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OPEN WATER BLADE STRAIN MEASUREMENTS ON A VERTICAL-AXIS TIDAL TURBINE

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Abstract

Open-water testing of marine renewable energy devices represents a significant milestone and hurdle for research teams and companies that seek to reduce the levelized cost of energy to allow these devices to compete in the open electrical generation market. For open-water testing of tidal energy converters (TECs), accurate measurements of loading characteristics on the blades and other structural components correlated with power performance metrics can be invaluable to further refine design principles and models, allowing continued improvement and cost reductions of new turbine designs. This paper will describe the modifications and additions made to a TEC system to achieve time-correlated blade strain measurements during full turbine operation along with a discussion on the overall impacts the required modifications had on the unmodified turbine.

Keywords: Tidal Power, Open Water Testing, Mechanical Loads

Nomenclature

Flatwise:	Rotation about the axis containing the chord line of the blade
Edgewise:	Rotation about the axis containing the thickness dimension of the airfoil; orthogonal to the span and chord aligned axes of the blade
Chord:	A line that connects the leading and trailing edge of an airfoil
Blade Span:	The length of the blade
TEC:	Tidal Energy Converter

1. INTRODUCTION

1.1 Project Motivation

Marine renewable energy devices that convert the energy of moving water into electricity represent a relatively new form of technology. Although the marine energy industry has seen increased research activity and growth over the past several decades, marine energy faces multiple challenges to achieving widespread, utility-scale deployments. One of these challenges is the availability of experimental data collected under open-water conditions. Field testing of tidal energy converters (TECs) provides validation data at relevant scales, which allows for the exploration of dynamics that might not be well-represented by laboratory testing or simulations, and enables researchers to assess devices under more realistic operating conditions. Open-water testing to evaluate TEC performance and loads is a critical step in enabling devices to move from the research stage to the commercial deployment stage.

Collecting detailed measurements on TECs in the field can be challenging, and the majority of past research has involved numerical simulations or laboratory experiments (Schmitt, et al., 2022). Furthermore, open-water tests documented in the literature have focused primarily on bulk performance characteristics such as power and thrust coefficients (Schmitt, et al., 2022; Atcheson, MacKinnon, & Elsaesser, 2015; Jeffcoate, Starzmann, Elsaesser, Scholl, & Bischoff, 2015; Cavagnaro & Polagye, 2016; Kirke, 2011; Kinsey, et al., 2011; Frost, Benson, Jeffcoate, Elsäßer, & Whittaker, 2018; Chancey, 2019; O'Byrne, 2022). Past studies that measured individual blade loads are largely limited to laboratory experiments (Milne, Day, Sharma, & Flay, 2015). The work that follows describes the instrumentation design, build, and redeployment of an open-water cross-flow turbine. Results will highlight the data sets collected and a preliminary discussion of the findings from operational periods from the end of 2022.

1.2 University of New Hampshire Turbine Deployment Platform

The University of New Hampshire (UNH) developed a turbine deployment platform (TDP) for use at the Tidal Energy Test Site at Memorial Bridge in Portsmouth, NH. The TDP is a ~15 m x ~6 m floating platform with high-density polyethylene (HDPE) pontoons for buoyancy and galvanized steel I-beams for structural support (**FIGURE 1**). The platform is moored to vertical guide posts attached to the Portsmouth-facing side of Pier No.2 of Memorial Bridge Pier on the Piscataqua River spanning Portsmouth, New Hampshire, and Kittery, Maine. Turbines are deployed through the 3.3 m x 5.7 m moon pool and connected to the platform via the turbine pitching mechanism assembly. The turbine pitching mechanism assembly consists of a spanning beam, turbine-specific interface bracket, strongback, and winch, which allows devices to be quickly deployed and removed from the water. UNH is continuing to develop this test site towards accredited testing under the new DOE-funded Atlantic Marine Energy Center (AMEC).

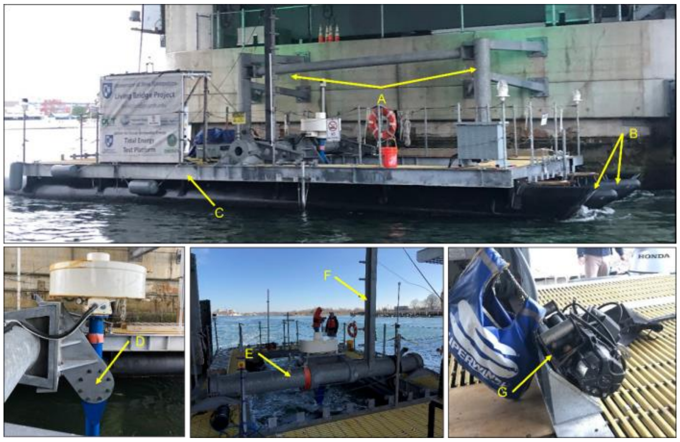

FIGURE 1: AN OVERVIEW OF THE PRIMARY TDP STRUCTURAL AND TURBINE PITCHING MECHANISM COMPONENTS. [A] VERTICAL GUIDE POST ASSEMBLY, [B] HDPE PONTOONS, [C] TDP STEEL FRAME, [D] ADAPTER BRACKET, [E] SPANNING BEAM, [F] STRONGBACK, [G] ELECTRIC WINCH. [FIGURE 2.2 FROM (O'BYRNE, 2022)]

