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Experimental Investigation of Turbine Blade Response Using Fiber Optic Strain Sensors

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Abstract

Blade strain measurements and load analysis have advanced significantly in wind turbine research with improvements in measurement durability, reliability, and accuracy employing fiber optic strain sensors (FOS), improved sensor configurations, temperature compensation methods to minimize errors, and application of finite element analysis (FEA) modeling to resolve the relationship between the strain field and load vector. Experience deploying advanced FOS sensor measurement techniques for marine turbine blades is relatively recent and rare. Published blade strain measurements for marine turbine blades are predominantly from conventional resistance strain gauges employed in scale-model axial-flow turbine studies in controlled laboratory testing. In this work, three turbine blades are tested for different loading configurations; to calibrate and validate FOS measurement and to validate a finite element analysis (FEA) model used to predict the blades response. Fiber optic-based sensors were selected as they have low noise and a relatively small footprint. In addition, based on the FEA simulations, the sensors should be capable of measuring the full range of strain that will be experienced during operations. The sensor layout for the blades is comprised of four rosettes at the blade root and four uniaxial strain gauges along the blade, as shown in Figure 1. The material and cuboid geometry of the blade root section was carefully designed so that placing the rosettes at this location meets the recommendations regarding the choice of sensor location. Bending moments (flapwise and edgewise) and twist moments were predicted using the OpenFAST model, which provides along-blade distributed loads, to mimic operational conditions. The maximum moments in the structural testing are replicated by applying a point force at specific locations on the blade that produces the same operational moment values. The locations of the point force were determined by comparing the deflections predicted using two FEA models; the first model used the distributed loads as input from OpenFAST, while the second model used a point force a selected locations on the blade. The objective of this modeling effort is to closely match the blade deflection profile between the two models for the same force magnitude. The overarching goal of this experimental testing is to perform a set of experimental testing to calibrate: 1) the bending moment values derived from the blade root fiber optic rosette strain sensors against a set of known loads along the flapwise, edgewise and combined flapwise and edgewise directions, and 2) the performance of the twist moment values derived from the rosettes. This is a critical step to ensure that accurate bending moment measurements can be derived from the rosette strain measurements for field deployment as part of a full rotor turbine assembly. Results from the experimental program showed promising potential to predict the loading on the turbine blades using implemented FOS.

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1. Introduction

Blade strain measurements and load analysis has advanced significantly in wind turbine research with improvements in measurement durability, reliability and accuracy employing fiber optic strain sensors (FOS), improved sensor configurations, temperature compensation methods to minimize errors, and application of finite element analysis (FEA) modeling to resolve the relationship between the strain field and load vector [1-3]. Experience deploying advanced FOS sensor measurement techniques for marine turbine blades, however, are relatively recent and rare. Published blade strain measurements for marine turbine blades are predominantly from conventional resistance strain gauges employed in scale-model axial-flow turbine studies in controlled laboratory testing [4]. FOS measurements for marine turbine blades were first demonstrated at the University of New Hampshire (UNH) tow tank almost a decade ago and currently employed at the UNH tow tank [5]. But neither study to date has used these strain measurements to compute and analyze load quantities of interest (LQOIs) (e.g., stresses, forces and moments). Limited number of studies of FOS measurements have been published for marine turbine blades deployed in the field to derive LQOIs under real turbulent flow conditions [6].

The International Electrotechnical Commission (IEC) 62600-3 technical specification (TS) defines the requirements for mechanical loads tests resulting in consistent and reproducible tests conducted by certified third-party test facilities and current energy converter (CEC) technology manufacturers. It details requirements and recommendations for the measurement of mechanical loads for a variety of purposes, including site selection, direct measurements of the design loads, and measurement of component structural loads. However, advanced methods and tools for accurate measurement and analysis of LQOIs and measurement uncertainty, including those under development or not fully characterized, are not widely accessible for technology developers and test facilities to implement the IEC 62600-3 TS. While marine turbine blades are expected to be advanced composite materials, a solid aluminum metal blade was selected to establish a baseline for subsequent composite blade testing and a baseline for evaluating and demonstrating low- and high-fidelity post-processing and analysis tools for computing blade loads in compliance with IEC 62600-3, as solid metal properties are isotropic (directionally consistent) and the modulus of elasticity (stiffness) is well characterized to ensure reliable modeling of stress-strain relationships and the load vector from the strain field. While measurement uncertainty is addressed in the IEC 62600-3 TS with reference to standard methods for uncertainty analysis, its propagation to LQOIs is not detailed.

