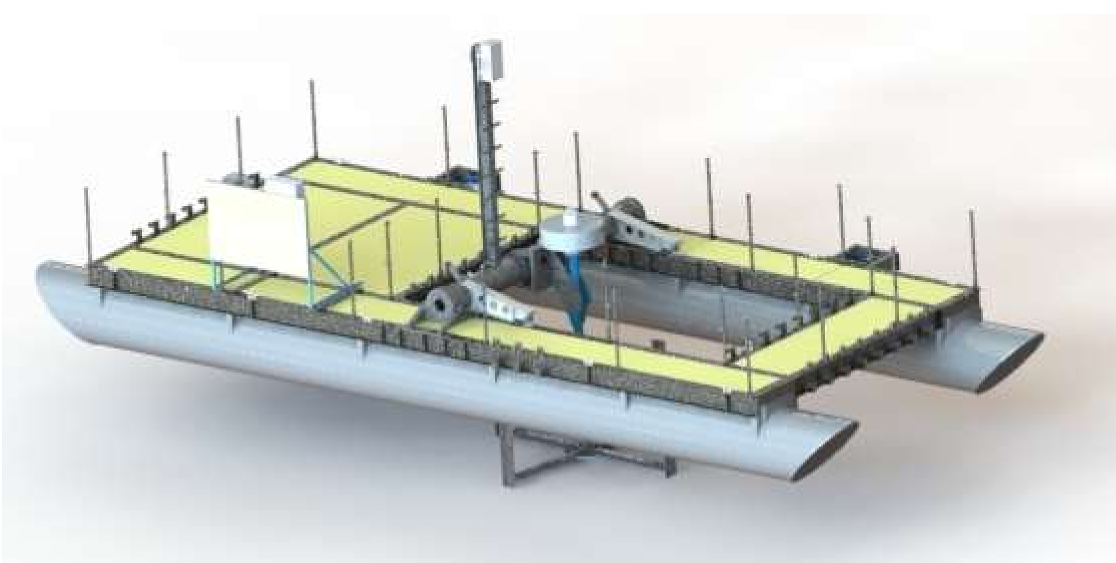


Figure 2. Department of Energy (DoE)-funded Turbine Deployment Platform (TDP). CAD rendering.

Figure 3. Department of Energy (DoE)-funded Turbine Deployment Platform (TDP). built and deployed TDP system at UNH Pier, prior to installation of the first hydrokinetic turbine.

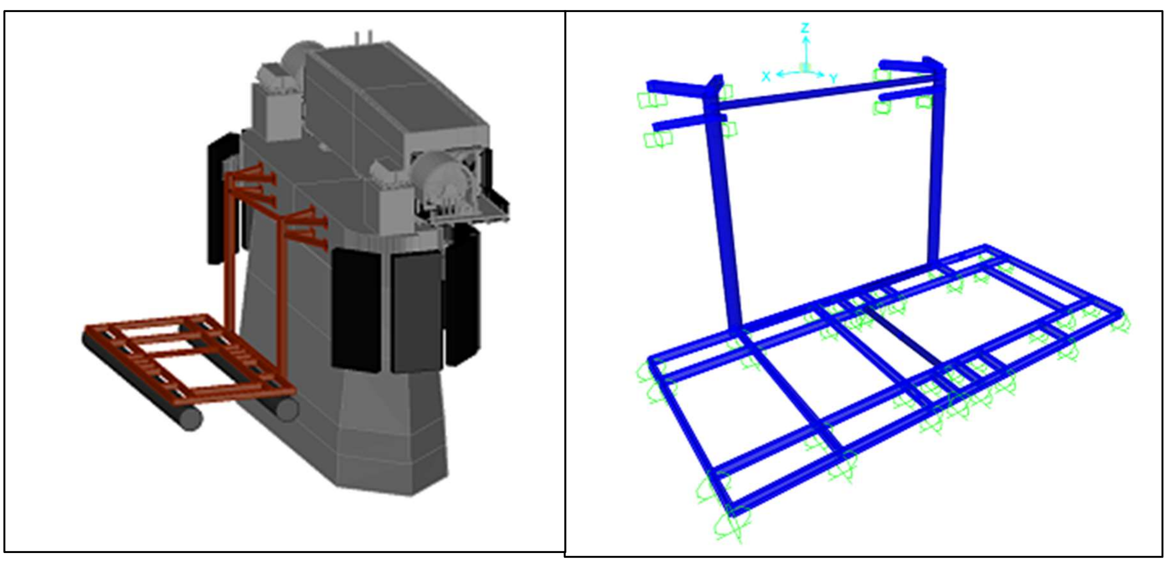


Figure 4. Three-Dimensional Image (left) and SAP2000® Model (right) of the Turbine Deployment Platform.

Table 1: Design specifications for the 50 ft x 20 ft Turbine Deployment Platform (TDP)

Design Specifications	
Maximum current speeds*	Memorial Bridge: >2.5 m/s General Sullivan Bridge: >2.5 m/s
Design wind speed	40 mph (platform removal required for extreme weather events, e.g. hurricanes)
Design wave height ($H_{1\%}$)	2.5 ft
Hull draft (moulded)	2.1 ft
Maximum crew	10 persons
Power management	Grid connected net metering (at Memorial Bridge) and stand-alone off grid load bank available (at both deployment sites, 25 kW)
Available utilities	120VAC (via utility grid at Memorial Bridge, via generator at General Sullivan Bridge) and internet via Ethernet (at Memorial Bridge)

The 3 m turbine diameter size, seen in Figure 5. Tidal Turbine during installation on the TDP at UNH Pier.

The Tidal Turbine Deployment Platform is considered appropriate for open-water tests of scaled MHK turbines at "nursery sites". Using this new test infrastructure, the MHK industry can perform medium-to-long-term testing with inexpensive device deployment and retrieval, and re-deployment to facilitate low-cost incremental testing of issues related to installation (deployment) and operation and maintenance.

Figure 5. Tidal Turbine during installation on the TDP at UNH Pier.

With regards to the US Department of Energy/Sandia Reference Model Project, this scale and the UNH infrastructure would allow open-water testing of a ~1:6 scale model of the Reference Model 1 (RM 1, D=20m rotor), and a ~1:2 scale model of one rotor of the Reference Model 2 (RM 2, D=6.45m rotor).

The DOE UNH Center for Ocean Renewable Energy infrastructure project was able to leverage the UNH-based "Living Bridge" Project, which in turn provided the U.S. marine hydrokinetic (MHK) energy industry with an easily accessible open-water test site for tidal energy conversion devices of up to 10 ft (3 m) in diameter. The Living Bridge (LB) Project is an ongoing smart transportation infrastructure project funded by the National Science Foundation (NSF), the New Hampshire Department of Transportation (NHDOT) and the Federal Highway Administration (FHA).

1.2 TDP Mooring System Design and Acquisition

The TDP needs to be moored securely during ebb and flood tides. The mooring system was designed to accommodate the combined loads from tidal currents, waves and wind. The loads from tidal currents included the turbine, platform hulls, and appendages for deploying instrumentation. The anticipated forces on the mooring attachment points were analyzed and studied in a 1:13 scale physical model test of the turbine deployment platform in the UNH towing tank.

1.2.1 TDP Mooring System Design and Acquisition (General Sullivan Bridge)

The UNH-CORE Tidal Energy Test Site at the General Sullivan Bridge is located in a constricted area in the estuary, with easy access from nearby marinas or the two local UNH marine facilities. The site has the fastest tidal current velocities in the estuary with maximum currents at over 5 knots (2.6 m/s), and typically greater than 4 knots (2.1 m/s), and hence it is an excellent site for testing tidal energy conversion devices. The test site has a nominal depth of about 10 m (with a minimum depth of >8 m at LLW) and can be used for MHK turbines up to 3-4 m in diameter.

Figure 6 shows a close-up of the constriction in the estuary at General Sullivan Bridge (top)/Little Bay Bridges (bottom two bridges). MHK turbines are deployed just to the Southeast of the navigation channel, as indicated by the dot in the figure, where the channel is actually slightly deeper than the navigation channel and has a flatter bottom.

Tidal resource assessments were conducted both with long-term bottom deployments (upward looking) and shipboard measurements (downward looking) using acoustic Doppler current profilers (ADCPs). During tidal turbine deployments the tidal energy resource at turbine inflow was also monitored with a downward looking ADCP and an acoustic Doppler velocimeter (ADV) [5].

In 2007 NOAA/NOS measured tidal current data with bottom-deployed Acoustic Doppler Current Profilers (ADCP) in Great Bay Estuary, including at the UNH-CORE Tidal Energy Test Site [20, 21]. Based on this data, NOAA publishes predicted times and magnitudes of ebb and flood peak velocities as well time of slack water. The predictions and the raw data are available on their website in the public domain (http://tidesandcurrents.noaa.gov/). Shipboard ADCP surveys are typically conducted with UNH vessels (R/V Gulf Challenger, R/V Gulf Sureveyor, R/V Galen J).

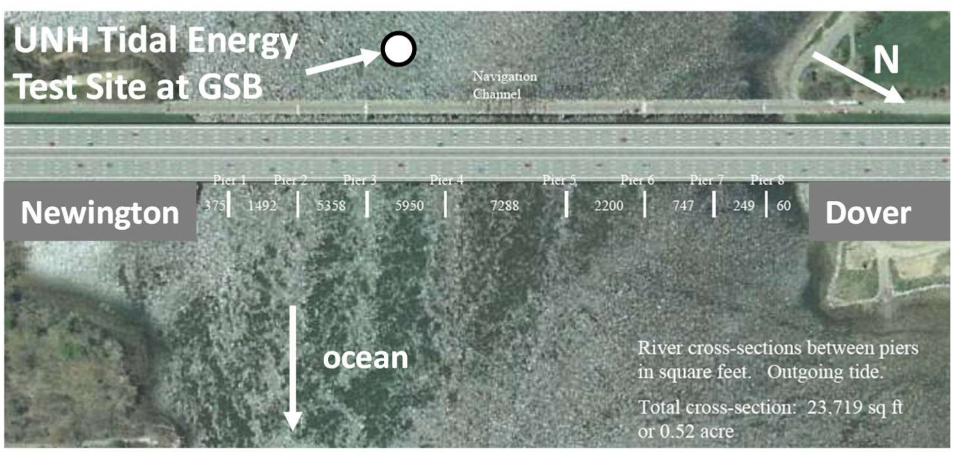


Figure 6. UNH-CORE Tidal Energy Test Site at General Sullivan Bridge (GSB) in Great Bay Estuary. The white dot is the approximate location of the test platform when deployed. (Note the changed orientation of this Figure, i.e., North arrow.)

During the highest tides of the year (King Tide) in 2011 the UNH "CBASS" (Coastal Bathymetry Survey System), an instrumented Yamaha Waverunner with a 192 KHz single-beam echosounder, 240 KHz Imagenex Delta-T multibeam sonar integrated with an Applanix POS-MV 320 GPS-aided Inertial

Measurement Unit, and a downward looking 1200 KHz ADCP, was used to sample the tides for 2x 6 hrs. CBASS [22] is capable of sampling in water depths ranging 1-25m – over relatively large (km) scales – the fine-scale seafloor bathymetry with very fine scale resolution coincident with the vertical structure of mean currents spanning the water column. The spatial distribution of the mean tidal current magnitude at the UNH-CORE Tidal Energy Test Site is shown in Figure 7, and exceeded 2.5 m/s in the top part of the water column for the 36 minutes (0.6 hours) of ADCP data that was averaged to create this plot.

Rowell et al. [1] provides an example of an MHK turbine deployment at the Tidal Energy Test Site at General Sullivan Bridge, under a DOE SBIR Phase 2 project and with NREL instrumentation support.