Since the summer of 2018, a New Energy Corporation Inc. (NECI) tidal energy conversion system has been deployed on the UNH turbine deployment platform consisting of a cross-flow turbine, turbine interface panel, rectifier, inverter, and resistor bank. The cross-flow turbine provided was a modified NECI EnviroGen-025H model with a slightly reduced overall diameter to accommodate the existing moon pool dimensions (**FIGURE 2**). The standard model 025H turbine has a diameter of 3.4 m and is rated at 25 kW at 3 m/s. The modified cross-flow turbine has a rotor diameter of 3.2 m and the standard blade height of 1.7 m. The blade profile is a NACA 0021 with a 0.25 m chord length. There are two struts per blade made from the same cross-sectional profile as the blades and impose a preset blade pitch angle β = +4° with a positive angle corresponding with the toe-in direction. Additionally, this is a clockwise-rotating rotor.

FIGURE 2: NEW ENERGY MODIFIED ENVIROGEN-025H CROSS-FLOW TURBINE INSTALLED ON UNH TURBINE DEPLOYMENT PLATFORM (SHOWN ROTATED OUT OF WATER).

The Modular Ocean Data Acquisition (MODAQ) system developed by the National Renewable Energy Laboratory (NREL) with National Instruments hardware and software is capable of high-speed data acquisition to meet ISO standards for water power device validation. Between June 2020 and September 2021, UNH and NREL worked together to develop an iteration of MODAQ to integrate an existing instrumentation package onto a common DAQ with a reliable GPS-based time source (**FIGURE 3**). During the fall of 2021, a significant data acquisition campaign utilizing this MODAQ iteration was completed, providing the baseline power systems operation and concurrent inflow power performance and thrust load data collection capability at this site (O'Byrne, 2022).

On March 25, 2021, a turbine blade assembly consisting of one blade and two struts was delivered to NREL from UNH.

FIGURE 3: UNH MODAQ BOARD [LEFT] AND DEPLOYED ON PLATFORM [RIGHT]. PHOTO BY PATRICK O'BYRNE/ UNH.

2. STRUCTURAL DESIGN AND TESTING

2.1 Blade Modifications

One of the four turbine blades was selected to characterize blade loading. Eight full-bridge strain sensors were installed that maximize bending response and minimize response from shear, tensile, and thermal stress. A design requirement was that the strain sensors minimally affected the hydrodynamic performance of the blade in the tidal flow. There will be some affect due to the minor change in airfoil surface quality and geometry, but this deviation is unavoidable without a significant increase in the strain sensor integration complexity. To minimize the hydrodynamic effects, the strain sensors were installed in machined pockets below the hydrofoil surface (**FIGURE 4**). These pockets removed a small amount (ratio of pocket depth to overall blade thickness) of material from the blade, ultimately reducing the blade thickness and therefore the area moment of inertia. The risk of blade failure because of this modification was determined to be acceptable because by our estimates, blades originally included a large factor of safety and the analysis of the modifications did not suggest that a blade failure would occur. The analysis used conservative estimates for the lift and drag loads the blade would experience at the deployment site, and the results suggested that the blade would have a high chance of survival for the limited deployment of the measurement campaign.

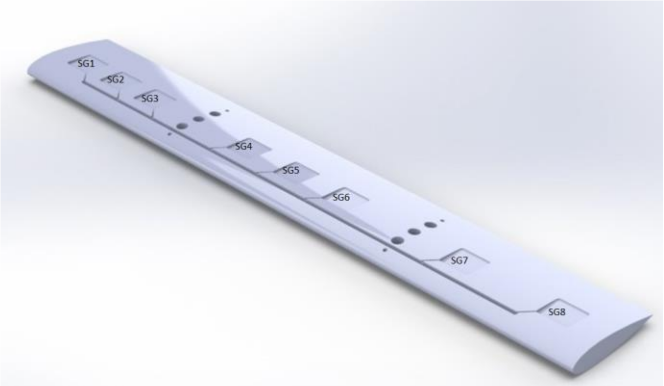

FIGURE 4: RENDERING OF MODIFICATION PLAN (ONE SIDE) FOR TIDAL TURBINE BLADE TO INSTALL_X_ NUMBER OF STRAIN GAUGES BELOW HYDROFOIL SURFACE.

2.2 Blade Strain Measurement Data Collection

The UNH iteration of MODAQ allows for time-synchronous collection of water velocity (using an acoustic Doppler velocimeter [ADV]), turbine thrust loading, platform motion, and power performance data sets. This system was expanded to include the integration of the wireless strain gauge data sets to allow for accurate correlation between measurements. The wireless strain gauge data system includes two Lord V-LINK-200 Wireless Strain/Analog Sensor Nodes with four strain channels each. These devices sample the strain gauges, multiplex the signal, and wirelessly transmit to an antenna that routes the signal into the MODAQ enclosure where it is received by a WSDA-2000 gateway. A gigabit network connection connects the WSDA output to the NI cRIO controller, which time-stamps and stores the strain data.