Herein, we present preliminary FOS measurement data from three (3) of Sandia's smart-sensor blades to be deployed on the rotor-assembly of the open-source tidal energy converter (OSTEC) testbed project [7], including FOS measurements collected in controlled static blade laboratory calibration tests prior to field deployment. The main objectives of this research are to: a) Demonstrate and verify advanced FOS measurement techniques for marine blades using Sandia's smart sensor blade, uniaxial FOS (temperature-compensated) strain measurement system along the pressure- and suction-sides of blade span, and novel FOS rosette system, and b) Develop streamlined workflows and methods to post-process blade strain measurements and derive LQOIs for the full spectrum of mechanical load cases (MLCs) described in the IEC 62600-3 TS. Low-fidelity methods using simple direct correlations with FOS measurements or beam theory to derive LQOIs will be employed and compared to high-fidelity methods using the FEA model of the SNL smart-sensor blade validated using static test data.

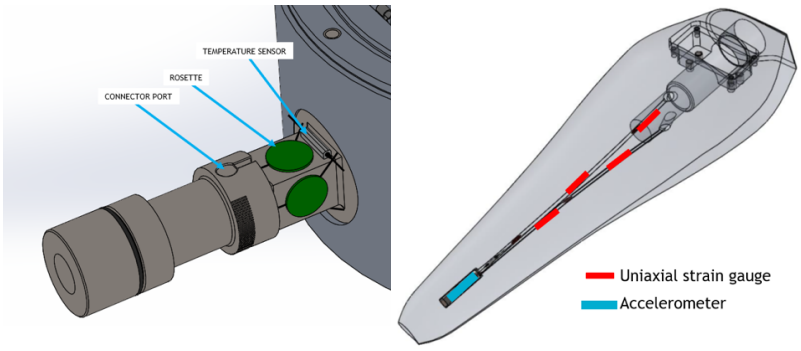


Fig 1. Sensor configuration for blade 1 & 2: at the blade root attachment (left) and along the blade (right).

2. Blade Testing

The three-dimensional blade geometry is based on the marine hydrokinetic family 1 (MHKF1) hydrofoils, consisting of three two-dimensional (2D) blade sections (hydrofoils), one for the inboard span of the blade (MHKF1-400), one for midspan (MHKF2-240), and one for the outboard span. These 3D blade sections were optimized for high hydrodynamic performance over a broad range of tip speed ratios while minimizing risks of cavitation, biofouling, and noise generation [8]. These 2D sections are re-dimensionalized, distributed radially along the span, and twisted to create the 3D blade geometry.

The turbine blades were designed to enable easy exchange and pitch adjustment of other blade designs and materials. The designed foils were left unmodified to retain their hydrodynamic characteristics [7]. Multiple blades were manufactured for the purpose of testing. The blades reported in this work will be referred to as B1, B2, and B4. The blades were made of Aluminum 6061-T6, which typically has a yield strength of 240 MPa. Cerakote, a ceramic-based finish, was applied to the blade to improve the blade's resistance to abrasion, corrosion, chemicals, etc. The weight of each blade ranges from 25.745 kg to 25.793 kg. The blade-hub interface connects a blade to the rotor hub and made of 17-4 PH steel. Each blade is jointed to the blade-hub interface using a clamping mechanism. The blade-hub interface has a cuboid root section on which the rosette strain gauges are mounted. Each rosette measures strains along the 0-, 45- and 90-degree axis and has a temperature-compensation feature. These strains will be referred to as ε_a, ε_b, and ε_c. An inner circular hole inside the interface enables fiber optic sensor cables routing from the blade and cuboid section to the fiber optic interrogator inside the hub. The blade and blade-hub interface assembly are jointed to the hub using six hex-head stainless steel bolts. Multiple roots were manufactured to be paired with the tested blades. Three different roots are reported in this work, referred to herein as R1, R2, R3, and R4. Finally, the roots were tested at 60° clockwise orientation around the longitudinal blade axis to optimize the strains distribution on each rosette. All reported cases herein are at the 60° orientation.

