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FIBER OPTIC INSTRUMENTATION FOR MEASURING ROTOR STRAIN

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INTRODUCTION

Marine and hydrokinetic (MHK) energy contribute to national energy objectives by providing clean energy to reduce oil dependency and lower carbon emission. In order to become cost-competitive, the US Department of Energy aims to reduce the levelized cost of energy (LCOE) for MHK devices to $0.12-$0.15 per kilowatt-hour (kWh) by 2030. Reliable load and structural prognostic and health monitoring (SPHM) systems for MHK can significantly reduce operations and maintenance (O&M) costs and maximize plant revenue, by providing a better servicing schedule, avoiding unnecessary shutdowns, and increasing device availability.

Strain measurements on the rotor blades are key information for assessing blade loads and improving blade design, but obtaining this measurement is challenging because high-frequency signals have to be transmitted off of a high speed rotating platform. There is also a safety concern in using conventional piezoelectric sensors (e.g. coil strain gauges) for this application because powered cables have to be attached into a spinning rotor and submerged in water. Fiber optic sensors, such as the Fiber-Bragg grating (FBG) sensor, do not require electric power at the sensor, and are immune to electromagnetic interference (EMI) and wire-induced noise. These are the main advantages of using fiber optic sensors, especially since MHK turbine generators produce electromagnetic signals that can cause signal interference to piezoelectric systems.

The primary goal of this work is to demonstrate the feasibility of FBG sensors for measuring dynamic strains on a scaled MHK turbine.

METHODS

Sandia National Laboratories (SNL) and the University of New Hampshire (UNH) integrated FBG sensors into the UNH's vertical axis turbine and ran experiments to simultaneously measure blade strain, inflow (carriage) velocity, torque and thrust in UNH's tow tank facility. The details of the wave tank facility and instruments used can be found in [1]. The tow/wave tank facility is 36.6 m long, 3.66 m wide and 2.44 m deep (Figure 1). The testing turbine was the UNH Reference Vertical Axis Turbine (UNH-RVAT), a one meter tall three-bladed vertical-axis rotor with a one meter rotor diameter (Figure 2). The rotor is constructed from 0.14 m chord NACA 0020 blades. The turbine is mounted to a carriage that can be actuated by a permanent magnet servomotor and timing belt to provide accurate tow velocities (Figure 3).

The turbine shaft RPM was measured and controlled by a servo motor and gearhead attached to the shaft. The shaft torque was measured at a 2 kHz sampling rate with an inline torque transducer mounted between the servo motor and turbine shaft. The torque measurement was be corrected for bearing friction by adding a tare torque, measured in air by driving the turbine shaft with the servo motor. Turbine power was calculated from the measured torque and angular velocity, which was computed by differentiating the shaft angle time series with a second order central difference scheme.

Turbine thrust/drag was measured using load cells mounted on the carriage. The thrust measurements were corrected by subtracting the tare drag, measured by towing the test frame with the turbine removed.

The strain FBG sensors used in this testing were the Micron Optics os3200 sensors [2] (Figure 4). A four-channel optical interrogator Micron Optics sm130 [4] that can accommodate up to 20 strain sensors per channel was used to sample the data at 500 Hz. A coarse finite element model of one turbine blade was developed to identify the mounting locations of the strain sensors (Figure 5), i.e. to ensure the predicted strain at the mounting location is greater than, or in the same order of magnitude, from the sensitivity of the strain sensor.

Six strain sensors were mounted on two of the rotor blades at various blade spans (Table 1.). A fiber optic slip ring was installed at the base of the shaft to transfer the measurement signal off of the rotor to the interrogator (Figure 6). The slip ring is a one channel Princetel fiber optic slip ring (RPC-155-28A-STX model), suitable for deep water measurements up to 20,000 psi [5]. SNL and UNH integrated the FBG sensor system into UNH data acquisition system, to synchronize the measurements of strain, inflow velocity, thrust, turbine shaft torque, turbine shaft RPM and turbine-generated power. The experiment was conducted with the turbine towed at 1.0 m/s and a Reynolds Number of $\sim 10^6$ (based on turbine diameter).

