Description of an Intermediate Scale Tidal Energy Test Site in Great Bay Estuary, NH, with Examples of Technology Deployments

Martin Wosnik[1,2], Matthew Rowell[1,2], Toby Dewhurst[1,2], Vincent Lyon[1],
Tom Lippmann[2,3], Ken Baldwin[1,2], M. Robinson Swift[1,2]
1-Center for Ocean Renewable Energy (CORE)
2-Center for Ocean Engineering (COE)
3-Center for Coastal and Ocean Mapping (CCOM)
University of New Hampshire, Durham, NH 03824
Corresponding author: martin.wosnik@unh.edu

Abstract*— The Center for Ocean Renewable Energy (CORE) at the University of New Hampshire (UNH) operates a sheltered, intermediate scale ("nursery") tidal energy test site suited for Marine Hydrokinetic (MHK) turbines up to 4 m (13 ft) in diameter at General Sullivan Bridge in Great Bay Estuary, NH. The UNH-CORE Tidal Energy Test Site is located in a constricted area, and 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). The test site has a nominal depth of 10 m, a flat bottom, easy access from two local UNH marine facilities and nearby marinas, and hence it is a cost-effective site for the testing of tidal energy conversion devices. An 11 m x 3 m test platform has been used for MHK turbines up to 1.5 m diameter since 2008, and a larger 20 m x 10 m test platform with a modular turbine deployment system was designed to accommodate larger turbines up to 4 m in diameter. A 4 m diameter axial turbine corresponds approximately to a 1:5 scale model of a utility-scale MHK turbine rated at 1 MWel (based on a full-scale diameter of 20 m, a tidal energy resource of 2.5 m/s and a water-to-wire conversion efficiency of 0.4). A number of MHK turbines have been deployed and evaluated at this test site, including cross-flow turbines with helical blades (Gorlov Helical Turbines), and more recently, an axial Mixer-Ejector Hydrokinetic Turbine designed by FloDesign Inc. under a US Department of Energy (DoE) SBIR phase 2 project. The UNH-CORE Tidal Energy Test Site is well suited to support open-water MHK testing through DoE Technology Readiness Levels (TRLs) 5-6 and 7 (not including grid connection).

Keywords—tidal energy, marine hydrokinetic turbines, test site, scale model testing, field deployment

I. Introduction

A. Marine Hydrokinetic Energy Conversion

Marine Hydrokinetic (MHK) turbines convert the kinetic energy available in moving water without the need to build dams or barrages. MHK turbines can operate in tidal or ocean currents, as well as in major inland rivers. Recent resource assessments sponsored by DoE showed that significant potential exists in the United States:

- <u>tidal energy resource:</u> about 50 GW (on average), or 440 TWh/yr – most of it in Alaska [1];
- <u>ocean current energy potential</u> for Florida Current portion of the Gulf Stream (via an energy balance of a simplified quasi-geostrophic ocean circulation model): about 5 GW, or 45 TWh/yr [2];
- <u>riverine resource (technically recoverable):</u> about 14 GW, or 120 TWh/yr [3].

While it is unknown what fraction of each resource is recoverable in practice, the first MHK turbine pilot-scale projects (100s of kW) in the US will connect to the electric grid in the near future, and the stated goal of DoE is to develop about 4 GW of installed capacity for MHK energy conversion by 2030. By comparison, the total net generation/consumption of electrical energy in the US in 2011 was about 4,100 TWh, or about 470 GW on average [4]. While the U.S. wave energy resource, estimated to be 1,170 TWh/yr, or 133 GW average at the continental shelf edge [5] – with more than half of it in Alaska, is larger than the tidal, ocean or riverine current energy resources combined, the technology necessary for harnessing hydrokinetic energy from currents is better understood and therefore the path to success is more clearly defined. According to the 2011 US Marine and Hydrokinetic Energy Roadmap [6], untapped MHK energy resources (current and wave) in the US have the potential to provide up to ten percent of the nation's electricity, more than the amount of electricity presently produced by all conventional hydropower [4]. Tidal energy is highly predictable, and tidal energy conversion could become a viable alternative to fossil fuel-based energy in locations with adequate energy resource.