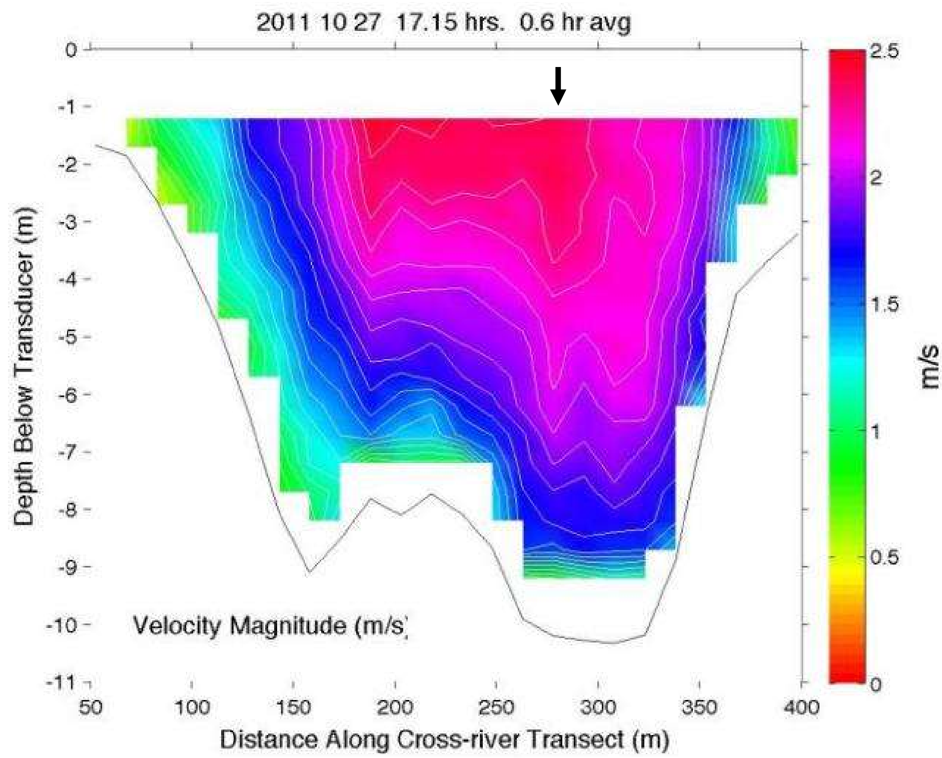


Figure 7. Mean current magnitudes (averaged over 0.6 hr) at max ebb flow measured at UNH-CORE Tidal Energy Test Site at General Sullivan Bridge, Great Bay Estuary, NH, during King tides in Fall 2011, looking downstream. Arrow marks typical location of turbine during testing.

The TDP can be deployed at the General Sullivan Bridge Tidal Energy Test Site using site-appropriate moorings. Forces on the mooring lines, based on analysis of the turbine deployment platform will be considered for the anchors required at the General Sullivan Bridge Location. The mooring system will be configured to allow testing during both the ebb and flood parts of the tidal cycle, and will include bottom anchors. Mooring line, chain and anchor configurations will be evaluated and acquired to be installed at the General Sullivan Bridge site.

Procurement of mooring components for GSB site

The estuary bottom at the GSB site is scoured rock, with some “micro-canyons”. The only anchors that will hold well in this situation are either drilled anchors or gravity anchors. Drilled anchors with a grouted-in chain were specified and a marine contractor gave an estimate for the installation at ~$30k at the beginning of the project. The project then went through an Environmental Assessment under NEPA, including a Biological Evaluation, through DOE Golden office, and eventually a finding of “Not Likely To Adversely Affect” (marine fauna, flora) was obtained. When the anchor installation was priced out again in 2016-17, the actual cost would have been $60k. A less expensive option, financially feasible within the budget, would have been gravity anchors (granite blocks, readily available in New Hampshire). This mooring type was not permitted under DOE’s NEPA review, could also not be purchased for future use after re-permitting.

The project then went ahead and procured other necessary mooring components for the GSB mooring configuration. This consisted of 4 shots of ¾ inch galvanized chain, large balls for buoyancy/floatation and large pennants. These are shown Figure 8.

Figure 8. Components of mooring system for Tidal Energy Test Site at General Sullivan Bridge. Left: buoyancy floats and pennants, right: 3/4" galvanized steel chain (currently in storage in Chase Ocean Engineering Laboratory).

1.2.2 TDP Mooring System Design and Fabrication (Memorial Bridge)

The Memorial Bridge is located between Portsmouth, New Hampshire and Kittery, Maine. It crosses the Piscataqua River in the Great Bay Estuary (GBE) system, which is one of the most energetic tidally driven estuaries on the East Coast of the United States. The tidal currents at Memorial Bridge reach speeds greater than 2.5 m/s during spring ebb tides at the project location, making it a good tidal energy test site, cf. Figure 9. At the project location, the nominal depth is about 18 m and the maximum tidal range is about 4 m. The TDP is moored to the bridge via vertical guide posts (VGP), attached to the face of the Portsmouth-facing side of Pier #2 (cf. Figures 3, 4). The VGPs are 22 ft (6.7 m) tall, galvanized steel 16 inch pipes, allowing the platform to travel vertically with changing water levels. The maximum travel is the 100 year flood elevation plus 2.5 ft (0.76 m) for wave motion (design wave). The Living Bridge project deployed a 3.2 m diameter and 1.7 m tall cross-flow turbine, supplied by New Energy

Corporation, with a rated capacity of 25 kW (rated at 3 m/s for a 3.4 m rotor; the 3.2 m rotor at Memorial Bridge will produce maximum power of ~15 kW). The turbine was first deployed in the summer of 2018, and has since been operated successfully in both *off-grid* (25 kW load bank) and *grid-connected* configurations (480V bridge grid).

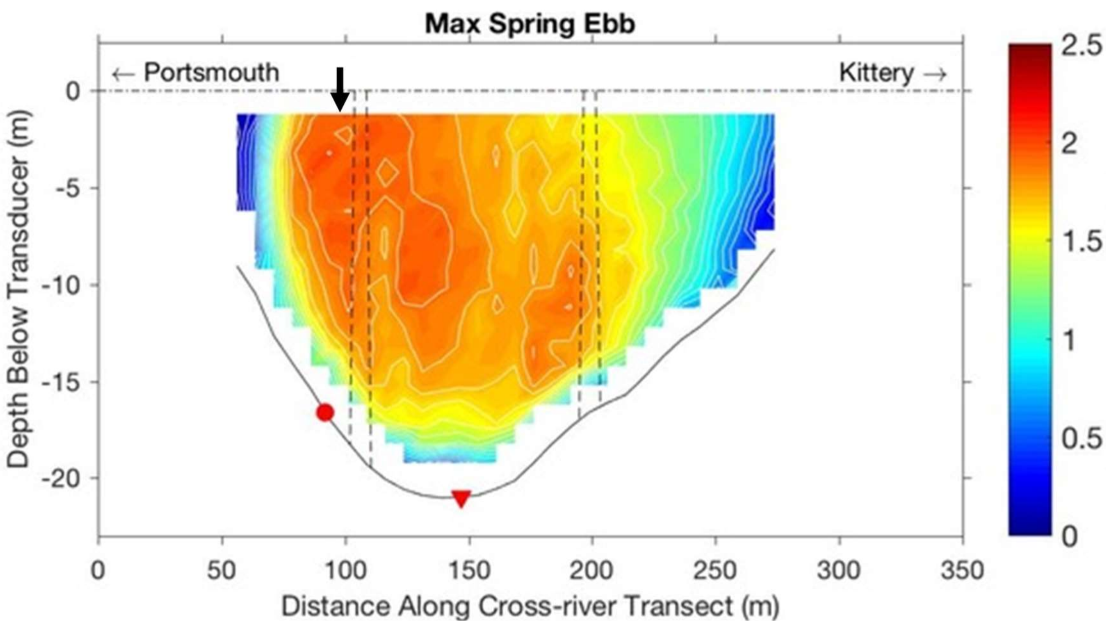


Figure 9. Spatial distribution of the tidal current magnitude at Memorial Bridge in Portsmouth, NH (42 minute average during a spring ebb tide). Black arrow indicates deployment location, dashed vertical lines represent bridge piers.

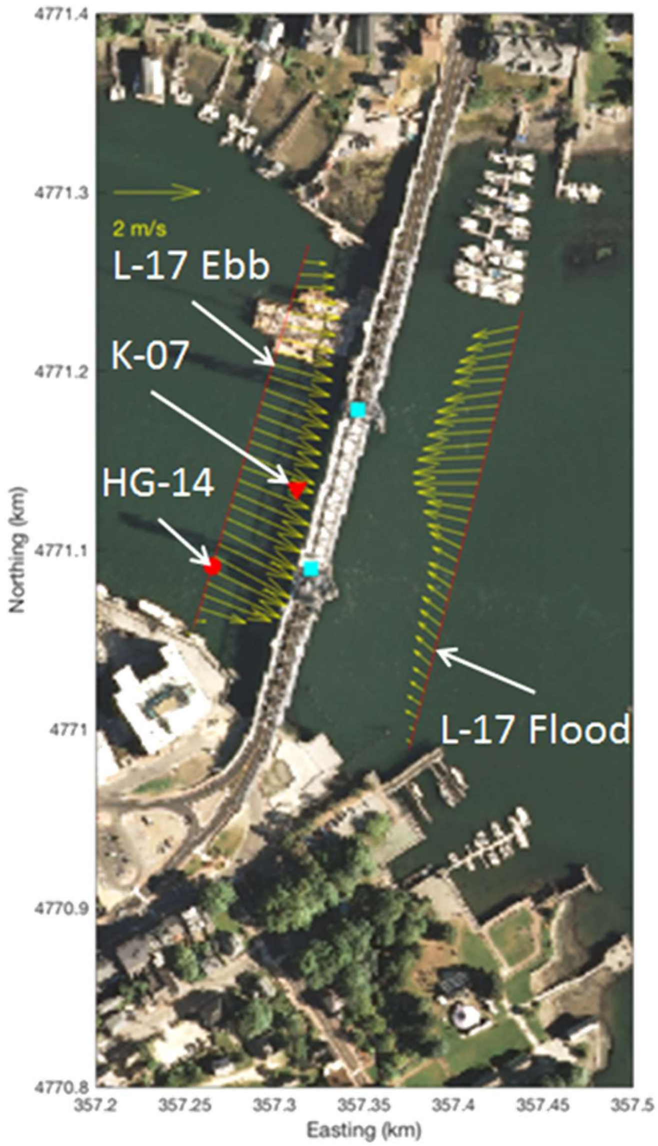


Figure 10. Surface current magnitude and direction at Memorial Bridge in Portsmouth, NH (42 minute average during a spring tide). Note the asymmetry between ebb and flood tide.

For the Living Bridge project at Memorial Bridge, the concept was to have the two vertical guide posts fixed to the bridge pier. The TDP then floats up/down vertically with the rise and fall of the tide. The guide posts become part of the bridge structure, which is owned and operated by NHDOT. NHDOT provided funds for this component of the turbine deployment system. These VGPs are attached to the bridge pier cap above the water line. The Memorial Bridge site deployment structure is independent from and has no contact with the estuary bottom, see Figure 11. The mooring system at the Memorial Bridge deployment site was designed to resist the strong tidal currents as well as waves and wind expected in that location. A pile-guide system with a robust box beam locking configuration, with redundant rollers and wear-resistant blocks, was custom-designed and installed to reduce the risk of

TDP damage, see Figure 12. The final turbine deployment system at the Memorial Bridge includes the VGPs and the TDP, see Figure 13.

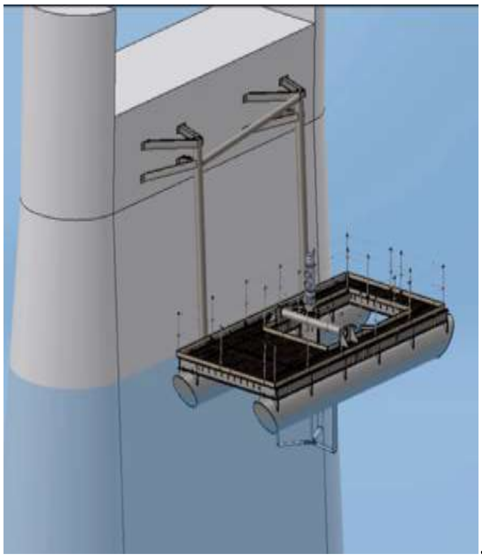


Figure 11. Schematic of the Tidal Turbine Deployment System attached to the Pier at the Memorial Bridge.

Figure 12. Mooring system for Tidal Energy Test Site at Memorial Bridge (Living Bridge Project). Custom-designed pile-guides with redundant rollers and additional redundancy recessed wear-blocks.