RESULTS

Power (C_P) and thrust (C_T) coefficient curves were developed using data collected from 31 test cases (with different tip-speed ratio). The power coefficient peaked at a tip-speed ratio of 1.8, while the thrust coefficient increases with tip-speed ratio (Figure 7). Mean strains were calculated at each sensor location, for all test cases (Figure 7). As shown in this figure, mean strain values are similar for sensors that are located at the same blade spans, over the whole tip-speed ratio range. Sensors 1, 3 and 6 were located at the same blade spans, 25% or 75% blade span. Sensors 2, 4 and 5 were mounted at 50% blade span. Each set of these sensors have similar mean strain values, and the values are in the same order of magnitude as those predicted using the finite element model.

CONCLUSIONS

This experimental test demonstrates that FBG sensors can be successfully used for measuring strain on a rotating hydrokinetic turbine. The sensors were not damaged even though they were kept underwater for approximately one week. Longer underwater testing in the field is required to determine whether FBG sensors are suitable for long-term MHK measurements, under real field condition.

ACKNOWLEDGEMENTS

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REFERENCES

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TABLE 1: LOCATION OF FBG SENSORS ON CROSS-FLOW TURBINE SHOWN IN FIG. 1.

Sensor Position	Blade 1	Blade 2	Blade 3
75% (upper portion)	Sensor 1	Sensor 6	None
50% (strut-junction)	Sensor 2	Sensor 4*, 5	None
25% (lower portion)	Sensor 3	None	None

* Sensor 4 was mounted at 50% chord span. Other sensors were mounted at 30% chord span (the thickest location of the chord).

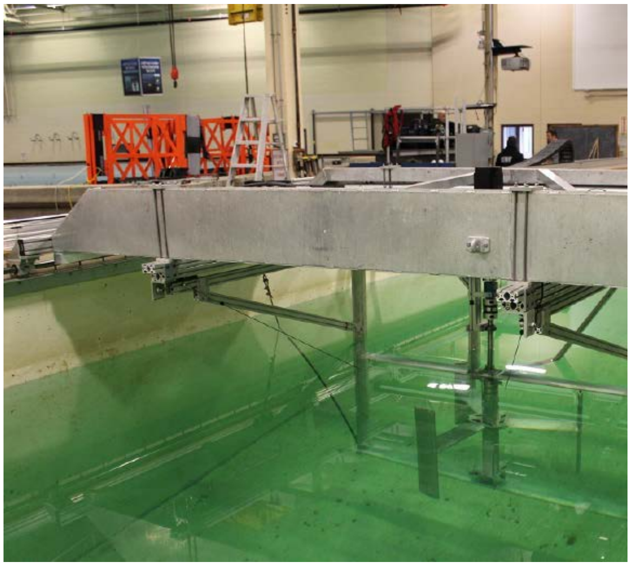

FIGURE 1 THE TOW/WAVE TANK FACILITY AT THE UNIVERSITY OF NEW HAMPSHIRE.

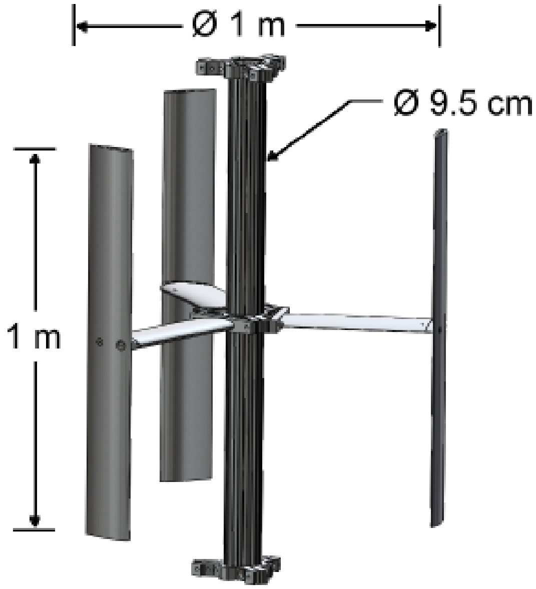

FIGURE 2 UNH REFERENCE VERTICAL AXIS TURBINE (RVAT): TURBINE MODEL AND DIMENSIONS [1].

