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Flume-scale testing of an adaptive pitch marine hydrokinetic turbine

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ABSTRACT

Modern marine hydrokinetic turbine blades are typically constructed from fiber reinforced polymer (FRP) composites, which provide superior strength- and stiffness-to-weight ratios and improved fatigue and corrosion resistance compared to traditional metallic alloys. Furthermore, numerical studies have demonstrated the possibility of tailoring the anisotropic properties of FRP composites to create an adaptive pitch mechanism that can improve system performance, especially in off-design or varying flow conditions. Potential benefits of an adaptive pitch system include increased lifetime energy capture, reduced hydro-elastic instabilities, reduced risk of mechanical failure, and improved efficiency, load shedding, fatigue life, and structural integrity. In this work, static and dynamic testing results for a flume-scale marine hydrokinetic turbine system are presented. Two sets of adaptive composite blades are compared to neutral pitch composite and rigid aluminum designs. Static testing was used to quantify the mechanical load-deformation response of each blade type. Additionally, instantaneous blade and full system loading was measured during dynamic flume testing, allowing a multilevel analysis of adaptive blade performance. Experimental results show notable shifts in the power and thrust coefficients and significant load adjustments induced through passive pitch adaptation, suggesting that adaptive pitch composite blades could be a valuable addition to marine hydrokinetic turbine technology.

1. Introduction

Marine hydrokinetic turbines are typically deployed in dynamic, energy-dense locations and are subject to complex spatially and temporally varying flow. To withstand the associated loads and survive in the harsh offshore environment, marine turbine blades are increasingly constructed from fiber reinforced polymer (FRP) composites, which provide superior strength- and stiffness-to-weight ratios and improved fatigue and corrosion resistance compared to traditional metallic alloys. Furthermore, numerical studies have demonstrated the possibility of tailoring the anisotropic properties of FRP composites to improve system performance, especially in off-design or varying flow conditions [1–6]. Through proper design, the intrinsic bend-twist deformation coupling behavior of anisotropic composites can be utilized to develop a passively adaptive pitch mechanism, where elastic deformations vary dynamically with loading condition. Potential benefits of an adaptive pitch system include increased lifetime energy capture, reduced hydro-elastic instabilities, reduced risk of mechanical failure, and improved efficiency, load shedding, fatigue life, and structural integrity [1,3,7].

In marine and ocean engineering, experimental investigations into passive pitch adjustment have until now focused mostly on propulsion systems. In [8–10], it was determined that flexible composite propellers could be tailored to be more efficient over a wider range of speeds when compared to traditional metallic alloy blades. In [11,12], the effects of material anisotropy in marine propellers in steady and unsteady flow environments were examined. Numerical and experimental results showed that adaptive composite propellers can provide improved cavitation performance and increased energy efficiency over their rigid counterparts when operating at off-design conditions or in spatially varying flows.

While the use of adaptive pitch blades for marine hydrokinetic turbines has been thoroughly explored numerically, little experimental work has been published to date. In [13], isotropic flexible blades were tested for use on an axial turbine in an oscillating water column device. The study compared a rigid urethane blade to two urethane blades with higher flexibility. However, the material used was isotropic, meaning it was not possible to tailor the twisting deformation of the blades. The results indicated that the flexible blades operated at a higher efficiency than the rigid blade, especially at low flow or off-design conditions. In a more complete experimental program, [14–16] outline the testing regime of the full scale variable speed, fixed pitch horizontal axis turbine developed by the company SCHOTTEL. The composite turbine blades

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presented were designed to be passively adaptive in order to reduce loading in overspeed conditions, and were shown to reduce thrust by approximately 50% compared to a rigid blade design in overspeed conditions. However, little detail is provided concerning the proprietary geometry of the blades; the results are therefore difficult to use or reproduce.

In order to validate and support continuing numerical studies of adaptive blades, it is necessary to provide baseline experimental data on these systems. To that end, this work presents the results of a series of static and dynamic tests carried out on a flume-scale adaptive pitch turbine system. An experimental program was conducted to investigate the mechanics of adaptive pitch blades and the impact these blades have on the performance of a marine turbine system. The performance of two sets of adaptive composite blades were compared to that of a neutral pitch blade design and an effectively rigid aluminum set. This program was designed to expand the numerical work and conclusions presented in [1].