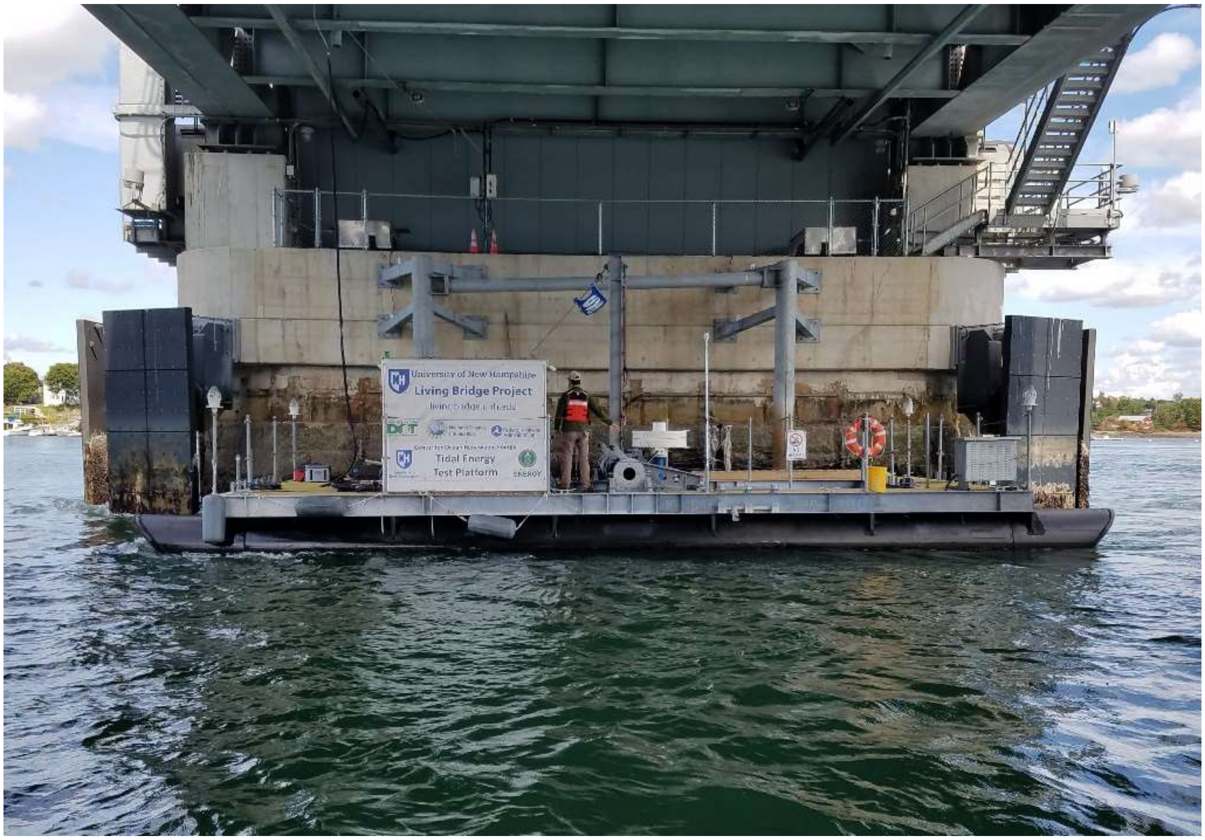


Figure 13. Tidal Turbine Deployment System at the Memorial Bridge in Portsmouth, NH including the Vertical Guide Posts anchored to Pier #2 and the Turbine Deployment Platform.

1.3 TDP Instrumentation

This subtask was discussed at a meeting with a potential industry user group. It is obvious there is a need to measure the current speed before and after it interacts with the turbine under test. This will be accomplished with Acoustic Doppler Current Profilers (ADCP) some distance upstream and downstream of the turbine under test (about 2D upstream and 2D downstream for a D=3m diameter turbine).

ADCPs and Acoustic Doppler Velocimeters (ADVs) will be used to measure the flow entering and exiting the turbine. The ADVs operate at ~6MHz and have an effective range of <1m (similar to medical ultrasound devices). The devices ensonify a 15mm diameter by 20mm long cylindrical volume. The data acquired with the ADVs provide a fine scale resolution of the turbulence, either of the incoming flow or in the turbine wake. These devices will be deployed for detailed resource assessments and when a turbine is under test. The ADVs will be deployed alongside the ADCPs, which provide flow velocity data on a larger scale and over the entire water column.

An list of available instrumentation is given in Table 2, a schematic of the general instrumentation configuration and integration for in-water test of hydrokinetic turbines at Memorial Bridge is shown in Figure 14, and the instrumentation layout on the platform and available mounting locations are shown in Figure 15.

Table 2: Overview of available instrumentation.

Available Instrumentation	
Tidal current velocity	2x LinkQuest FlowQuest 1000 ADCP, 2x Nortek Signature 1000 ADCP 2x Nortek Vector ADV (w/ built-in IMU)
Video	2 Luxus Compact underwater cameras
Rotor Thrust	2 LCM Systems Load 100kN load cells
Mooring loads	Strain gages on vertical guide posts (8x) 4x 20 kip waterproof in-line load cells
Water quality	1 Valeport MIDAS CTD+ with turbidity and chlorophyll sensor
Wave measurements	Spoondrift Spotter Buoys Wave Staff and IMU
Atmospheric Conditions	2x AirMar 200WX weather stations thermal anemometry
Generator voltage, current, and speed (RPM)	Voltsys generator controller
Data Acquisition	1x custom built MacArtney underwater multiplexer connected to SCADA system (can live stream data to project website) 1x NI CompactRio based system (similar to NREL MOIS), many analog & digital I/O

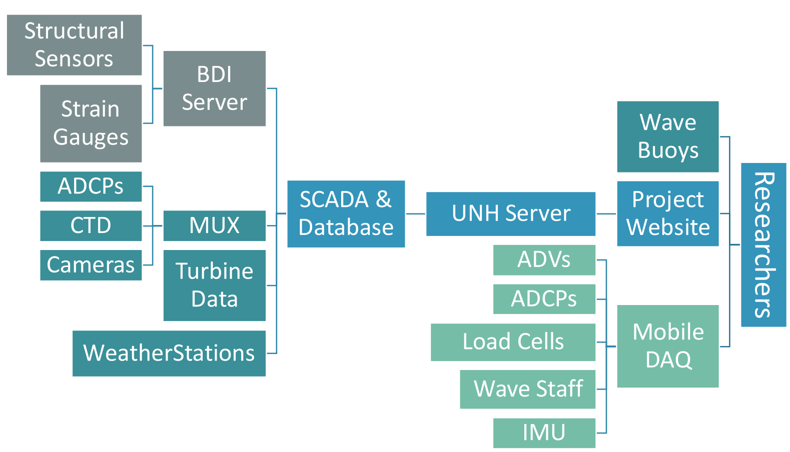


Figure 14. Living Bridge Project: schematic of general instrumentation configuration and integration for in-water test of hydrokinetic turbines, Memorial Bridge, Portsmouth, NH [5].

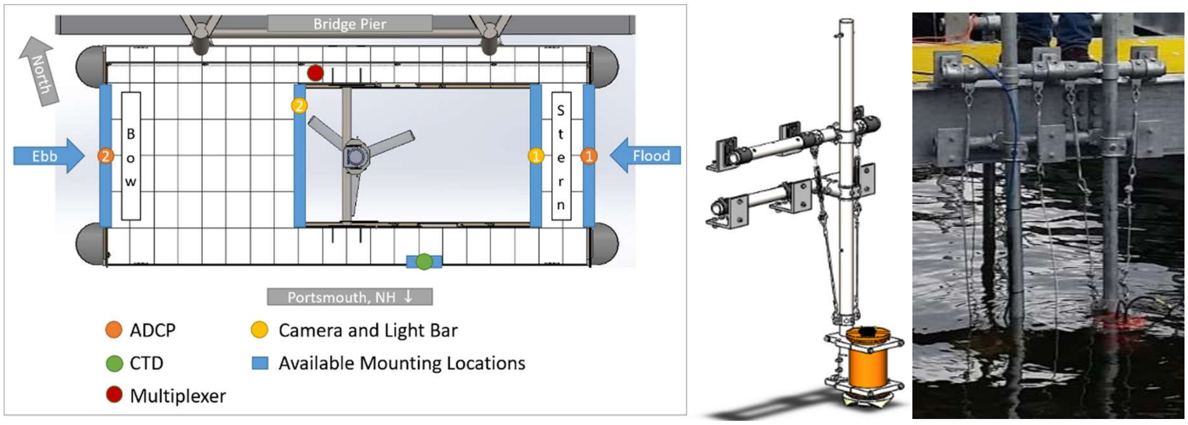


Figure 15. Left: Layout of basic instrumentation on platform and available mounting locations for additional instrumentation (blue); center: universal instrument mounting system designed for safe and easy deployment; right: example of two instruments deployed side-by-side [5].

The electrical output of the generator associated with the system can be used to assess the water-to-wire efficiency of the device under test. Additional instrumentation is needed to assess the mechanical efficiency of the turbine and any other mechanical components. Mooring loads can be measured during testing to determine the drag on the platform due to the particular turbine under test.

The same instruments will be used at the GSB and MB sites, however, there differences in the instrumentation and data acquisition systems used at each site.

1.3.1 TDP Instrumentation (General Sullivan Bridge)

At the GSB site, a mobile data acquisition system will be used for all measurements: This system will be based on the Modular Ocean Instrumentation System (MOIS) developed by the National Renewable Energy Laboratory (NREL) (c.f. Nelson, 2015 [23], also see [24]) and will use a National Instruments CompactRIO platform (or comparable hardware) for data acquisition and control. This data acquisition system will be used for all measurements discussed above.

1.3.2 TDP Instrumentation (Memorial Bridge)

The tidal turbine deployment system installation at Memorial Bridge also includes instruments and sensors that are leveraged from the Living Bridge project. They can be broadly organized into two instrumentation and data acquisition systems:

(1) SCADA system on bridge: The standard TDP instrumentation includes two downward looking ADCP's (located about 20ft upstream and downstream of the turbine attachment location), a Valeport CTD+ (Conductivity, Temperature, Pressure, Turbidity, Chlorophyll) and underwater cameras, which all connect through a MacArtney Multiplexer to the Living Bridge SCADA system (running on GE Cimplicity). Turbine performance data (power, RPM), data from strain gages on the VGPs (8 uniaxial strain gages) and from two weather stations (one mounted on the TDP, one on top of the south bridge tower) is also

recorded through the SCADA system. The SCADA system also records data from all structural health monitoring sensors on the bridge as part of the NSF/FHWA Living Bridge project.

(2) The mobile data acquisition system described under 1.3.1, loosely based on the MOIS developed by NREL, will be used at the Living Brigde/Memorial Bridge site for all instrumentation that is not connected to the SCADA system. This includes instrumentation that will be used for special measurement campaigns, e.g., detailed turbine wake measurements. Some additional development efforts are needed to bring this system up to the capabilities offered by NREL's MODAQ system.

1.4 Turbine Deployment Structure

This structure, also referred to as the Turbine Pitching Mechanism (TPM), allows the turbine to be rotated in and out of the water. The deployment structure provides the required torque to rotate the turbine into and out of the water, i.e., allow controlled rotational deployment of the turbine, cf. Table 3. The TPM consists of a large diameter steel pipe spanning the moon pool for structural support, anchored in custom roller bearings on each side. A steel "strongback" provides a winch attachment point for deploying and retrieving turbines. The TPM has a universal mounting bracket with a defined bolt pattern, to which turbine developers can mount their turbine, cf. Figure 16.

Table 3: Design specifications for the Turbine Pitching Mechanism

Design Specifications	
Maximum Rotor Thrust	23 kN (5280 lbs)
Moon pool clearance width	3.39 m (11 ft 1-1/2 in)
Moon pool clearance length	5.74 m (18 ft 10-1/4 in)
Turbine attachment	Mounting bracket with universal bolt pattern
Turbine deployment	Rotation in/out of moon pool