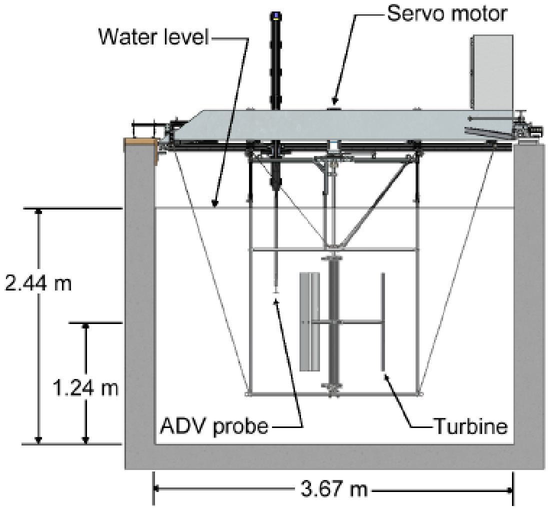

FIGURE 3 EXAMPLE EXPERIMENTAL SETUP OF UNH-RVAT IN UNH TOW TANK, WITH TANK DIMENSIONS [1].

FIGURE 4 MICRON OPTICS STRAIN GAGE OS3200.

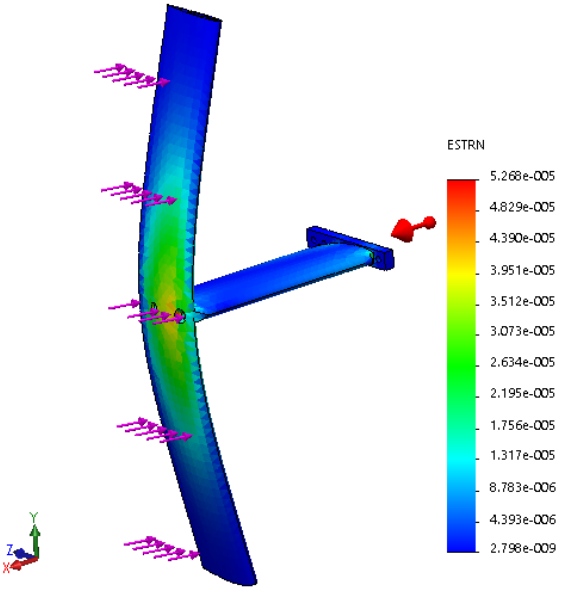

FIGURE 5 PRELIMINARY FINITE ELEMENT ANALYSIS OF UNH-RVAT TURBINE BLADE.

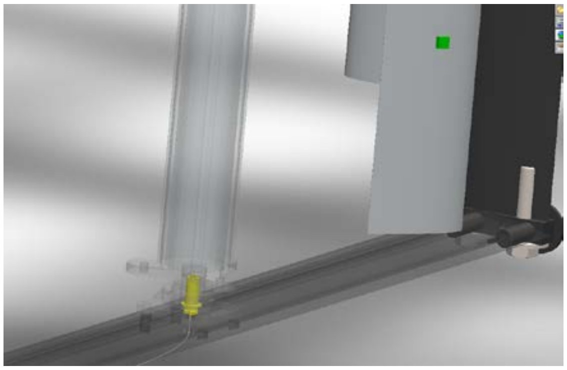

FIGURE 6 THE MOUNTING LOCATION OF THE FIBER OPTIC SLIP RING (YELLOW) AT THE BASE OF THE SHAFT.