2.3 Instrumentation Mast

A major challenge of this measurement campaign was to transmit the strain sensor measurements off the underwater rotating blade to the stationary above-water MODAQ system. Of the various methods to transmit data wirelessly under water, all have their challenges that make them less than ideal for this application. To stay within the project budget and implement a reliable solution, it was determined that the best option would be to transmit the wireless strain sensor measurements above the surface of the water. The key benefits of this approach are that an off-the-shelf wireless (above-water) strain sensor system can be implemented, the DAQ enclosures do not need to be marine depth-rated submersible electronics enclosures, and the turbine would not have to be significantly modified to include a data communication capable slipring. The enclosures would be supported above the water surface by an instrumentation mast that rotates around the turbine's fixed bearing/driveshaft housing, which provides the structure to support the thrust loading on the turbine rotor. The instrumentation mast utilizes a novel low-friction plastic bearing, which is low-cost, robust, and lubrication-free. These characteristics are highly valuable in this field deployment. A fairing was also included to reduce the drag load on the mast structure. The exploded view of the assembly can be seen in **Error! Reference source not found.**, and the assembled instrumentation mast can be seen in **FIGURE 6**.

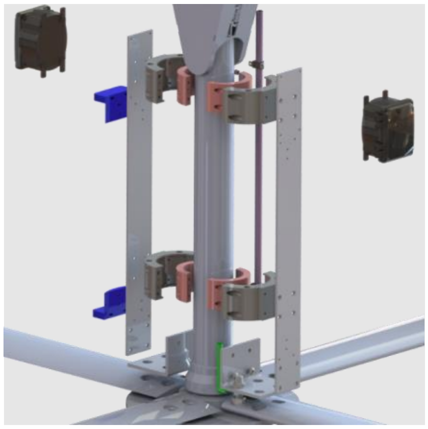

FIGURE 5: RENDERING OF EXPLODED VIEW OF THE TURBINE INSTRUMENTATION MAST.

The addition of this hardware on the turbine rotor increases the swept area and therefore the drag loading, which prompted a supporting design analysis to prevent failure during deployment. The analysis of this hardware was completed using elementary mechanical analysis using the same conservative assumptions utilized for the blade modifications analyses.

The analysis began with determining the drag load that would be experienced by the mast. This required assuming the drag coefficient of the designed fairing. The shape of the fairing does not resemble any standard or previously studied geometries with known drag coefficients. For the purposes of design load estimations, a conservative coefficient of 0.5 was selected as a balance between the drag coefficient of a cylinder (1) and more frequently used foil geometries when aligned with the direction of flow (<0.1).

The drag force was used in ensuring the bearing design and mast structure would endure the loading from the tidal flow with some factor of safety. The lowest factor of safety was determined to be in the threaded rods that attach the instrumentation mast to the blade struts. The risk of failure was determined to be low and acceptable for this limited-duration deployment.

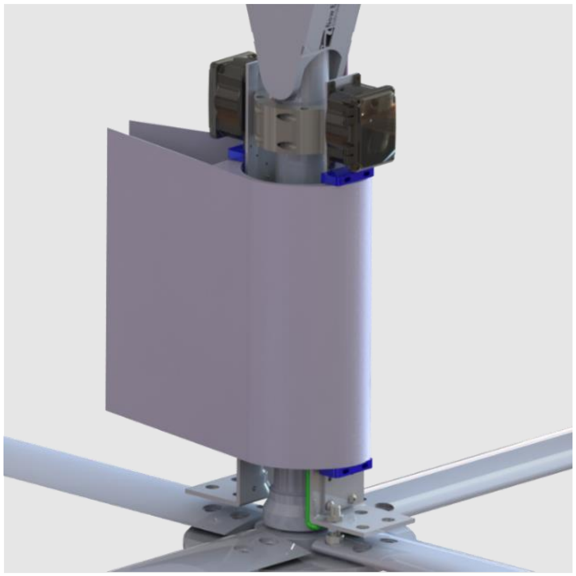

FIGURE 6: RENDERING OF ASSEMBLED VIEW OF THE TURBINE INSTRUMENTATION MAST.

3. INSTRUMENTATION INSTALLATION, BLADE INTEGRATION, AND TURBINE REDEPLOYMENT

3.1 Strain Gauge Installation

The installation of a foil-based strain gauge that can survive for a long time on open-water tidal turbine deployments is becoming a larger area of interest for researchers and commercial developers working in this space. Foil strain gauges and the required cabling are susceptible to several points of failure, such as corrosion, delamination, and electrical shorts, all of which can be induced by salt water. Strain gauge installation occurred in the NREL water power lab to control and monitor the material adhesion and curing processes (**Error! Reference source not found.**) and to ensure the new instrumentation had a good chance of long-term survival. In this work, the assembly process followed and further built on experience from previous field and laboratory deployments. The result was a strain gauge assembly that adheres to the NREL quality assurance standards and is suitable for measurements on an open-water tidal turbine.

FIGURE 7: WIDE VIEW OF OUTER SIDE OF NEW ENERGY BLADE AFTER MACHINING SHOWING STRAIN GAUGE RECESSIONS AND WIRE ROUTING CHANNEL. PHOTO BY ANDREW SIMMS / NREL.

The strain gauges applied to the blade were sourced from HBM, and the installation materials and cabling were purchased from Micro-Measurements (MM). MM provides a comprehensive selection of installation supplies and instructions, and NREL has a long history of successful measurement campaigns using these products. The HBM 1-DY43-1.5/350 strain gauges used in this work have a polyimide backing that is compatible with MM installation supplies. The major elements of the strain gauge assembly used in this work were:

- Strain Gauge: 1-DY43-1.5/350
- Strain Gauge Adhesive: MM AE-10
- Bondable Terminal: MM CEG-75
- Cabling: MM 426-FTE
- Protective Coating: MM M-Coat JA.