The risks to the marine environment and marine organisms posed by tidal energy conversion installations, especially of large, utility scale arrays of turbines, are far from fully understood [7], however, it is generally expected that MHK energy conversion can be implemented so that is comparatively

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benign. For example, the first experiments with MHK turbines and live fish in large flumes at two laboratories demonstrated fish survival rates approaching 100%, close to indistinguishable from control populations [8, 9].

B. The case for an intermediate scale tidal energy test site

For MHK energy conversion to become viable it is essential to field test MHK devices in an environment similar to the one they are designed to eventually operate in. Field deployments of tidal turbines can range from intermediate scale process models to full scale devices deployed at tidal energy test sites, with the eventual deployment of full-scale devices at tidal energy project sites. Deployments to test and evaluate MHK turbine technology in the field are expensive, and the cost increases significantly with device scale. Deployments of *scaled MHK devices* at a pre-permitted, easily accessible, sheltered tidal energy test site at a scale sufficient to obtain meaningful results with regards to performance, loads, inflow and wake velocity data, environmental data, etc., are a cost-effective way to develop MHK technologies and play an important role in the scale-up process. Testing in the natural environment at sufficiently large scale removes laboratory problems, such as low Reynolds number or blockage effects, and introduces the many complexities of a real tidal site, while still operating in an environment more benign than at most tidal energy project sites. Such a scaled tidal energy test site serves two main purposes:

- Deployment and evaluation of specific MHK developer designs in a real tidal flow. The scaled test site thereby serves as a “nursery site” for new MHK technologies.
- Deployment of intermediate scale (e.g., 1:5) reference models of MHK turbines to obtain field validation data sets to be made publicly accessible for validation of numerical design tools. The device specification for a reference model is typically public (open-source), e.g. DoE/NREL Reference Model 1 (RM1) [10] or DoE/Sandia Reference Model 2 (RM2) [11].

If the scaled tidal energy test site is spatially constrained and the appropriate instrumentation is available, as is the case for the UNH test site, then it is possible to couple device performance and flow measurement data with high-fidelity bathymetry and resource characterization to validate coupled far-field/near-field simulations of turbine deployments.

It should be noted that the European Marine Energy Centre (EMEC) in the Orkney Islands, Scotland, recently also brought a scaled tidal energy test site online, after already offering full scale testing at a more exposed test site with a higher tidal energy resource for several years [12].

II. Great Bay Estuary, New Hampshire

The Great Bay Estuary (GBE) system in New Hampshire, shown in Fig. 1, is a tidally driven estuary that is one of the most energetic on the East Coast of the United States. The typical tidal range is on the order of 2.5 m at the Gulf of Maine mouth and decreases to about l.8 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 m with maximum currents ranging between 0.5 m/s and 2.0 m/s [13]. The historic General Sullivan Bridge and the adjacent new Little Bay Bridges separate the Lower Piscataqua River from Little Bay, which leads to Great Bay. The inner estuary, consisting of Little Bay and Great Bay proper, has depths on the order of 10 m and currents on the order of 0.5 m/s. The typical 2.5 m tidal sea level excursions of the Gulf of Maine cause almost half of the volume of Great Bay to be exchanged 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.