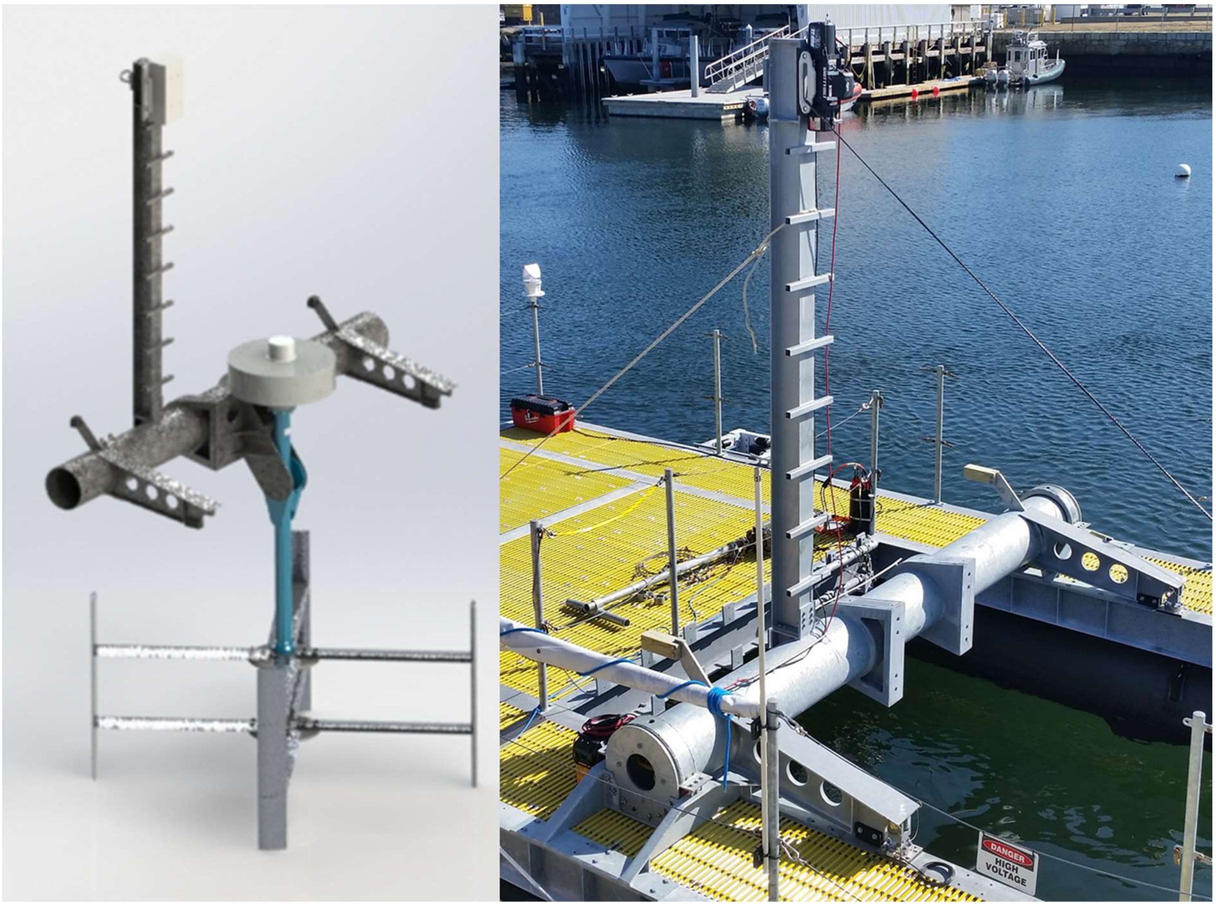


Figure 16. Left: Turbine Pitching Mechanism, rendering and installed on TDP at UNH Pier. The universal mounting bracket with the defined bolt pattern (8 holes) can clearly be seen.

Task 2 Chase Lab Upgrades

The upgrades to the tow tank facility at the Chase Lab were designed to meet the needs for model stage testing of ocean renewable energy devices. Upgrades were made to the tow carriage so it can accommodate various turbine designs and enable the measurement to provide the data required for an engineering evaluation of the devices. A recently renovated high-speed water tunnel was outfitted with a new, optically accessible test section and can be used for turbine blade/hydrofoil research. The water quality system for a tank was improved to maintain water clarity for visual and optical observation.

2.1 Tow Carriage

The combined Tow & Wave Tank enables research where test bodies can be towed, subjected to wave action, or both. It is 12 ft wide, 8 ft deep, 120 ft long (3.66 m x 2.44 m x 36.6m). It has a flap-style wave maker that can generate waves with 1-5 s periods up to 0.4 m wave height (regular waves, random seas). It is equipped with a wave-energy-absorbing geo-textile beach.

A turbine test bed had been developed for measuring the performance (mechanical power and overall rotor drag or thrust) of large laboratory scale ($O(1m^2)$ frontal area) cross-flow turbines. Despite its usefulness in collecting a relatively small amount of data for two helical cross-flow turbines, c.f. [25], this "first generation" system had a number of issues to be addressed, which are detailed in [26].

The tow carriage needed to be upgraded to enable tow speeds up to 3 m/s for various, appropriately sized turbines. This required an assessment of the existing tow system in combination with a careful evaluation of the systems available and adaptable to the tank. The existing tow carriage was a light, aluminum open frame which is adaptable to a variety of scenarios, but had difficulties with large, high drag models.

The "foundation" of the experimental setup was the tow tank, which was addressed first. The main goals for the tow tank upgrades were to increase max speed and acceleration, add closed-loop positioning and velocity control, stiffen the tow member to reduce longitudinal resonance, and add onboard power and networking to the carriage for data acquisition and other peripherals. A summary of the old system and new target specifications is shown in Table 4.

Table 4: Specification summary for previous and new, upgraded towing system

Spec	Old system	Target
Maximum speed	1.4 m/s	3.0 m/s
Maximum acceleration	0.1 m/s^2	2.0 m/s^2
Control system	Open loop velocity only	Closed loop position/velocity
Onboard power	4×12 V batteries	Continuous 120 and 220 VAC

Linear guides

The previous linear guide system, shown in Figure 17a, consisted of a "master" guide constructed from 4x4 inch fiberglass tubing, and a "slave" guide constructed from aluminum angle, on which plastic wheels rode. Over time, the fiberglass tubing had failed structurally and was covered with stainless steel bars fixed with double-sided tape. These bars could shift around during towing and were a source of noise in the measurements. A new set of linear guides was designed from 1.25 in diameter Thomson 440C stainless steel linear shafts and super self-aligning linear bearings, shown in Figure 17b. The existing carriage was modified to retrofit the linear bearings, and a series of parts were designed to adapt the stainless shafts to the existing quasi-level mounting surfaces, which helped keep cost down. The shafts were mounted via 3/8-24 inch threaded rods in oversized holes to allow adjustment in all three dimensions, a concept which was inspired by similar linear guide setups at the University of Minnesota's Saint Anthony Falls Laboratory (SAFL). The shafts were aligned in the cross-tank direction using a piece of monofilament line stretched along the path. The vertical alignment was set by spacing the shaft from its mounting surface equally along the path via machined blocks. When the existing level surfaces were set in 1996, these were measured to be level within $\pm$1/16 inch.

Figure 17. Comparison of old (left) and new, upgraded (right) linear guide system on the "master" side of the tank.

Motion and control

The tow tank's old motion system consisted of a 10 horsepower AC induction motor powered by a Yaskawa V7 variable frequency drive. The motor was coupled to a speed reducing gearbox, on which a pulley was mounted to drive a 0.25 inch diameter wire rope. It was seen in previous testing that this system had very low acceleration ($\approx$0:1 m/s^2), which severely reduced steady state towing durations. The relatively low spring constant of the wire rope tow member also gave the system a low natural frequency, which resonated due to cross-flow turbines' cyclic forcing. Furthermore, the system was only velocity-controlled, and in an open-loop manner. This meant positioning was done manually, which took a skilled operator, and reduced usable tank length further to allow for coasting to a stop.

These issues were addressed by changing the motor to a 26.1 maximum horsepower Kollmorgen AKM82 permanent magnet servo motor and 10:1 gearbox, shown installed in Figure 18, which was sized to tow turbines with 1 m^2 frontal area up to 3 m/s, while accelerating at 2 m/s^2. The motor was powered by a Kollmorgen S700 servo drive, controlled by an 8-axis ACS NTM EtherCAT master controller, providing closed loop position and velocity control. A series of emergency stop buttons were also installed to increase the safety of the system.

A 7.5 cm wide steel-reinforced polyurethane timing belt was chosen as the new drive member. The most robust timing belt profile—an ATL20—was chosen for maximum stiffness per unit width. Custom timing belt and pulley housings were designed to move both the upper and lower runs of the belt above the tank wall, shortening the overall length, which when combined with the higher specific stiffness belt increased the total drive member spring constant roughly by a factor of 7.

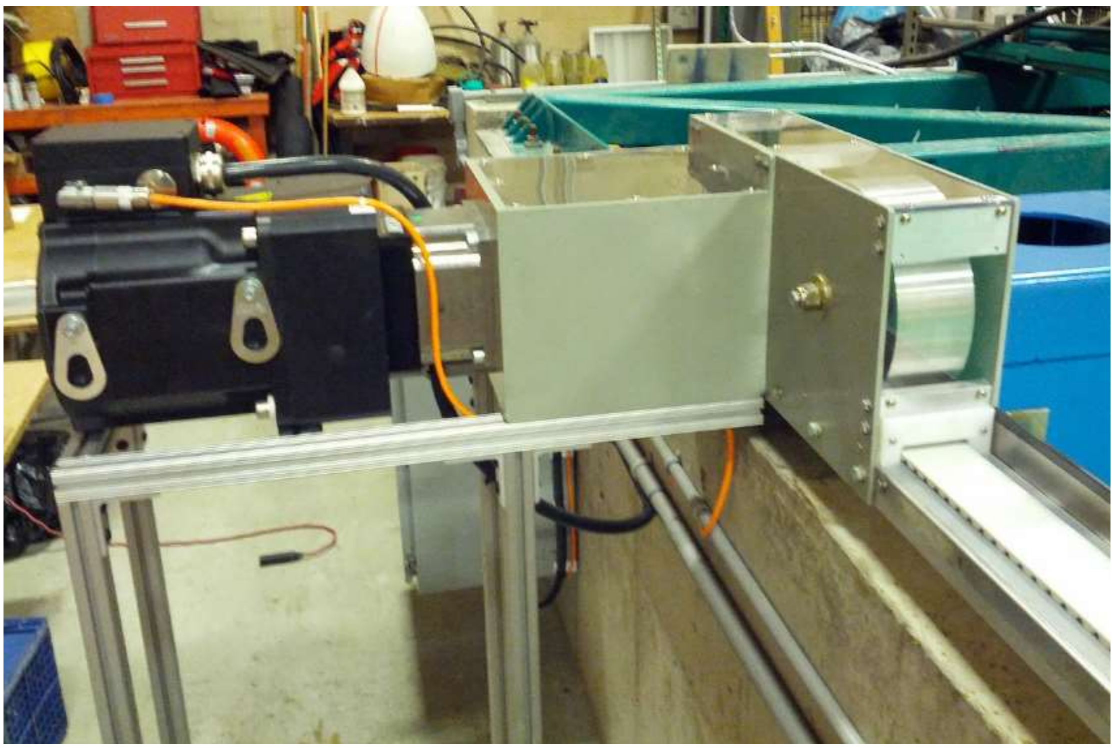


Figure 18. Upgraded tow system servo motor, gearbox, and custom-designed timing belt pulley housing.

2.2 Wave and Tow Tank Instrumentation

Data acquisition and onboard accessories

A new DAQ system was designed based around a National Instruments (NI) 9188 Compact-DAQ Ethernet chassis. NI 9237, 9205, 9401, and 9411 modules were installed for analog bridge, analog voltage, digital, and quadrature encoder signals, respectively. A single CAT5e cable was dedicated for this system. Additional cables were run for the EtherCAT and Internet connectivity on the carriage. An 8-port Ethernet-serial server was installed for accessing serial devices, e.g., a Nortek Vectrino+ ADV. For measuring carriage speed, and therefore inflow velocity, a Renishaw LM15 linear encoder with 10 mm resolution was installed and connected to the NI 9411 module. Networking, power, and control signal cables were run through an Igus cable carrier, installed along the "slave" or +y side of the tank.

Requirements for onboard power were derived from the goal of fully automating both motion and data acquisition. It was also determined that the UNH ME department's high frame rate particle image velocimetry (HFR-PIV) system would be used on the carriage at some point, which included laser power supplies and a laser chiller that could not be powered by the previous generation's isolated battery/inverter system.

An onboard electronics cabinet was designed by Minarik, Inc. as part of the upgraded motion system. A 45 amp, 120 VAC circuit and 20 amp, 240 VAC single phase power cable were run through the cable carrier to power outlets on the side of the onboard electronics cabinet. An additional 240 VAC three-phase supply was connected to a Kollmorgen AKD servo drive, also installed in the cabinet, which was sized to power a servo motor to control turbine shaft position and speed. The AKD drive's digital outputs were setup for triggering instrumentation, e.g., the NI 9188 chassis, via the main motion controller.

Upgraded turbine test bed

For this work, the turbine test bed was kept mostly intact, but modified for fully-automated operation. To reduce low frequency resonance in the frame caused by turbine side forces, and help redistribute some of the streamwise force from turbines towed at higher speeds, two pairs of steel guy wires were added. These solutions were chosen based on a finite element analysis (FEA) of the turbine mounting frame, which showed more improvement regarding stiffening in the desired directions compared to simply adding 45 degree flat bar braces in the corner joints. To ensure drag from the outer guy wires was included in the overall streamwise force measurement, an additional set of linear bearings was added to the carriage for their connection.

Summaries of turbine test bed sensors and instrumentation are presented in Table 5 and Table 6, respectively. A drawing and photo of the test bed are shown in Figure 19. Details on each subsystem are presented in following sections.

Table 5: Turbine test bed sensor details. Note that "(2)" denotes a secondary redundant measurement. "Turbine torque (2)" nominal accuracy is estimated by combining load cell accuracy and arm machining tolerances as root-sum-square. Cited literature refer to numbering in (Bachant 2016, [26]).