A large project requirement was that the blade profile was maintained once the instrumentation was installed, therefore limiting the impact on turbine performance once redeployed. This then required a finished surface that followed the original blade contour, secure cables in recessed channels, an exit for the cabling at a point that does not impact the turbine performance, and overall protection for the cabling until it reached the DAQ. Following the MM installation recommendations for bonding the strain gauges, providing an initial coating with M-Coat JA, and returning the machined channels back to the foil shape with epoxy filler and fairing compound. **FIGURE 8** highlights the steps taken to fully install and protect a strain gauge.

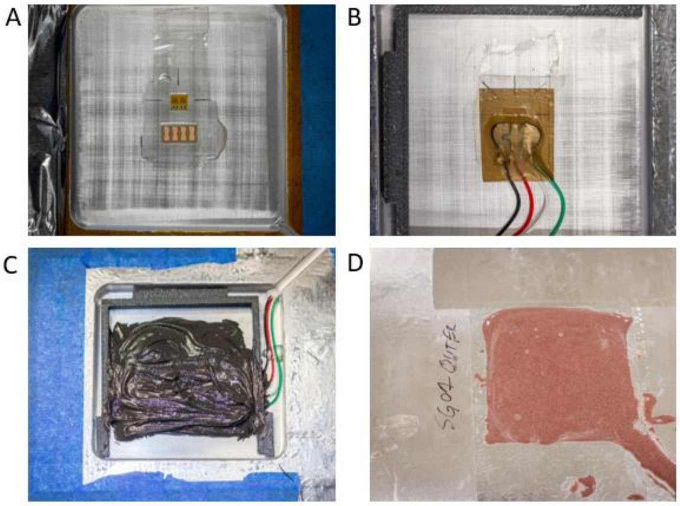

FIGURE 8: EXAMPLE OF THE INSTALLATION STEP USED FOR THE BLADE STRAIN GAUGES AND THE PROTECTIVE LAYERS. A) BOND THE FOIL STRAIN GAUGE TO THE BLADE, B) CONNECT WIRING HARNESS AND INITIAL COVERING, C) COVER WITH M-COAT JA AS A FLEXIBLE WATERTIGHT COVERING AND D) FILL THE REMAINING VOID WITH WEST SYSTEM EPOXY FILLER AND FAIRING COMPOUND.

FIGURE 9: INSTRUMENTED BLADE, CABLING, AND INSTRUMENTATION MAST SUPPLIES PRIOR TO SHIPMENT. PHOTO BY ANDREW SIMMS / NREL.

3.2 Blade Assembly and Shipping

With the strain gauge and wiring protective measures established, the decision was made to fully assemble the entire instrumented blade for return to New Hampshire. This decision was made because a portion of the instrumentation cabling had to run directly through the blade and be protected with epoxy coatings, effectively making the blade and strut a single unit. Completing the instrument installation at NREL allowed for consistent procedures to be followed and initial system testing to be performed, reducing the number of predeployment tasks that would otherwise need to be accomplished at UNH. The final shipped product is shown in **FIGURE 9** and was successfully received at UNH with no damage to the instrumentation or structural components.

3.3 Instrumented Blade Installation and Strain Gauge Calibration

The instrumented blade assembly was shipped to the UNH Judd Gregg Marine Facility in New Castle, New Hampshire, where it was assembled onto the awaiting cross-flow turbine pn the TDP using a boom truck crane (**FIGURE 10**, left). The instrumentation mast assembly was then installed on the fixed turbine bearing housing and connected to the rotor at two opposing strut locations (**FIGURE 10**, right). The strain gauges were checked for continuity, and the wireless telemetry system was tested with the system above water. All strain gauges safely survived transport and initial assembly. After the functionality of the instrumentation mast assembly was verified, the fairing was installed on the turbine (**FIGURE 10**). For deployment, the platform was towed from the UNH Pier to the Memorial Bridge (approximately 2 miles) on the tail end of a flood tide and moored to the existing vertical guide posts.

FIGURE 10: INSTRUMENTED BLADE AND STRUT ASSEMBLY LIFTED AND INSTALLED ON ROTOR. INSTRUMENTATION MAST WITHOUT JUNCTION BOXES OR FAIRING INSTALLED. PHOTO BY MASON BICHANICH / UNH [LEFT], MICHAEL MONAHAN / UNH [RIGHT].

3.4 UNH TDP Instrumentation

After the platform was secured to the bridge, additional instrumentation was deployed to characterize tidal current inflow and wake velocities around the turbine (**FIGURE 11**). LinkQuest FlowQuest 1000 acoustic Doppler current profilers (ADCPs) were installed at the bow and stern of the platform to characterize the inflow and wake profile over the water column. Nortek ADVs were installed as close to the turbine as possible in upstream and downstream locations with probe heads aligned with the center of the turbine-swept area. A Midas CTD (conductivity temperature and depth) device was installed to quantify changes in seawater density during the deployment, which is strongly dependent on salinity and temperature. A YOST inertial measurement unit was installed to capture platform motion, and an Airmar WeatherStation was deployed to monitor atmospheric conditions.