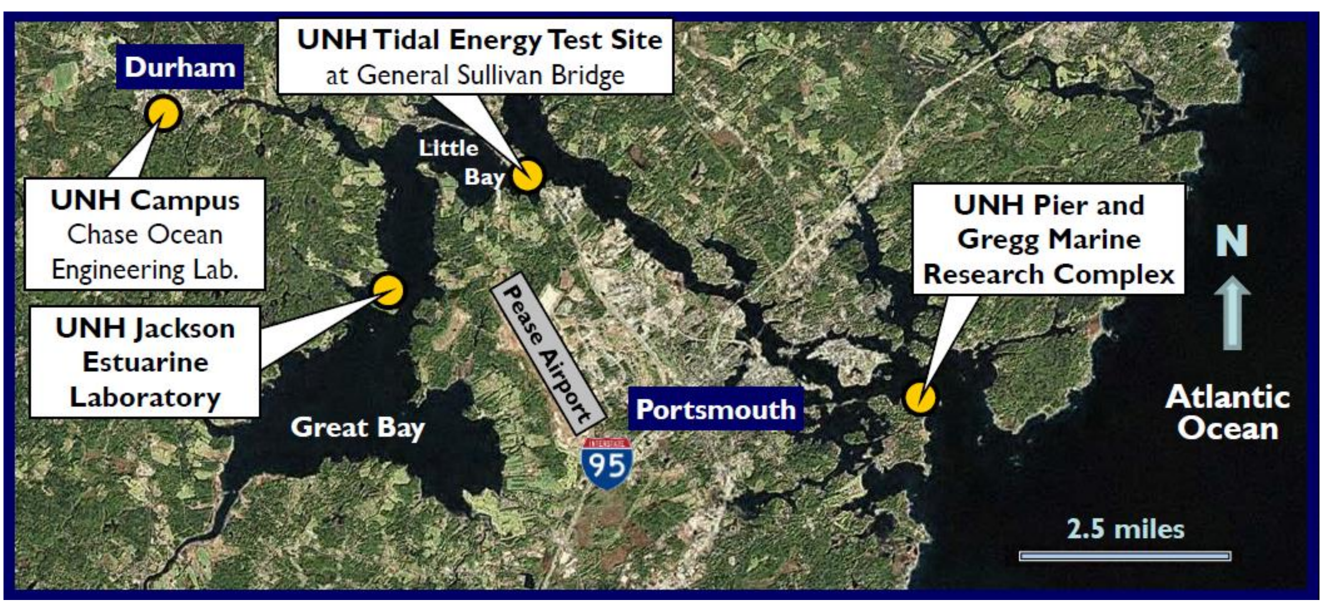

Fig. 1. Satellite image of Great Bay Estuary, New Hampshire. The UNH-CORE Tidal Energy Test Site is located at a constriction in the estuary at General Sullivan Bridge. UNH support infrastructure includes marine installations with support vessels and high bay laboratory.

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 [14]. 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 [15], [13] and [16] (in order of publication).

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 4 m in diameter.

III. Tidal Energy Resource

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. Fig. 2 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.

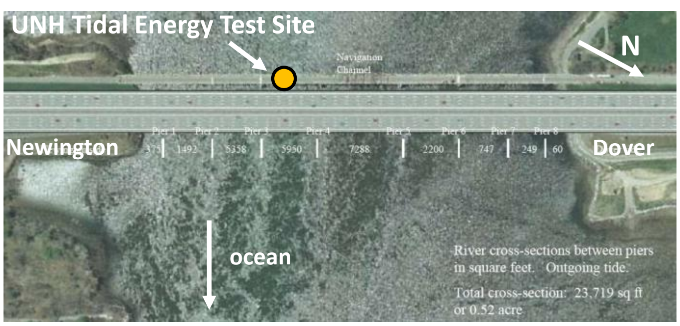

Fig. 2. UNH-CORE Tidal Energy Test Site in Great Bay Estuary. The orange dot is the approximate location of the test platform when deployed. (Note the changed orientation, i.e., North arrow.)

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 [17, 18]. 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/).

The times series harmonic constituents were calculated from the raw NOAA/NOS data with the Simply Currents code that employs Harmonic Analysis Method of Least Squares (HAMELS) [19]. The dominant harmonic constituents were determined iteratively from one lunar month of raw data, and verified by comparing a three day tidal current prediction based on those constituents to three days of the actual recorded tidal current data. The solutions were then used to predict tidal currents for deployment dates of interest at the UNH-CORE Tidal Energy Test Site.