Measured quantity	Device type	Mfg. & model	Nominal accuracy
Carriage position	Linear encoder	Renishaw LM15	10 μm/pulse [157]
Turbine angle	Servo encoder output	Kollmorgen AKD	10^5 pulse/rev [105]
Turbine torque	Rotary transducer	Interface T8-200	$\pm$0.5 Nm [97]
Turbine torque (2)	Load cell (& arm)	Sentran ZB3-200	$\pm$0.2 Nm [163]
Drag force, left	Load cell	Sentran ZB3-500	$\pm$0.6 N [163]
Drag force, right	Load cell	Sentran ZB3-500	$\pm$0.6 N [163]
Fluid velocity	ADV	Nortek Vectrino+	$\pm$0.5% $\pm$1 mm/s [144]

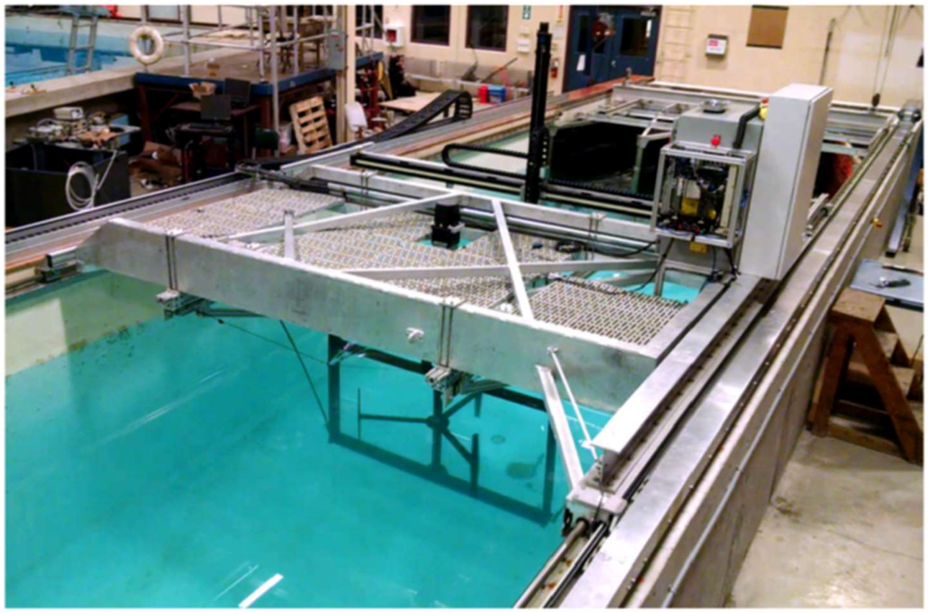
Table 6: Details of the instrumentation used to perform experiments with the turbine test bed. Note that "(2)" denotes a secondary redundant measurement.

Measured quantity	Device type	Mfg. & model
Carriage position	Differential counter	NI 9411
Carriage velocity (2)	Motion controller	ACS NTM
Turbine angle	Differential counter	NI 9411
Turbine RPM (2)	Motion controller	ACS NTM
Turbine torque	Analog voltage input	NI 9205
Turbine torque (2)	Analog bridge input	NI 9237
Drag force, left	Analog bridge input	NI 9237
Drag force, right	Analog bridge input	NI 9237

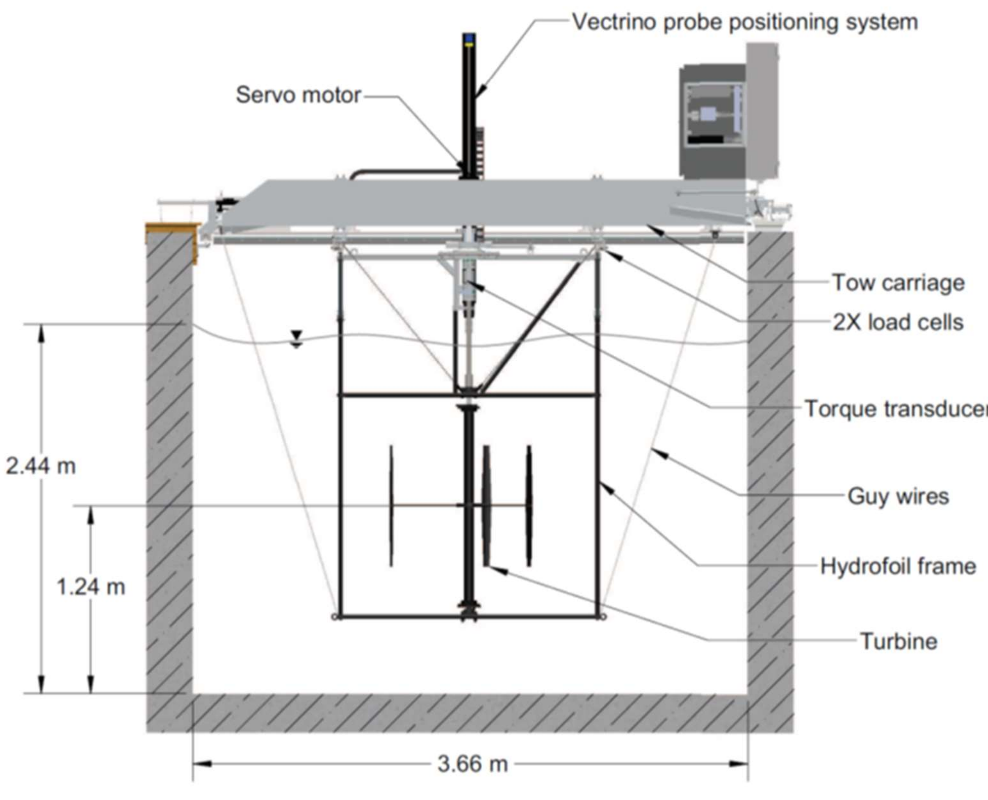
Turbine loading, speed control, torque, and drag measurement

In order to control turbine shaft angular velocity, a Kollmorgen AKM62Q servo motor and 20:1 ratio gearhead were added with a custom retrofit mounting plate and housing. Two zero-backlash R+W EKH/300/B curved jaw couplings were added above and below the rotary torque transducer.

An additional torque measurement system was added by mounting the servo/gearhead assembly to a slewing ring bearing, and holding its mounting housing in place by a Sentran ZB3 890 N capacity load cell attached at a fixed distance by a 0.406 m long arm. This system served as a redundant torque measurement for values up to 200 Nm, and extended the maximum torque range to approximately 360 Nm.



(a)



(b)

Figure 19. turbine test bed photo (a) and cross-section drawing (b).

Turbine shaft angle is measured via the AKD drive's emulated encoder output, set to $5x10^3$ (pre-gearbox) or $1x10^5$ (post-gearbox) lines-per-rev in an A-quad-B configuration. This signal is sampled by either the NI 9401 or the NI 9411 modules. Shaft speed is computed by differentiating the angle time series with a second order central difference scheme. A moving average filter ~10 samples wide was applied to smooth the resulting angular velocity time series such that it agreed nearly identically with the shaft RPM measured by the servo motor's resolver feedback as sampled by the motion controller.

The two drag slide assemblies for overall streamwise drag or thrust measurement were retained from the previous setup. All turbine performance related signals were sampled by modules in the NI 9188 CompactDAQ chassis at a 2 kHz sample rate.

Turbine Wake Measurement System—Traversing Systems

Point measurement techniques for turbine wakes such as ADV and LDV are typically required for many locations in the flow field at different times to measure profiles of various statistical flow quantities. Automated positioning systems are therefore important for improving positioning accuracy and reducing time and effort when performing measurements at many locations.

In order to characterize turbine wakes, a Nortek Vectrino+ acoustic Doppler velocimeter (ADV) was purchased with a Hubbard Fund grant from UNH. An ADV is capable of measuring three components of velocity at a single point in space (technically over a small volume), and the Vectrino+ was set to sample at 200 Hz. This system was considered desirable compared with hot wire or hot film anemometry as it required no calibrations, and the sensor element is significantly more robust. Spatial resolution is typically lower—the Vectrino's measurement volume is 6 mm in diameter —but this is still small compared with the typical length scales of a turbine model. ADV was also preferable to laser Doppler velocimetry (LDV) in this case since the tow carriage is a high vibration environment, which would make LDV alignment a challenge.

A 2-axis y–z positioning/traversing system with 10 ft horizontal and 4 ft vertical travel was designed and built for the ADV Vectrino probe for use with the turbine test bed in the UNH tow tank and is shown in Figure 20 (CAD rendering). This system consisted of two Velmex BiSlide linear stages—the y-axis driven by belt and the z-axis by ball screw. Both drive systems were powered by stepper motors with approximately 0.001 inch resolution. These motors were driven by an ACS UDMLC EtherCAT drive, connected to the tow tank's main motion controller for integrated synchronous motion. Figure 21 shows the 2-axis traversing system, as built. Figure 22 shows traversing system installed in the UNH tow tank (on right), ready for flow measurement with the ADV. A high frame rate PIV system installed on the tow carriage can also be seen in this picture.

Currently used are a standalone ACS NTM EtherCAT controller and UDMLC drive, with two Velmex Bi-Slides and Velmex-supplied and installed stepper motors. This setup is ideal as it allows the tow carriage, turbine RPM, y- and z-axes to be controlled in real time from a single controller. We also feel that the ACSPL+ control programming language is more expressive compared to Velmex's, and the ACS C library contains more flexible high-level functions. Velmex functions for both C and LabVIEW involve sending Velmex language programs into the controller as strings, then executing those programs. The Velmex controller communicates over RS232, which can be somewhat slow compared to USB or the TCP/IP communication employed by the ACS controller.

When operating the Vectrino, the tank was seeded with 11 mm mean diameter hollow glass spheres. Seeding was added along the tank length, generally at the surface, and was mixed by towing the turbine through the tank. This process was repeated until the Vectrino's signal-to-noise ratio (SNR) was approximately above 12 dB. Seeding was added throughout experiments as necessary—totaling approximately 1–5 cups (dry) per day. Note that while acquiring ADV data the y- and z-axis stepper drive had to be disabled to reduce noise. The axes were re-enabled to position the probe before each run.

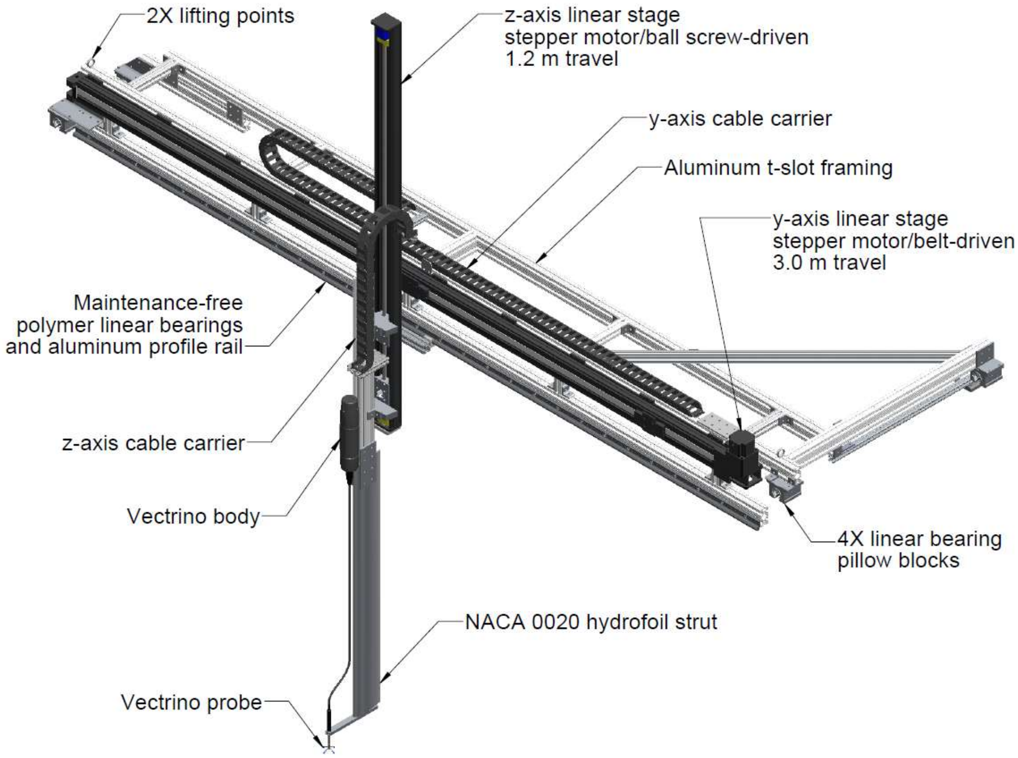


Figure 20. Rendering of the UNH towing tank 2-axis traversing system, with 10 ft horizontal and 4 ft vertical travel, shown with a Nortek Vectrino+ probe installed.

Figure 21. UNH towing tank 2-axis traversing system shown in Figure 20, as built.