Thrust loads on the entire submerged turbine and instrumentation mast assembly were measured via a reaction moment about the spanning beam (a structural member that allows the turbine to be rotated in and out of the water). Two locking arms extend out from the spanning beam toward the stern of the platform and keep the turbine in place via a pinned connection to a clevis (**FIGURE 12**, left). Each locking arm is pinned to a clevis, which is mounted to an LCM Systems PTC-1 100 kN, 100 Hz load cell capable of measuring both tensile and compressive loads (**FIGURE 12**, left). The combined load measured from both load cells can be used to determine the thrust force on the turbine by assuming a resultant thrust force at the center of the turbine-swept area (**FIGURE 12**, right).

The ADV, thrust load cell, power performance, blade strain, and rotational position sensor (compass) data sets were all collected using the MODAQ system.

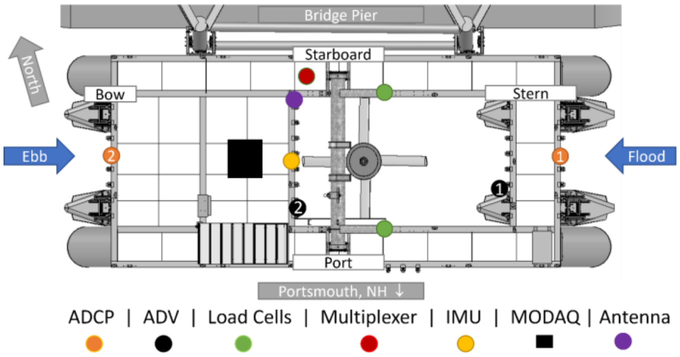

FIGURE 11: PLAN VIEW OF TURBINE DEPLOYMENT PLATFORM INDICATING INSTRUMENT LOCATIONS RELATIVE TO THE TURBINE.

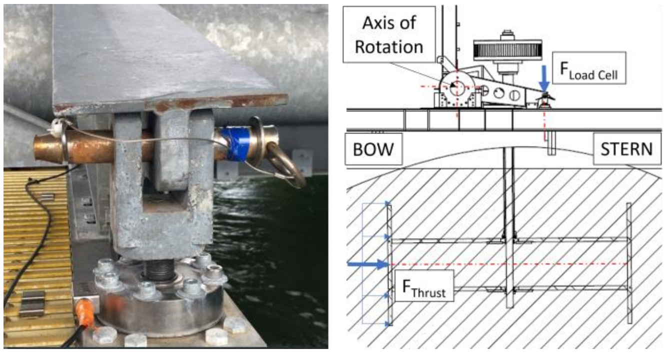

FIGURE 12: [LEFT] PHOTO OF CLEVIS AND LOAD CELL ASSEMBLY (1 OF 2), BOLTED TO THE TDP AT THE EDGE OF THE MOON POOL. [RIGHT] TDP ILLUSTRATING THRUST LOADING AND LOAD CELL LOCATION; MOMENT ARMS ABOUT AXIS OF ROTATION: $F_{\text{LOAD CELL}}$ = 1.23 m, F_{THRUST} = 2.46 m [SOURCE FIGURE 4.1 IN (O'BYRNE, 2022)].

3.5 UNH TDP Operation

To safely operate a tidal energy device, a method of regulating shaft speed is required. This can be achieved mechanically through a braking system or electrically with a motor/generator. At the UNH turbine deployment platform an electrical load is available to regulate shaft speed, which can be applied either in grid-synchronous or off-grid modes. In both modes, power is directed to a rectifier that converts the variable frequency alternating current into a direct current (DC) signal. In grid-synchronous mode the DC signal is routed to a grid-tie inverter that is synchronized to the Memorial Bridge three-phase 480 VAC bus. In off-grid mode the DC signal is routed to a 25 kW resistor bank, or "dumpload," which dissipates power as heat.

Off-grid operation mode was selected to test the turbine with the instrumented blade installed because it allows for turbine shaft speed regulation over the complete operating range. This means that as soon as the turbine begins to rotate, power is dissipated to the dumpload under control from the rectifier. The rectifier uses pulse width modulation to regulate the flow of power to the dumpload to try to match the manufacturer, New Energy, specified power curve as generator voltage increases and decreases with changes in tidal current inflow velocity. In grid-connected mode the turbine can rotate freely until the minimum voltage level is reached for the inverter to operate. This would allow high initial shaft speeds and impose unnecessary risks and loads on the instrumented blade.

3.6 Instrumented Blade Test Log Summary

An operational requirement for the instrumented blade was "manned" operation, meaning the turbine would only be deployed and collecting data when operators were available. This protects the assets, instrumented blade, and instrumentation mast from being damaged due to debris strikes but limits the available operating time frames. Trial data collection runs were completed, building confidence in the instrumentation mast performance and adapting to the battery charging requirements (Error! Reference source not found.).

FIGURE 13: INSTRUMENTATION MAST AND FAIRING DEPLOYED WITH TURBINE BRAKED (I.E., NOT ROTATING). PHOTO BY MICHAEL MONAHAN / UNH.