Representative comparisons of predicted and measured tidal currents for two MHK turbine deployments are shown in Figure 3, one with good agreement (top) and one with poor agreement (bottom). Predictions of tidal currents are typically far less accurate that predictions of tidal height [20]. Many factors beyond celestial gravitational effects can affect tidal currents, for example geography and bathymetry, and hence tidal current variation us rarely sinusoidal [21]. Here tidal current velocity measurements were made during deployments with a Nortek Vector Acoustic Doppler Velocimeter (ADV) mounted on the bow of the test platform [22, 23]. Note that the Vector ADV output data at 32 Hz, which was re-sampled to match Simply Currents prediction interval of 12 minutes.

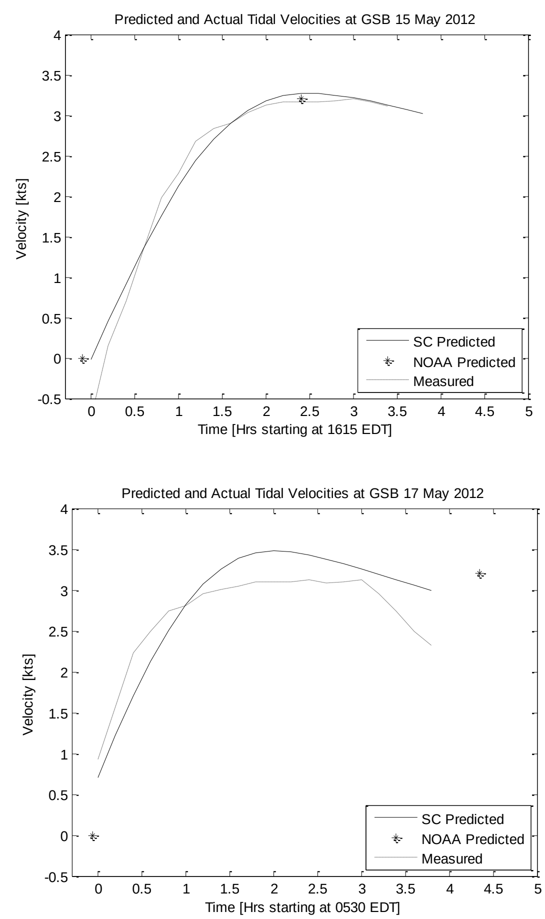

Fig. 3. Predicted and measured tidal current velocity during two sample deployments at the UNH-CORE Tidal Energy Test Site.

An example of the velocity profile at peak current is shown in Fig. 4. Velocity data were measured from a floating platform-mounted ADCP and ADV. A schematic of the experimental setup is shown in Fig. 6. Plotted are data from a 42 minute period during which the tidal current velocity was nearest its maximum and approximately constant.

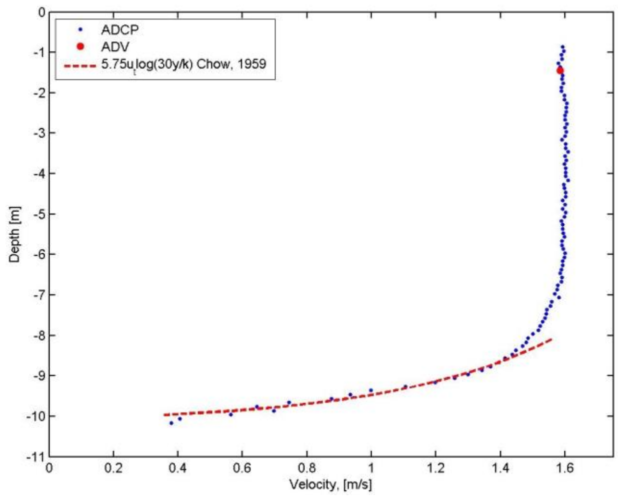

Fig. 4. Mean velocity measured with ADV (point) and ADCP (profile). logarithmic profile for open channel flow [24] included for comparison.

Note that the MHK turbine with a nominal diameter of about one meter was mounted 5.7 m downstream of these measurement devices, and with a beam divergence of 20° the effects of the MHK turbine on the upstream inflow measurements could be neglected. The mean velocities measured at the same depth with both the ADCP and ADV agree to within 0.35%. For reference, a logarithmic velocity profile for open channel flow over rough surfaces [24] was also plotted. Note that the Reynolds number based on channel depth is approximately 16 million.