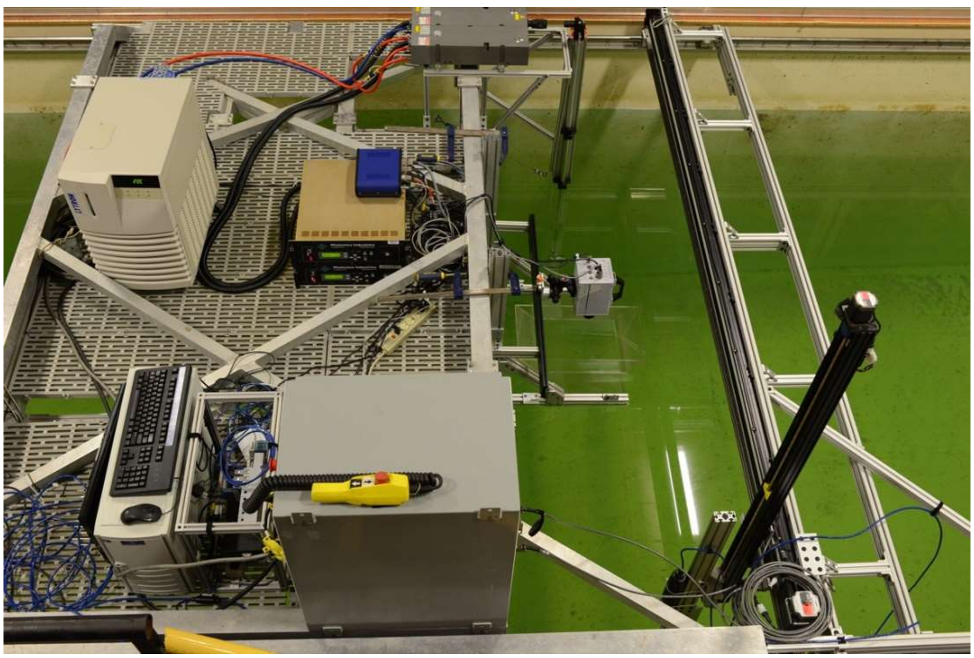


Figure 22. 2-axis flow measurement traversing system installed in UNH tow tank (on right). Also installed on tow carriage is a high frame rate PIV system (note camera pointing downward and acrylic "viewing sled" to image through free surface).

Software

Software was developed to automate the entire turbine testing process. Dubbed TurbineDAQ, the desktop application was written in Python due to its reputation as a good "glue" language for systems integration. The graphical user interface (GUI), shown in Figure 2.5, was built using the PyQt bindings to the Qt framework. Communication with the tow tank's motion controller, data acquisition system, and ADV were integrated into a single application. This, combined with the ability to load and automatically execute test matrices in comma-separated value (CSV) format, allowed for experiments consisting of thousands of tows, where the previous generation test bed could only realistically achieve around 100. The TurbineDAQ GUI is shown in Figure 23.

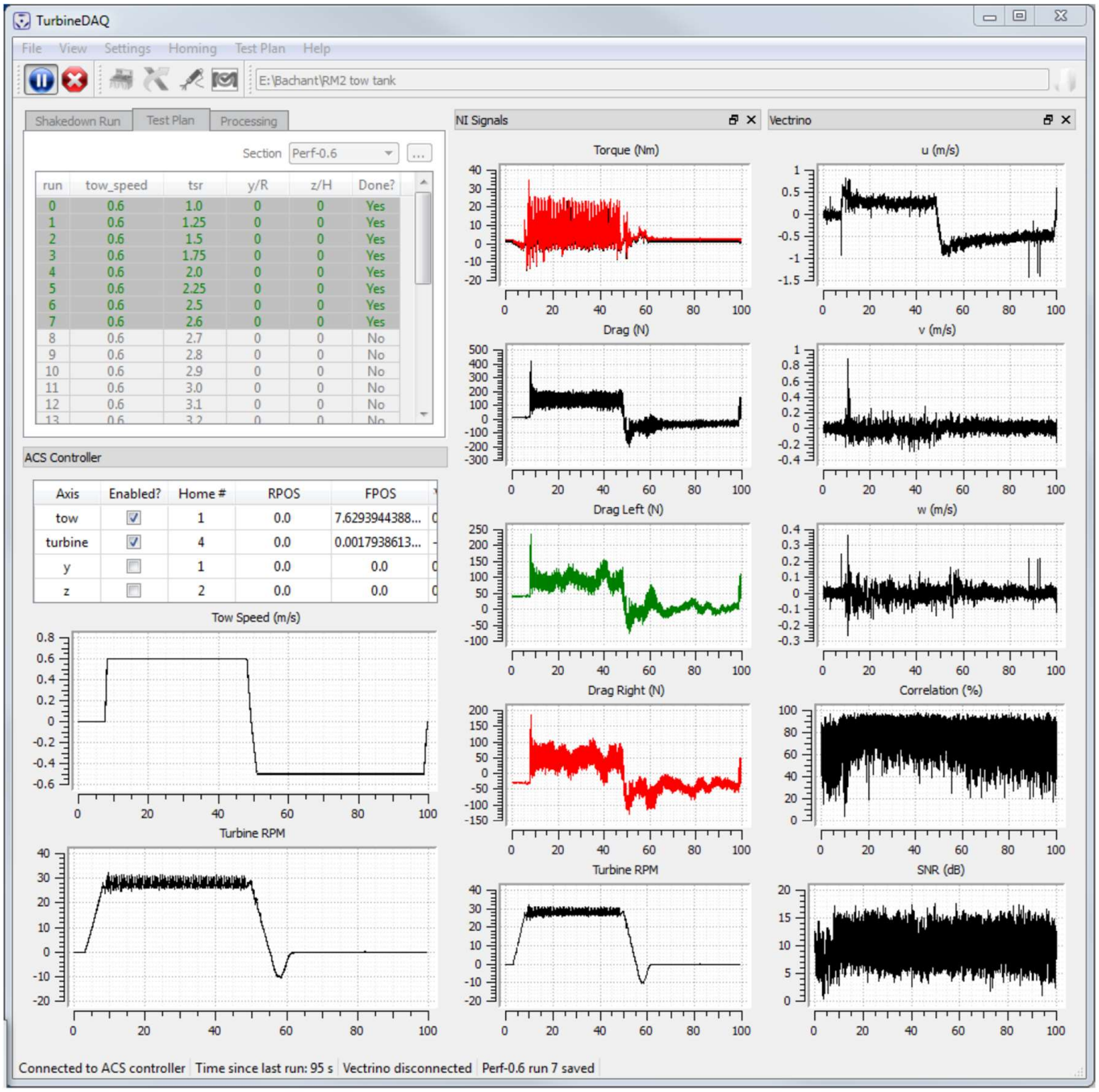


Figure 23. TurbineDAQ turbine test bed automation, graphical user interface

Turbine performance measurements and example results

Turbine manufacturers need reliable power curves from model tests to be able to validate numerical models, predict Annual Energy Production (AEP) and scale-up to larger sizes. This can be accomplished with curves of turbine power coefficient (non-dimensional power) versus tip speed ratio (non-dimensional rate of rotation). This curve, along with device geometry, can be used to size the power take-off and the other measurement devices. An example of a power curve for an MHK turbine is shown in Figure 24 (UNH-RVAT).

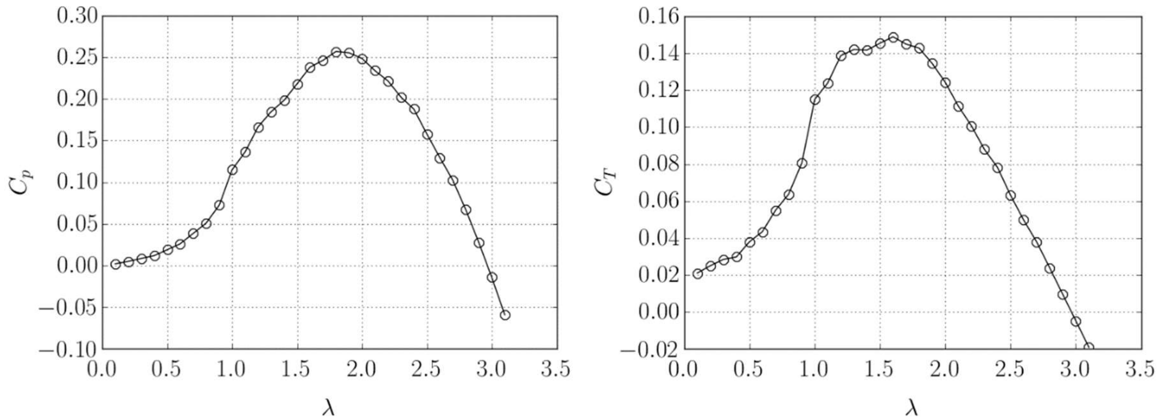


Figure 24: Example power (left) and torque (right) curves for a cross-flow MHK turbine (UNH RVAT) [27].

We can use the provided curve to calculate the nondimensional torque coefficient first, and then calculate dimensional torque, which we will use in designing the experimental apparatus. The torque coefficient is defined as

$$C_T \equiv \frac{T}{\frac{1}{2}\rho A_f R U_\infty^2} = \frac{C_P}{\lambda}, \tag{1}$$

In Figure 24 example power (left) and torque (right) curves for a cross-flow MHK turbine (UNH RVAT) are shown [27]. From the peak torque coefficient shown we estimate that for a $1\ \mathrm{m}^2$ frontal area, 0.5 m radius turbine operating in a 1 m/s flow, mean torque will reach approximately 38 Nm. To estimate the unsteadiness in torque, the device design must be taken into account. For example, the UNH RVAT 3-bladed vertical-axis cross-flow turbine's torque fluctuations have an amplitude approximately 70% of the mean value at $\lambda = 1.9$.

Thrust/Drag Measurements

The thrust or drag force acting on a turbine in the streamwise direction can be accurately measured by affixing the turbine mounting frame to some type of linear bearings, allowing the drag to be transferred to one or more force measurement transducers, e.g., load cells. The tare drag associated with the mounting frame can be easily quantified for a given flow velocity and subtracted out in post-processing. This method has been successfully implemented in the turbine test bed for the UNH tow tank. Note that since the flow is accelerated around the device in operation, the tare drag is not exactly its true value without a turbine installed. Therefore any mounting structures should be streamlined as much as possible to avoid uncertainty associated with this discrepancy.

A device manufacturer interested in experimental testing should likely also have a prediction for the drag loading on their device as a function of tip speed ratio. An example of measured drag (rotor thrust) curve for an MHK turbine is shown in Figure 25. If a similar figure is not provided by the manufacturer, the method described in the Turbine Mounting Considerations section above can be used to estimate forces.

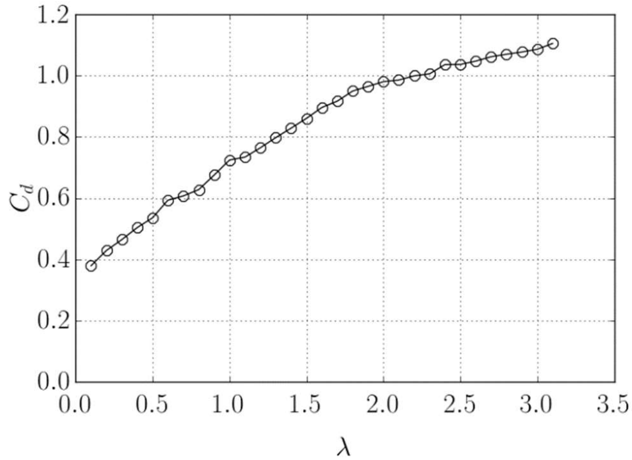


Figure 25: Typical MHK turbine drag (thrust) curve (UNH RVAT) [27].

Figure 26 and Figure 27 provide an example of the Reynolds dependency of power and drag (thrust) coefficients, in this case for a cross-flow (vertical) axis turbine (US DOE Reference Model 2) [28]. It can be seen that the power coefficient depends more strongly on Reynolds number than the drag (thrust) coefficient. For the Reynolds number range investigated, the power coefficient *does not* become independent of Reynolds number for this turbine, but is seen to be only weakly dependent on Reynolds number for $Re_c > 200{,}000$. Figure 28 shows performance data for a different, higher-solidity turbine (UNH-RVAT). For this turbine, it can be seen that the power coefficient *does* become independent of Reynolds number for $Re_c > 200{,}000$ [29].