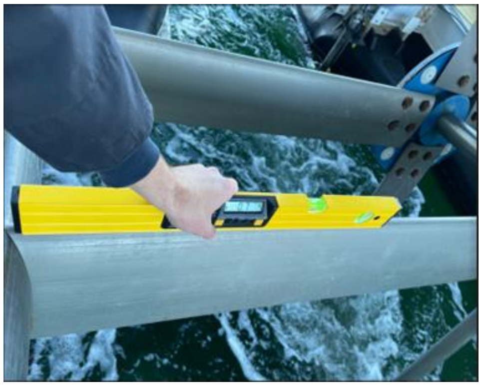

FIGURE 14: ELECTRONIC LEVEL ON THE BLADE STRUT HORIZONTAL) USED TO ALIGN THE INSTRUMENTED BLADE (VERTICAL). PHOTO BY MICHAEL MONAHAN / UNH.

A regular operating routine was established to include battery charging and rotational position alignment verification of the compass used to record azimuthal position of the instrumented blade during each rotation. To establish a known compass position, with the turbine out of the water, the instrumented blade was positioned vertically, perpendicular to the waterline. This was verified with an electronic level on the strut of the non-instrumented blade that follows the instrumented one (**FIGURE 14**). A series of rotations, with the turbine out of the water, were manually completed while collecting data to provide insight on the accuracy of the compass between successive rotations to the known starting point. The instrumented blade was again aligned vertically using the level and the electric brake engaged prior to lowering the turbine into the water. The electric brake was released and the turbine was then free to "cut in" (i.e., begin rotating) once sufficient tidal current velocities were present. The instrumented blade was aligned several times during the deployment

4. RESULTS AND DISCUSSION

The MODAQ system operating on the UNH Living Bridge platform successfully operated as intended through the testing period (through the end of 2022). The measurements associated with the blade strain sensor addition continued to operate as designed and, through repeated measurement periods, continued to produce values within the expected range

The initial operation began as the daylight hours were becoming shorter and colder temperatures on the water were beginning. These temperatures are believed to have had a negative impact on overall battery capacity. They forced potential operating time to be dedicated to recharging the wireless systems batteries, shortening the allowable manned operational periods due to the reduced daylight hours.

A networking component failure in the legacy DAQ system on the platform resulted in the ADCPs and CTD being run independently and not connected to a time-synchronous DAQ. The internal instrument clocks were synchronized to a reliable time source prior to deployment, and the clock drift was estimated over the deployment.

On Nov. 27, 2022, the ADV deployment support pipes were struck by an unknown object causing significant damage to the upstream (ebb tide direction) ADV deployment pipe (**FIGURE 16**) and minor damage to the downstream pipe (platform security camera footage revealed this event to occur between 4:45 p.m. and 5:15 p.m.). On Dec. 8, 2022, the upstream ADV was removed, and turbine testing continued with only the downstream ADV installed on Dec. 8 and 9, 2022. On Dec. 21, 2022, the stern (downstream) ADV pipe was removed; damage was also observed to that deployment pipe.

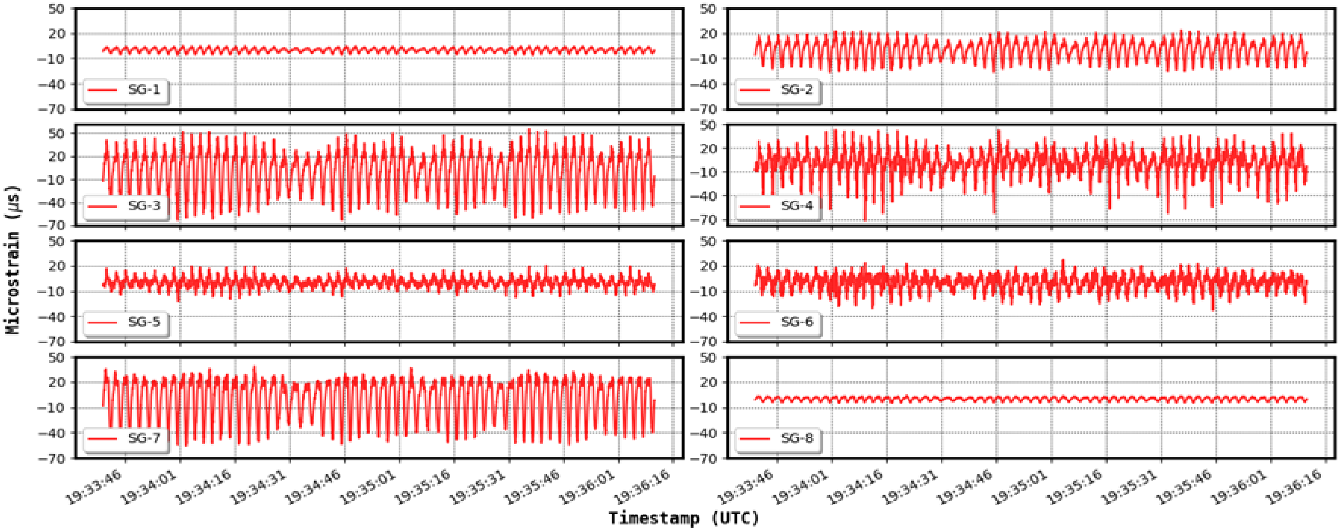

Figure 15: EXAMPLE OF THE STRAIN VALUES COLLECTED DURING TURBINE OPERATION ON 11/22/2022.

FIGURE 16: BENT ADV DEPLOYMENT PIPE (UPSTREAM) ON 12/8/22. PHOTO BY MICHAEL MONAHAN/ UNH.