The locations of the four uniaxial strain sensors are staggered along the blade at approximately 25% to 75% blade chord length, two on each side of each blade, to measure local strains and capture the dominant structural modes of the blade. The strain sensors are adhered into the groove made along the blade, and then the groove is filled with marine epoxy and sanded, as needed, to minimize surface imperfections.

Four Linear Variable Differential Transformers (LVDTs) are placed along the blade, at 40%, 60%, 80%, and 100% blade span, to measure deflections along the principal force direction. 0% blade span is defined here as the outermost side of the blade root attachment (same as the origin of the moment arm). The blade root is mounted to a vertical steel wall using a custom-made wall interface that can be rotated along the blade's pitch axis to allow testing of off-angle forces. The wall interface is designed to have four slots to allow fiber optic cable egress.

The experimental quasi-static blade twist testing was accomplished using an MTS 242 linear hydraulic actuator that will apply prescribed forces through a rotationally adjustable saddle clamp (ROAM) that grips the blade at a specified moment arm length. The orientation of the ROAM can be adjusted to follow the blade pitch angle, as shown in Figure 2. The zero- and 180-degree tick marks on the ROAM correspond to the position in which the actuator applies load along the edgewise direction. The 90- and 270-degree tick marks on the ROAM correspond to the position in which the actuator applies load along the flapwise direction.

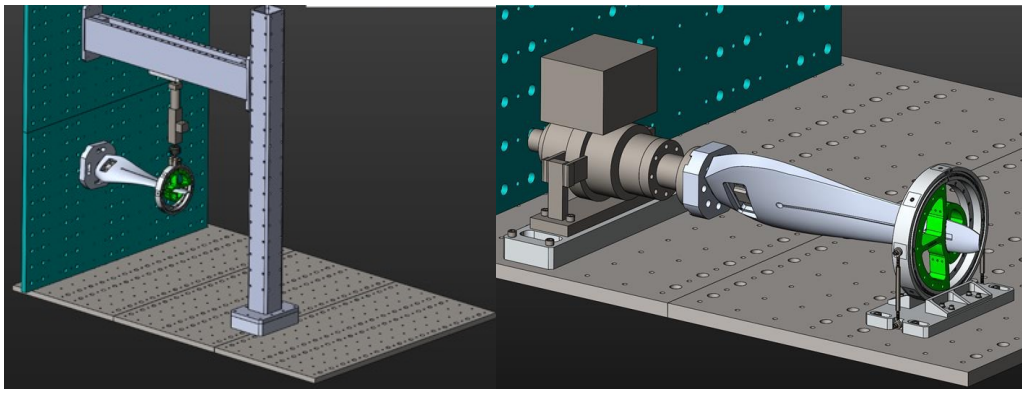


Fig 2. Schematic of the bending moment (left) and twist (right) test setup

The maximum flapwise and edgewise root bending moments, and pitch moment were predicted using OpenFAST blade element momentum model simulations for the OSTEC turbine rotor under different design load cases and turbulent inflow conditions specified in the IEC 62600-2 design standard [7]. The maximum values of the flapwise root bending, edgewise root bending, and pitch moments derived from OpenFAST results are 4.928 kNm, 1.146 kNm, and 0.32 kNm respectively. Table 1 summarizes the testing parameters and matrix for all reported blades.

Table 1. Summary of Blade Testing Matrix.

Blade/Root	Applied Load	Load Direction	Blade Pich Angle
B3R3	5.25-5.27 kN	Push/Pull	0 (flapwise)
	2.38 kN		-90º (edgewise)
	4-5.27 kN		-30º
	0.19 kN.m	Torque	-
B4R1	5.44 kN	Push/Pull	0 (flapwise)
	5.27 kN		-90º (edgewise)
	4 kN		-30º
B2R2	5.44 kN		0 (flapwise)
	4.23-5.27 kN		-90º (edgewise)
	4 kN		-30º

3. Results and Discussion

The performed tests covered a wide range of loading cases to obtain good correlation between applied moments and strain measurements. Since the blade tested is a statically deterministic cantilever configuration, the bending moment at any location of the blade could be estimated as the product of the applied force and orthogonal moment arm measured from the load application to point of interest. Also, any twist moment applied will remain a constant value along the blade. The twist moment measured on the blade was due two one of two sources, either the applied twist or the constrained loading condition of the saddle in cases of bending.