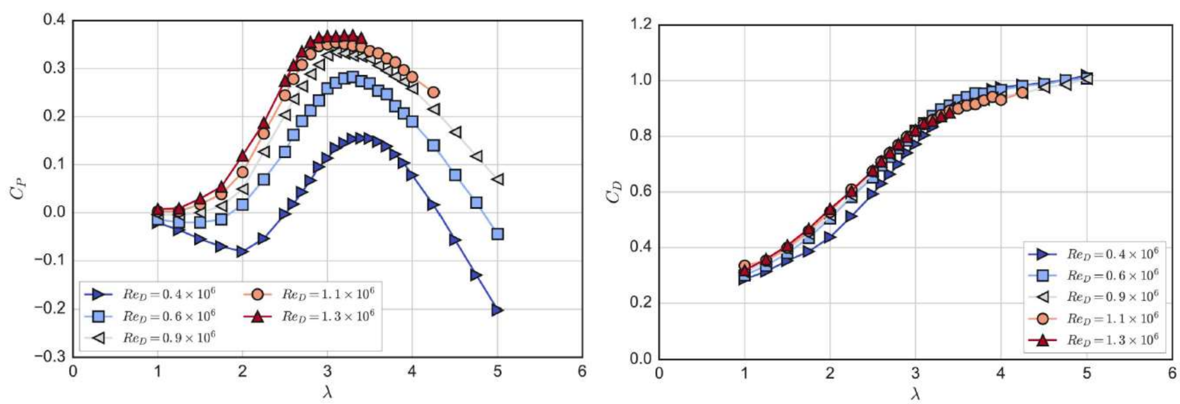


Figure 26: Power and drag (thrust) coefficients for the US Department of Energy's Reference Model vertical-axis cross-flow turbine (RM2) tested in a towing tank [28].

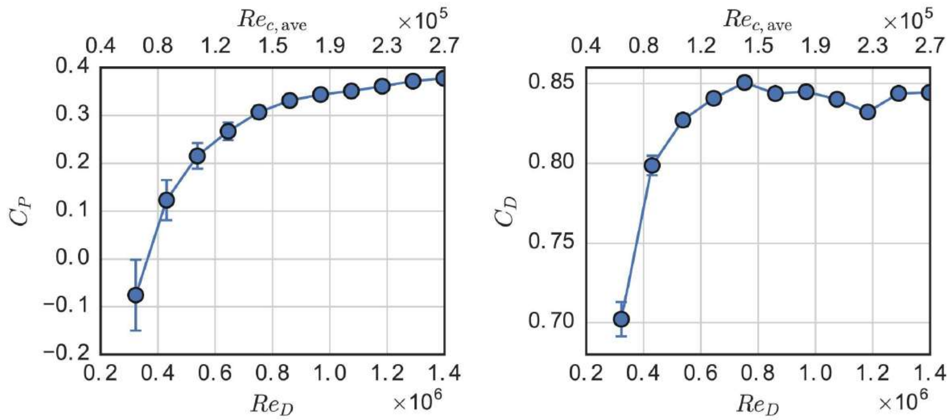


Figure 27: Effect of Reynolds number on performance. Power (left) and thrust (right) coefficient for reference model RM2 at λ = 3.1 plotted versus turbine diameter and approximate average turbine blade root chord Reynolds number [28].

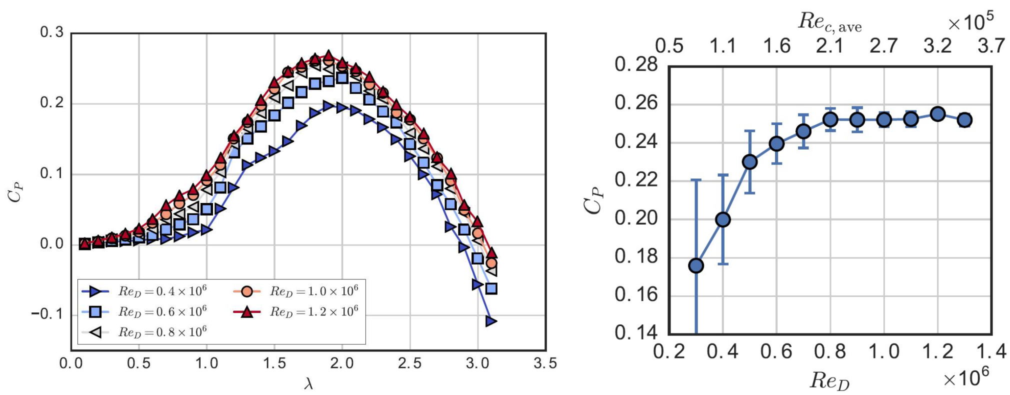


Figure 28: Effect of Reynolds number on performance. Power coefficient vs tip speed ratio (left) and power coefficient at λ = 1.9 plotted versus turbine diameter and approximate average turbine blade root chord Reynolds number (right), both for UNH-RVAT turbine [29]

Figure 29 shows the traversing system in the UNH tow tank installed at x/D=1 downstream of a 1m diameter cross-flow MHK turbine, as well as a typical traversing grid for detailed ADV near-wake measurements. Finally, sample results from ADV traversing, in the form of contours of mean streamwise velocity and turbulence intensity from a wake map of 270 turbine tows, are shown in Figure 30.

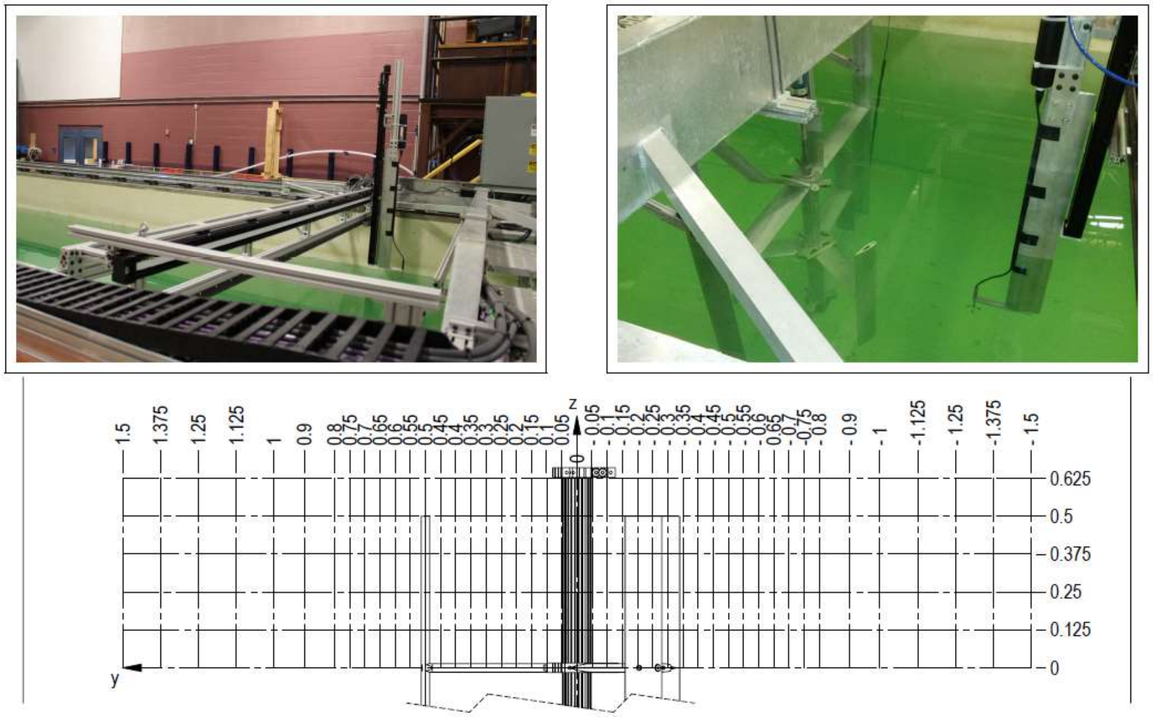


Figure 29. Top: 2-axis flow measurement traversing system in UNH tow tank installed at x/D=1 downstream of a 1m diameter cross-flow MHK turbine (UNH RVAT). Bottom: Typical traversing grid for detailed ADV near-wake measurements.

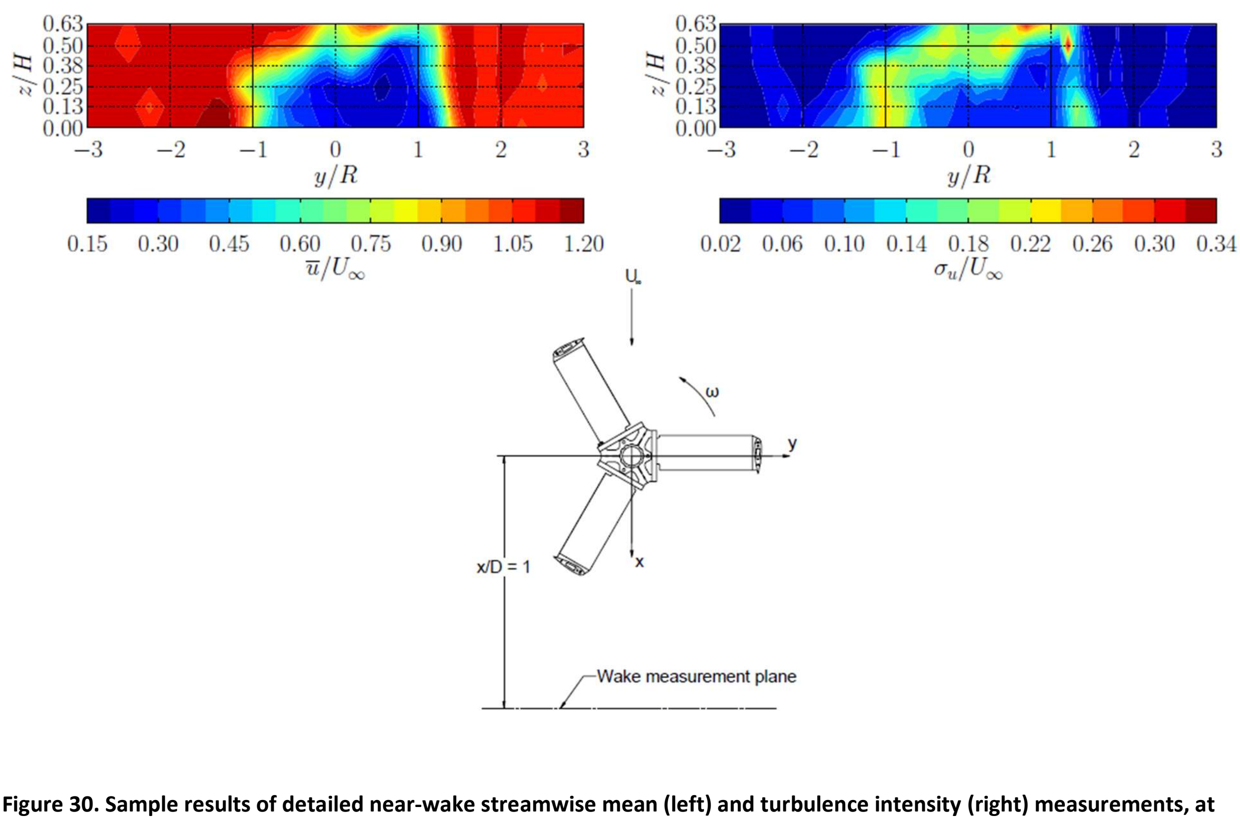


Figure 30. Sample results of detailed near-wake streamwise mean (left) and turbulence intensity (right) measurements, at x/D=1 downstream of UNH RVAT cross-flow turbine.

2.3 Water Quality System

All the kinematic measurements on models deployed in wave testing are made optically from outside the tank. The clarity of the water in the tank is an issue in preserving the quality of these measurements as they are based on contrast between the model base color, white, and a black dot which is 'followed' from pixel to pixel with the optical system. The water quality system pumps and filters were replaced.

2.4 High Speed Water Tunnel

The test section of an existing high speed water tunnel was upgraded for use in hydrofoil and turbine blade research and development. This tunnel originally was the 1:6 scale model of the U.S. Navy's 36-inch Variable Pressure Cavitation Tunnel at David Taylor Model Basin, and was transferred to UNH from St. Anthony Falls Laboratory at the University of Minnesota.

The new test section has a square cross-section of dimensions 6" x 6", and is 36" long. Extensive computational fluid dynamics (CFD) studies were carried out to ensure that the desired flow characteristics and tunnel performance will be achieved. The maximum test section velocity will be 17 m/s (unit Reynolds number of >1,500,000/m). Test section velocity and pressure can be controlled independently, which allows investigation of cavitation phenomena on turbine blades. The test section allows optical access for Laser Doppler Velocimetry (LDV) (PDA) and Particle Image Velocimetry (PIV) measurements, and was outfitted with a lift/drag balance for hydrofoils and turbine blade sections.

For details of all the cavitation tunnel upgrades, including numerical simulations for design studies and verification measurements of test section conditions using laser Doppler velocimetry, see [30] and for hydrofoil performance and cavitation measurements see [31].