Despite these challenges and damage to the original measurement configuration, the measurement campaign as a whole continued into December 2022 and was finally decommissioned and electronics were removed from the water and platform as the temperatures dropped too low for manned operation. The remainder of this section will highlight a portion of the data set obtained during this deployment, which will be accessible via open-source databases in the upcoming months.

4.1 Blade Strain Measurements

The primary goal of this measurement campaign was to collect blade strain measurements on the rotating cross-flow turbine correlated to tidal current inflow velocity. A sample of the time-correlated strain measurements collected from the instrumented blade is shown in **FIGURE 15**. The distributed strain measurements highlight the variation of stress experienced by the blade during an operational cycle. The strain gauges were numbered as deployed, downward from the top of the blade (top is the end of the blade closest to the water's surface): strain gauges 1−3 above the top strut, 4−6 between the upper and lower strut, and 7−8 below the lower strut.

The largest peak-to-trough variation in strain through a turbine rotation is seen in strain gauges 3 and 7, both situated above and below the blade struts. This can be attributed to these strain gauges positioned closest to the strut responsible for supporting the moment generated by top and bottom thirds of the blade. The strain gauges next to and between both struts (4 and 6) also show large peak-to-trough strain but not to the extent of gauges 3 and 7. This is indicative of the high degree of material stress near the struts and the larger bending moments in that location. Statistics of the peak-to-peak strain variation from each gauge are shown in **TABLE 1**.

The variation in the strain appears very regular over each rotation of the turbine with distinct features at regular intervals. A notable result is the apparent imbalance in the strain between the top and bottom of the blade. The calculated statistics show larger measured values appearing around the top strut. This may be an indication of a variance of the inflow velocity across the swept area of the turbine. In future analysis, the inflow velocity measurements made by the ADCPs will provide data suitable to investigate this further. For the current study, we will discuss the fluid inflow measurements based on ADV measurements.

TABLE 1: PEAK-TO-TROUGH DIFFERENCE STATISTICS FROM EACH STRAIN GAUGE ON THE UNH TURBINE BLADE. VALUES ARE GENERATED FROM THE NOVEMBER 22, 2022, DEPLOYMENT.

STRAIN GAUGE	**MEAN**	**MAX**	**MIN**	**STD**
1	8.1	12.1	4.3	1.1
2	37.1	118.3	21.7	5.7
3	86.8	120.8	51.0	11.4
4	55.6	91.3	24.2	10.8
5	21.5	37.3	9.7	4.5
6	35.7	63.3	17.8	7.0
7	69.7	100.1	40.6	8.0
8	6.3	10.1	4.1	0.7

4.2 ADV Measurements of Inflow Velocity

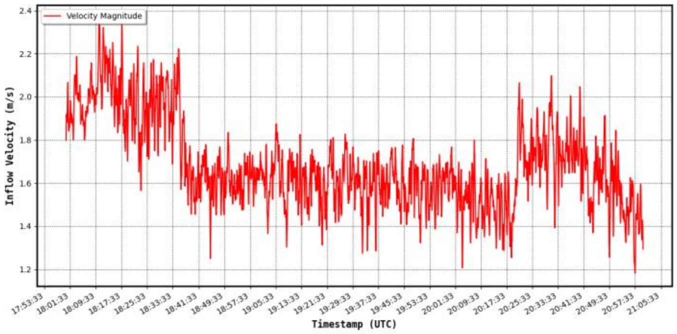

FIGURE 17: INFLOW FLUCTUATION DUE TO THE PRESENCE OF THE TURBINE. THE ADV POSITION WAS INCHES UPSTREAM OF THE TURBINE AND THE FLOW IMPACT CAN BE CLEARLY SEEN.

The ADV data provided in this work were collected from a device positioned within inches of the diameter of the operating turbine. This makes the measurements collected subject to flow impacts due to the presence of the turbine itself. During the deployment we can quite clearly that there is a distinct reduction in the inflow velocity directly upstream of the turbine (**FIGURE 17**). The ADV measurements repeatedly indicate that the turbine has a significant and measurable impact on the surrounding environment. Investigating the relationship between turbulent characteristics of the inflow and the apparent variations in the strain measured on the turbine blade could reveal important operating conditions that could impact the overall design of the turbine, leading to possible cost reductions in the manufacturing process or improvements in the longevity and survivability of the turbine.

FIGURE 18 provides an example of the ADV measurements in relation to the strain measurements captured from the turbine. The ADV measurements were averaged over 32 samples for visualization purposes. It is notable that a clear connection between the inflow velocity fluctuations and the strain measured on the blade is not immediately apparent. In future work, a more detailed investigation into the turbulence characteristics of the measured inflow will be calculated and related to the measured strain. This investigation was beyond the scope of the current study.

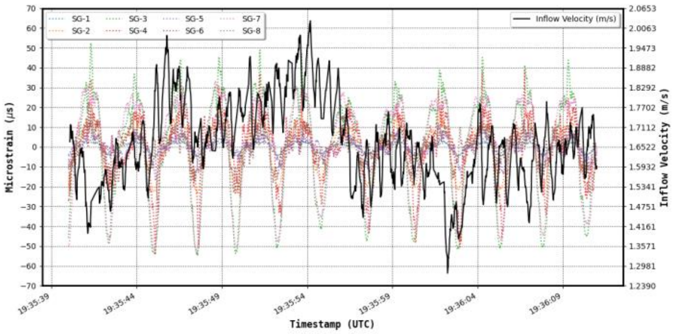

FIGURE 18: TIME SERIES OF INFLOW VELOCITY MAGNITUDE OVERLAID ON THE CORRELLATED STRAIN MEASUREMENTS FROM THE TURBINE. THE ADV MEASUREMENTS DISPLAYED ARE AVERAGED OVER 32 SAMPLES.