Shipboard ADCP surveys are typically conducted with UNH vessels (R/V Gulf Challenger, R/V Meriel B or R/V Galen J). During the highest tides of the year (King Tide) in 2011 an instrumented Yamaha GP1200 Waverunner, the Coastal Bathymetry Survey System or “CBASS”, was used to sample the tides for 2x 6 hrs. The CBASS, shown in Fig. 5. includes 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 500-1200 KHz ADCPs [25, 26]. CBASS 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. In Fig. 6 the tidal current velocity at the UNH-CORE Tidal Energy Test Site in the top quarter of the water column exceeds 2.5 m/s over the 36 minutes (0.6 hours) averaged for this plot.

Observed wavenumber spectra show that the noise floor of the resolved multibeam bathymetry is on the order of 2.5 – 5 cm in amplitude (at water depths ranging 2 – 6m) and about 30 cm in wavelength. Inflow/outflow boundary conditions and detailed bathymetry can be obtained with the CBASS survey system, while detailed tidal energy resource measurements at the turbine deployment location will be obtained by ADCP and ADV onboard the tidal energy test platforms. In this way detailed boundary conditions and performance and flow measurements are available for numerical model validation. Tidal constituents and resource estimates are available from long-term bottom-deployed ADCP measurements, as previously discussed.

Fig. 5. The CBASS survey system: underway in New River Inlet, NC (top); schematic showing CBASS and the instrumentation integrated into the vessel (bottom).

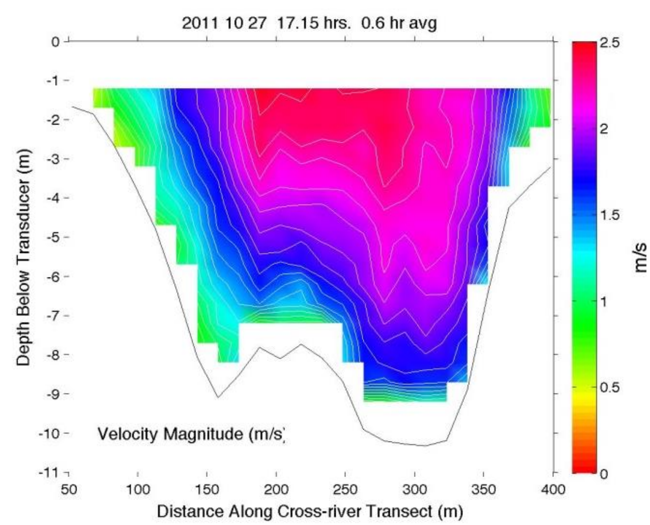

Fig. 6. UNH-CORE Tidal Energy Test Site in Great Bay Estuary. Mean current magnitudes (averaged over 0.6 hr) at max ebb flow measured at UNH-CORE Tidal Energy Test Site during King tides in the Fall of 2011.

IV. TIDAL ENERGY TEST PLATFORMS

Two test platforms accommodate deployment of MHK turbines: An 11 m x 3 m test platform has been used for cross-flow, axial, and ducted axial MHK turbines MHK turbines up to 1.5 m diameter since 2008 (with the first deployment at the UNH Tidal Energy Test Site occurring in February 2009), and a larger 20 m x 10 m test platform with a modular turbine deployment system was designed to accommodate larger turbines up to 4m in diameter. Note that a 4 m diameter axial turbine corresponds approximately to a 1:5 scale model of a utility-scale MHK turbine rated at 1 MWel (Mega-Watt Electric), based on a full-scale diameter of 20 m, a tidal energy resource of 2.5 m/s and an assumed water-to-wire conversion efficiency of 0.4.