Based on the strain rosettes orientation, ε_c was allied with the direction of blade bending, thus equal to the axial strain. The shear strain could be calculated as $\gamma = \varepsilon_b - 0.5(\varepsilon_a + \varepsilon_c)$. The strain rosettes data was used to predict the applied loads on the blades with high accuracy. In cases of bending, if one defines $\Delta\varepsilon$ as the difference of strains on two opposites faces, the moment applied corresponding to these strains could be estimated as $M = 0.5\ \Delta\varepsilon\ ES$; where E is the root modulus elasticity and S is the root section modulus. Then, by estimating the moment on the two orthogonal directions based on the data of the four faces, one could estimate the applied loads and moments based on the root orientation.

In the cases of twist, the hollowed root is assumed of a thin wall such that the following approximation for the applied twist could be used T = 2 γ G J/h; where G is the root shear modulus, J is the root polar modulus, and h is the distance from root center to the strain rosettes. Each strain rosette would provide an independent prediction of the applied twist. Which all were reasonably within the same range of the applied twist.

Figure 3 illustrates sample flapwise testing results and the corresponding axial and shear strains. The applied load in the presented case is 5.27 kN. The predicted load is 5.77 kN, within 10%.

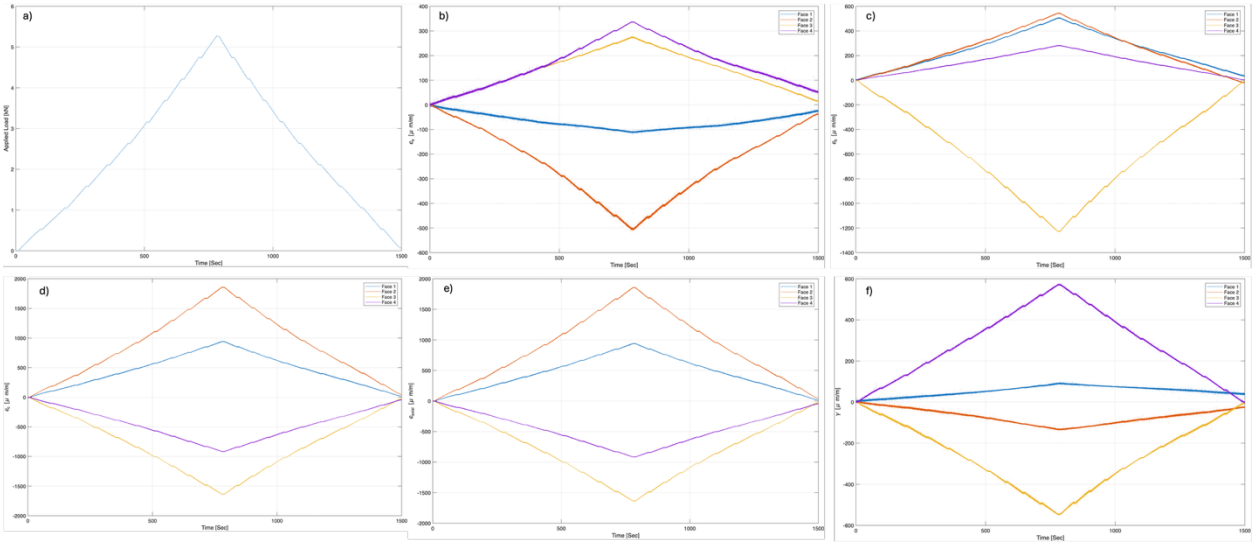


Fig 3. Sample Data and Analysis of Flapwise Bending Test: a) applied load, b-d) strain rosettes, e) axial strains, and f) shear strains.

4. Conclusions

A quasi-static blade testing was performed at Sandia National Laboratories to calibrate and validate FOS measurements in preparation for open water deployment on the rotor-assembly of the open-source tidal energy converter (OSTEC). The applied flapwise, edgewise, and pitch moments were estimated via OpenFAST simulations for the OSTEC turbine rotor under different design load cases and turbulent inflow conditions specified in the IEC 62600-2 standards. The blade was extensively instrumented, including four strain rosettes on each of the face of the blade cubical roots. Since the blade could be represented as a cantilever beam, the strain rosettes measurements were used to predict and be compared to the applied testing loads. This simplified structural model was able to predict the applied loads with reasonable accuracy, within about 10% of the testing measurements.

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