4.3 Turbine Electrical Power Output

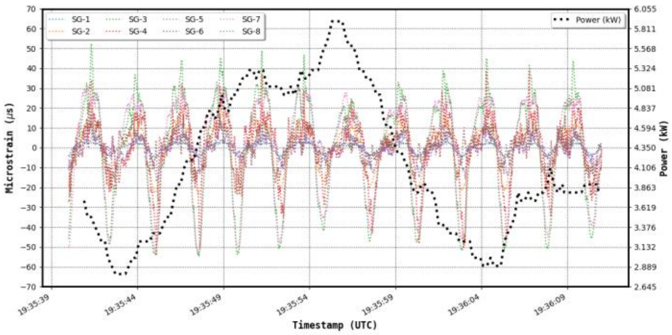

FIGURE 19: TURBINE POWER PERFORMANCE OVERLAID ON THE STRAIN VALUES MEASURED FROM THE TURBINE BLADE.

Ultimately, for any tidal turbine, maximizing the power output of a device is the goal. The measurement system available in this study was able to provide 1 second averages of the output power from the turbine. **FIGURE 19** shows an example of the power output from the turbine in relationship to the strain values measured from the turbine blade. The output power appears to vary independently of the fluctuations in strain. The power output through the course of this deployment corresponds to that measured in previous studies. With the time stamp correlation provided with the MODAQ system, a detailed analysis can be made between the mechanical loads experienced by the turbine. The revolutions per minute of the turbine are derived from the three-phase AC generation frequency and closely follow those values. The revolutions per minute (rpm) through this deployment fluctuated between 18 and 31 rpm. **FIGURE 20** shows the revolutions per minute in relationship to the strain values measured from the turbine blade. It is notable that the variations of the rotational speed do not appear to have a significant impact on the strain fluctuations seen on the turbine blades.

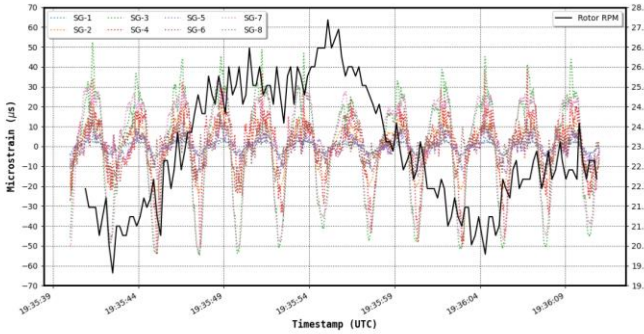

FIGURE 20: TURBINE RPM OVERLAID WITH THE STRAIN MEASUREMENTS CAPTURED FROM THE BLADES. RPM MEASUREMENTS ARE DERIVED FROM THE AC POWER OUTPUT FLUCTUATIONS.

4.4 Turbine Thrust Measurements

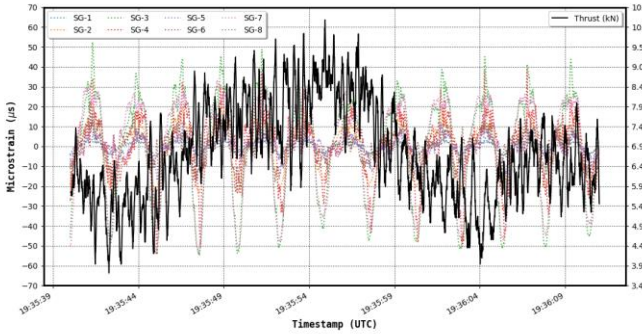

FIGURE 21: MEASUREMENTS OF TURBINE THRUST OVERLAID ON THE STRAIN MEASUREMENTS CAPTURED FROM THE BLADES.

An example the turbine thrust measured from the pancake load cells located on the platform. **FIGURE 21** shows the turbine thrust in relation to the measure strain from the turbine blade. The turbine thrust during this deployment had a mean value of 6.4 kN with peaks up to 11.5 kN. Thrust variation over the deployment do not appear to be reflected in the peak-to-trough variation in the blade strain; however, the relationship between these measurements will be investigated in future studies.

5. CONCLUSION

This paper discussed the turbine instrumentation, redeployment, and outcomes of the measurement campaign of the New Energy cross-flow turbine on the UNH Living Bridge Platform. This project has produced a new open-source data set that is intended to be used to improve model accuracy and the overall improvement of this type of turbine. Key outcomes from the work focusing on the measurement system build show that it is feasible to extend the useful life of research equipment given the availability of all the necessary pieces. This deployment has produced data sets with clock-synchronized blade strain data to turbine thrust, electrical power and flow speed values measured on the Living Bridge platform. The data presented here show preliminary analysis of the combined data sets. Interesting results show minimal relation of the rotational rate of the turbine to the overall strain on the blade, which is counterintuitive to previous lab and model results.

Future work will further investigate the correlation of the measured strain to inflow characteristics and the other important quantities measured by the MODAQ system on the Living Bridge.

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