A. *Tidal Energy Test Platform v1*

The UNH-CORE Tidal Energy Test Platform v1 is an 11 m long and 3 m wide pontoon boat dedicated to hydrokinetic turbine testing. A turbine deployment mechanism that allows turbine retrieval under full load/tidal currents, instrumentation mounts and wake traversing mechanism were installed. This system enables rapid and safe turbine deployment and extraction at the test site. A fixed gantry crane with a 2000 pound capacity hoist was used to rotate the tripod turbine frame [22]. For recent deployments, the pontoon modifications were analyzed for seaworthiness with FEA simulations under different loading and wave scenarios [22].

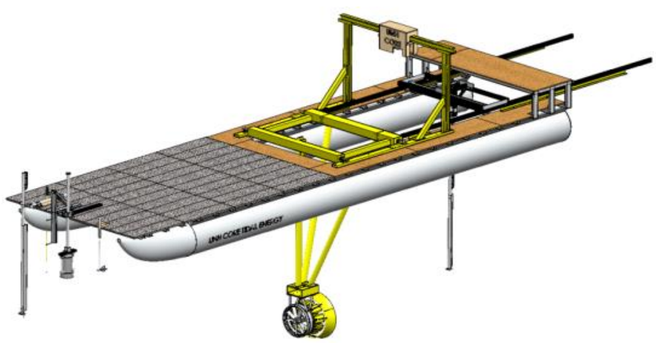

Fig. 7. Rendering of the 11 m x 3 m UNH Tidal Energy Test Platform v1, which has been used for cross-flow, axial, and ducted axial MHK turbines with diameters up to 1.5 m. Here the FloDesign ducted MEHT is shown, installed on a mounting box at the end of a streamlined tripod frame.

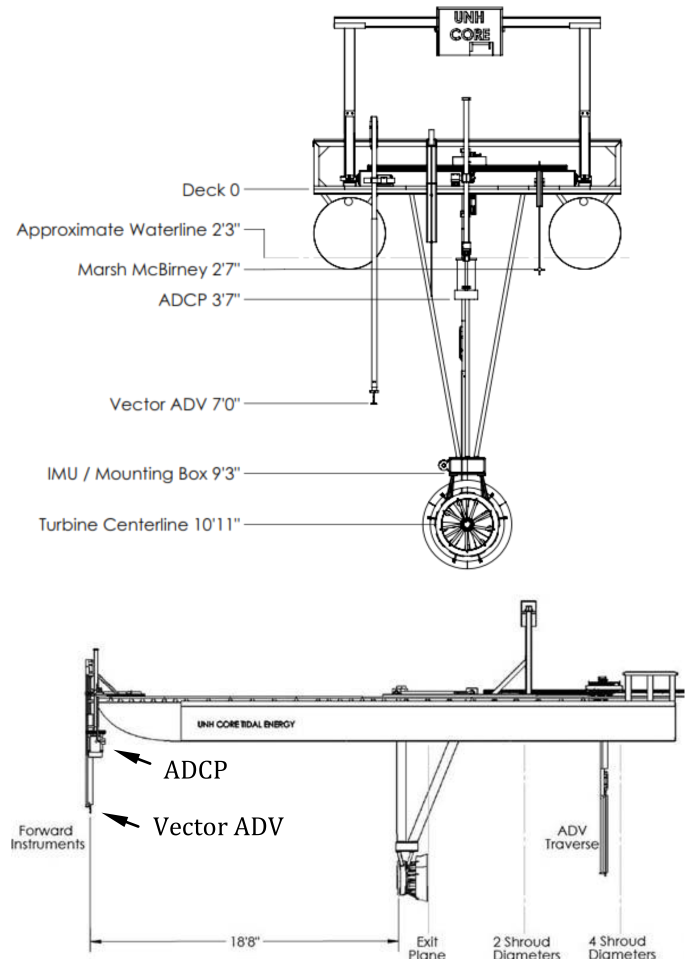

Fig. 8. Setup of Instruments on bow of UNH Tidal Energy Test Platform v1 [22, 23].