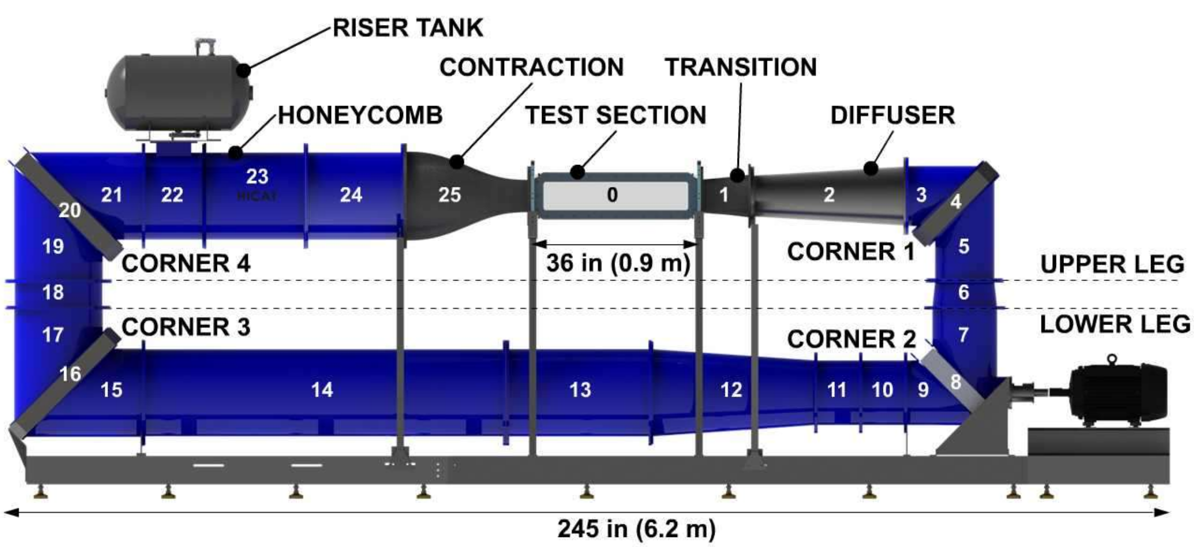


Figure 31. High-Speed cavitation tunnel (HiCaT) with new contraction, test section, transition-diffuser, motor and drive.

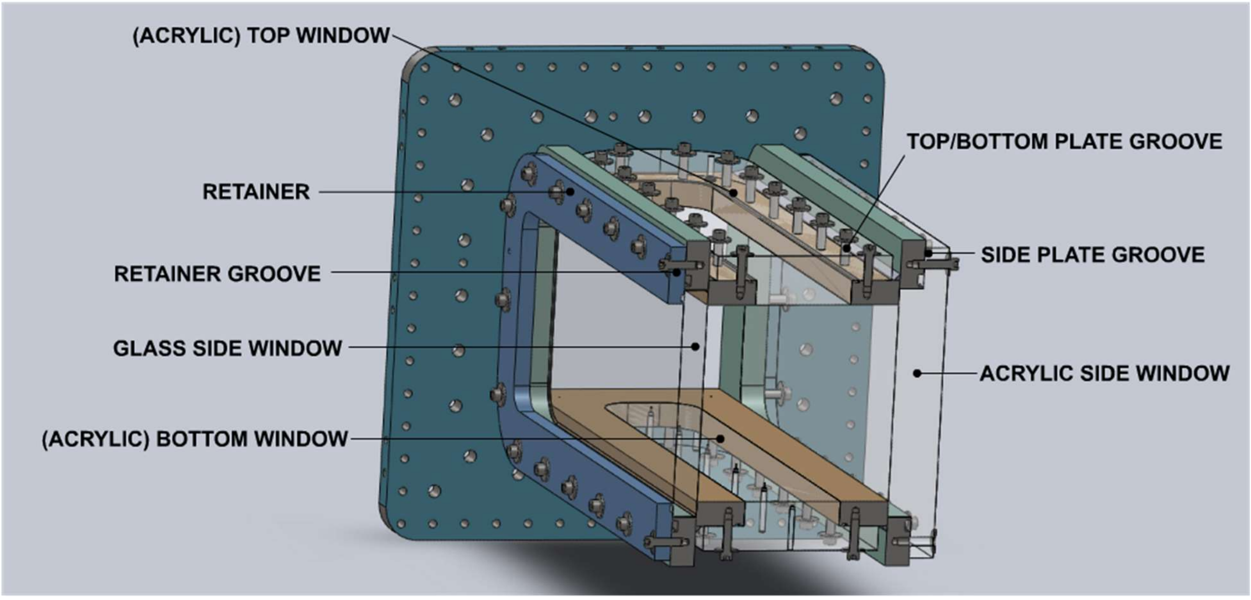


Figure 32. High-Speed cavitation tunnel (HiCaT): design of test section with optical access from all four sides.

Figure 33. High-Speed cavitation tunnel (HiCaT): in its new home in 176 Chase Ocean Engineering Lab.

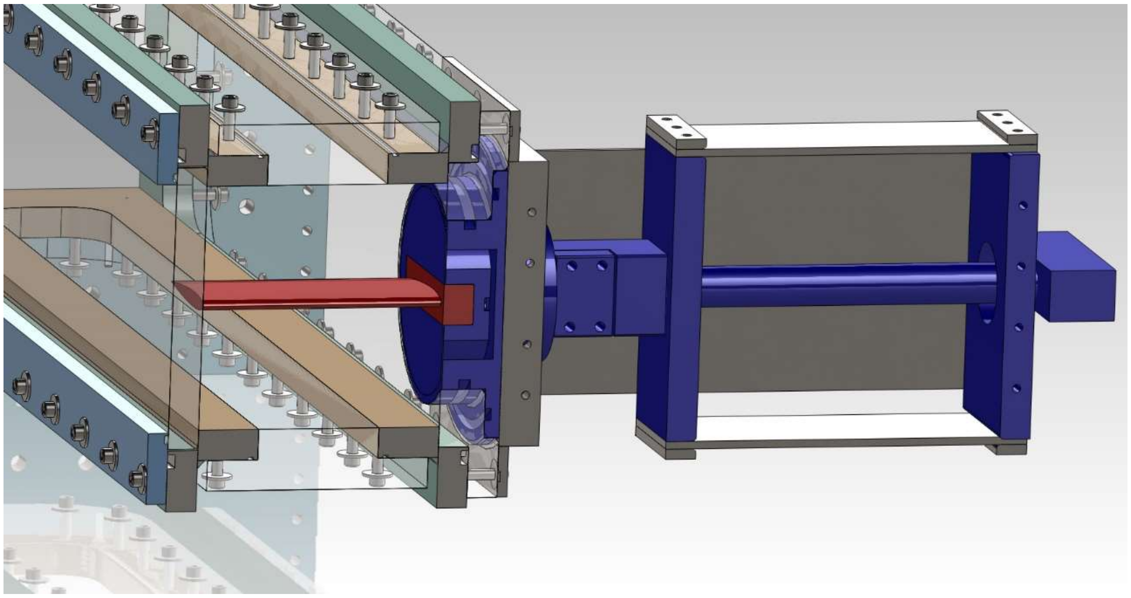


Figure 34. High-Speed cavitation tunnel (HiCaT): Force balance for hydrofoil studies which allows separation of lift and drag measurements.

Task 3 Offshore Wave/Wind Test Site Environmental Buoy

The enhancement to the offshore wave and wind energy site included upgrading an environmental assessment buoy for use at the site. This buoy had wave measurement capability and a Conductivity, Temperature and Depth (CTD) for water property assessment deployed on the subsurface component of the buoy system. The above surface structure had a weather station for measuring wind speed and direction and atmospheric temperature. The data acquisition system was designed to accommodate these measurements and others necessary for specific projects. The refurbished UNH Environmental Buoy was deployed with the Neptune Wave Power wave energy converter (WEC), cf. Figure 35.

3.1 Environmental Buoy Water Column Sensors

The UNH offshore test site, originally developed as the Open Ocean Aquaculture site of the Atlantic Marine Aquaculture Center (AMAC) in 1999, had an environmental buoy which was in need of refurbishing. The water column sensors required are an Acoustic Doppler Current Profiler ADCP for currents, the wave following motion sensor and an acoustic release for retrieval. The acquisition of these sensors provided a redundant system and maintained the data stream integrity. This requiresd increased data storage card capacity, a radio telemetry link, a lower noise accelerometer for wave measurement, a surface current meter and an acoustic profiling current meter. These systems measured air temperature, sea surface temperature and salinity, three axes of acceleration for determining significant wave height and dominate wave period as done by the Gulf of Maine Ocean Observing System (GoMOOS) buoys, near surface water velocities and water column velocity and acoustic backscattering profiles (which do not include the surface and bottom boundary layers). The wave data, surface water temperature, salinity and velocity were sent via a telemetry system to UNH hourly, archived and provided to program participants on a web site.

3.2 Environmental Buoy Mooring Components

Completing the system required replacing some of the mooring hardware and instrumentation support components that had exceeded their life expectancy. Other miscellaneous supplies such as a mid-water float, a mooring line, shackles, a swivel, zinc anodes and a Coast Guard approved navigational light, solar panels, batteries two acoustic recovery systems were needed. These components were combined with existing components and support hardware to provide a complete mooring system.

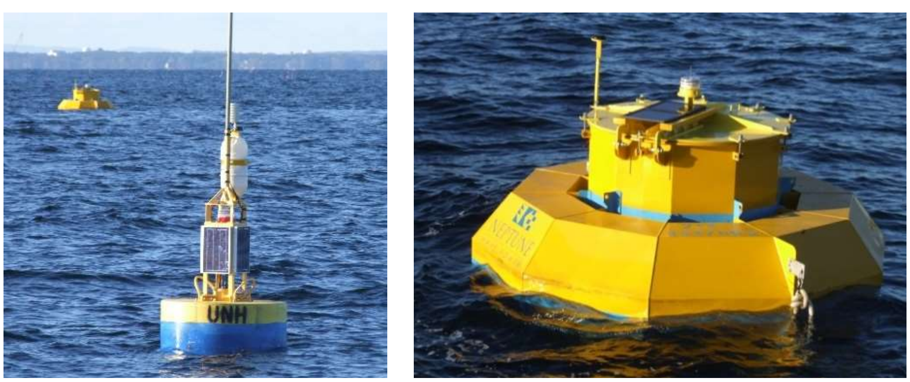


Figure 35. Refurbished UNH Environmental Buoy during deployment with Neptune Wave Power WEC v3.1

Summary

The objective of this project was to enhance three principal components of the University of New Hampshire (UNH) Center for Ocean Renewable Energy (CORE) research, development and evaluation infrastructure for marine renewable energy (MRE) systems. These three components consisted of a Tidal Turbine Deployment Platform (TDP) for use at the two UNH tidal energy test sites in Great Bay Estuary/Piscataqua River, Laboratory Upgrades for Chase Ocean Engineering Laboratory (COEL), and a Wave/Wind Offshore Test Site Environmental Buoy (for use with WEC testing).

The UNH-CORE Infrastructure Enhancement Project was very successful. Existing MRE infrastructure was improved and upgraded and new MRE infrastructure was created at UNH. The infrastructure has already been extensively utilized by MHK industry and collaborators from National Laboratories and other universities, and will continue to serve the R&D mission in support of MRE and PBE industry.

Lessons learned that are important from a DOE WPTO programmatic perspective:

- Scale models of marine hydrokinetic turbines need to bested above a certain threshold combination of size and water speed (=Reynolds number) so that performance of the scale models becomes independent of Reynolds number, or only depends weakly on Reynolds number. For most design configurations, a model size of nominally 1 m diameter and a water speed (flow or tow speed) of 1 m/s should be considered the minimum requirement. Note that smaller size can be compensated with higher speed, and vice versa, as long as flow blockage remains reasonable.
- Testing infrastructure for marine hydrokinetic (MHK) turbines was created which enables very cost-effective testing of intermediate scale turbines in a real tidal flow. A floating Turbine Deployment Platform (TDP) of dimensions 50 ft x 20 ft (15 m x 6 m), which can be used to deploy and test axial-flow or cross-flow marine hydrokinetic (MHK) turbines with diameters up to approximately 10 ft (3 m), is now available for the marine energy industry. The platform is moored via pile-guides in a “floating-dock” configuration next to a bridge pier at Memorial Bridge in Portsmouth, NH, and turbines can be rotated in and out of the water via a turbine pitching mechanism. Using this new test infrastructure, the MHK industry can perform medium-to-long-term testing with inexpensive device deployment and retrieval, and re-deployment to facilitate low-cost incremental testing.
- During the long-term deployment of a tidal energy converter

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Appendix

More information and public data sets available at:
https://marine.unh.edu/center-ocean-renewable-energy