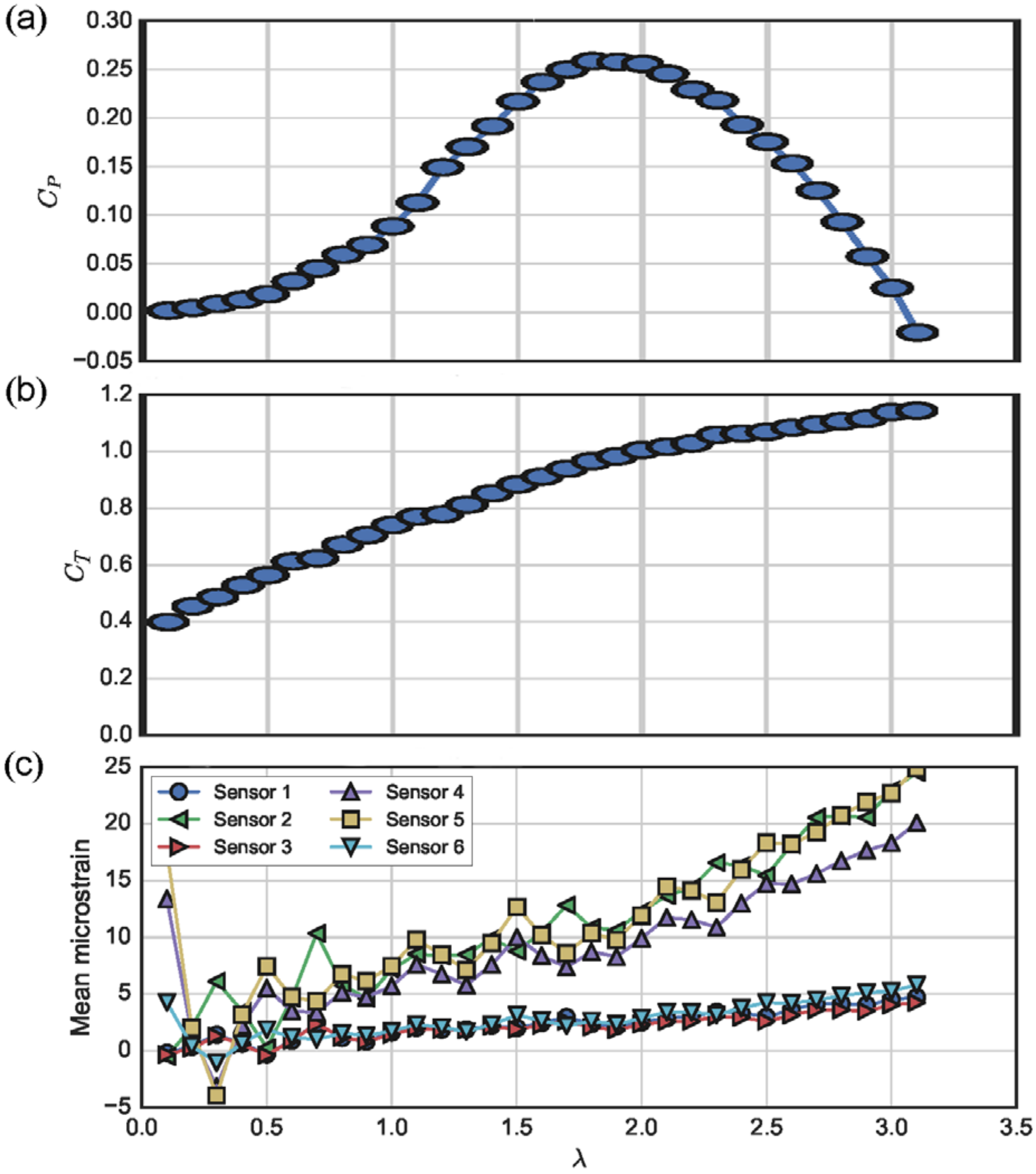

FIGURE 7 POWER (A), THRUST (B) AND MEAN MICROSTRAIN (C) VS. TIP-SPEED RATIO. MEAN STRAINS ARE SIMILAR AT THE SAME BLADE SPANS. SENSORS 1, 3 AND 6 WERE LOCATED AT THE SAME BLADE SPANS, 25% OR 75% BLADE SPAN. SENSORS 2, 4 AND 5 WERE MOUNTED AT 50% BLADE SPAN.