B. *Tidal Energy Test Platform v2*

UNH-CORE received an infrastructure grant through the US Department of Energy to construct a new tidal energy test facility with improved capabilities. The new Tidal Energy Test Platform v2 is expected to allow the deployment and evaluation of MHK devices at approximately the following scales: In-stream turbines up to 4 m in diameter, cross-flow turbines up to 5 m x 3 m, and ducted/shrouded turbines with a drag limited of 7000 lb. The new test platform and turbines are shown schematically in Fig. 9. Hull design criteria included limiting tipping angles to less than 1° under maximum loading conditions. The facility will employ a modular turbine deployment design that will support each of these various turbine styles as well as allow for quick recovery and re-deployment throughout a tidal cycle to facility incremental testing. The test platform is a custom twin hulled deck barge with a moon pool, with nominal dimensions of 20 m length and 10 m width. Extensive finite element analysis was performed to ensure structural integrity and a scaled physical model was constructed and tested in various current and wave environments in the UNH tow/wave tank. A mooring system consisting of four anchor points will keep the facility on station during both flood and ebb tides [27]. Funding for the larger test platform was secured, and the mooring and acoustic monitoring systems are currently in the final stages of an environmental assessment through the US Department of Energy (DoE).

Fig. 9. UNH Tidal Energy Test Platform v2 . Schematic of test platform and MHK turbines: axial (top), cross-flow – horizontal orientation (middle) and ducted (bottom).

V. Summary and Outlook

The Center for Ocean Renewable Energy (CORE) at the University of New Hampshire (UNH) operates a sheltered, intermediate scale (“nursery”) tidal energy test site suited for Marine Hydrokinetic (MHK) turbines up to 4 m (13 ft) in diameter at General Sullivan Bridge in Great Bay Estuary, NH. The UNH-CORE Tidal Energy Test Site is located in a constricted area, and 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). The test site has a nominal depth of 10 m, a flat bottom, easy access from two local UNH marine facilities and nearby commercial marinas, and hence it is a cost-effective site for the testing of tidal energy conversion devices. An 11 m x 3 m test platform has been used for MHK turbines up to 1.5 m diameter since 2008, and a larger 20 m x 10 m test platform with a modular turbine deployment system was designed to accommodate larger turbines up to 4m in diameter.

A number of MHK turbines were deployed and evaluated at this test site, including cross-flow turbines with helical blades (Gorlov Helical Turbines), and more recently, an axial Mixer-Ejector Hydrokinetic Turbine designed by FloDesign Inc. under a US Department of Energy (DoE) SBIR phase 2 project. The UNH-CORE Tidal Energy Test Site is well suited to support open-water MHK testing through DoE Technology Readiness Levels (TRLs) 5-6 and 7. Note, however, that the UNH CORE Tidal Energy Test Site is not grid connected, and plans to connect to the electric grid are not being pursued at this time.

Further, a research program to investigate the spatio-temporal structure of turbulent flows relevant to marine hydrokinetic (MHK) energy conversion, including turbulent inflow and turbine wakes, was recently initiated at UNH [28]. MHK energy conversion devices are subject to a wide range of turbulent scales, either due to upstream bathymetry, obstacles and waves, or from wakes of upstream devices in array configurations. The commonly used, robust Acoustic Doppler Current Profilers (ADCP) are well suited for long term flow measurements in the marine environment, but are limited to low sampling rates due to their operational principle. The resulting temporal and spatial resolution are insufficient to measure all turbulence scales of interest to the device, e.g., “blade-scale turbulence”. The inflow upstream of the turbine under test was characterized using an acoustic Doppler Velocimeter (ADV) and an acoustic Doppler current profiler (ADCP), which vary considerably in temporal and spatial resolution as well as practical applicability in this environment. The turbine was operated at previously determined peak efficiency for a given tidal current [22, 23]. The wake of the turbine was measured with a second, traversing ADV during ramp-up and at peak tidal current velocities, at two to six shroud diameters downstream. Among other results, the mean velocity deficit in the wake downstream of the turbine was found to recover more quickly with increasing levels of free stream turbulence, which has implications for turbine spacing in arrays.

Acknowledgment

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