The experimental regime was conducted in two parts. In a static testing environment, bend-twist load deformation characteristics of each set of blades were obtained. Force–deflection and force-twist response were measured, and an empirical deflection-twist relationship was calculated. In corresponding dynamic flume tests, instantaneous forces and moments on the entire rotor and on one of the three blades were recorded during operation over a range of tip speed ratios. Each test was repeated at varying inflow velocity conditions. These data were used to calculate blade forces and moments as a function of tip speed ratio, as well as overall system performance curves at several inflow velocities. Trends in performance results showed good agreement with those published in previous numerical studies, including notable shifts in the power and thrust coefficients and significant load adjustments induced through passive pitch adaptation.

2. Blade design and fabrication

All blades discussed in this work were designed to identical geometric parameters; the tailored bend-twist mechanism in the adaptive models was created solely on the material level. The blade geometry was determined using an optimization routine in HARP_Opt (Horizontal Axis Rotor Performance Optimization) code developed by the National Renewable Energy Laboratory (NREL). HARP_Opt implements the WT_Perf Blade Element Momentum (BEM) theory to predict rotor performance while iteratively optimizing the hydrodynamic shape of the blade chord lengths, twist, and thickness distributions. Primary input for HARP_Opt includes a distribution of design current velocities and aerodynamic coefficients for the desired blade profiles (i.e. lift, drag, pitching moment, and minimum pressure coefficients). In this case, the system was designed to operate in conditions typical to Puget Sound, WA, as outlined in [17,1]. As a result, the blade section profiles transition from a circular root at the hub radius ($d_H/2 = 0.055$ m) through a series of NACA-44xx profiles to the tip of the blade ($d_T/2 = 0.225$ m). The blades were aligned at a resting position of 0° pitch (i.e. 2.97° pre-twist at the tip). The NACA-44 series was chosen because it has been used extensively for marine hydrodynamic turbines due to the benefits of low critical Reynolds number for transition from laminar separation bubble, high lift to drag ratio, large structural rigidity, and acceptable cavitation resistance. See Table 1 for full details of the geometry.

The bend-twist coupling mechanism that creates an adaptive composite blade is a function of material design. In general terms, the anisotropic nature of the composite fibers in the blade define a material strong axis that can be rotationally offset from the longitudinal axis of the blade by a specified amount. This creates an elastic load-dependent deformation mechanism in which an applied shear load, for example, will result in twisting as well as bending deformations even in the absence of a torsional load. The degree of coupling between the bending and twisting deformations can be controlled by the magnitude of the offset angle, while the direction of offset determines the direction of blade twist. With this strategy, blades can be designed to either increase or decrease pitch angle under load. Because the magnitude of the deformation is load-dependent, it is possible to design a blade that will adapt to changing flow conditions via a nearly instantaneous structural response. Further detail on this subject can be found in [12,1,2].

Table 1
Blade geometry characteristics, NACA-44xx profiles.

r/R	c/r	t/c	Pre-Twist (°)
0.23	0.35	1.00	15.40
0.24	0.34	1.00	15.40
0.25	0.36	0.93	15.40
0.26	0.42	0.86	15.40
0.27	0.53	0.54	15.40
0.29	0.66	0.39	15.40
0.30	0.66	0.28	15.40
0.32	0.64	0.24	15.40
0.35	0.57	0.23	15.27
0.39	0.49	0.21	12.63
0.43	0.42	0.20	10.73
0.47	0.35	0.19	9.36
0.51	0.29	0.18	8.34
0.56	0.25	0.17	7.55
0.60	0.21	0.17	6.92
0.64	0.18	0.16	6.39
0.69	0.16	0.15	5.93
0.73	0.15	0.15	5.51
0.77	0.14	0.15	5.12
0.81	0.13	0.15	4.77
0.84	0.12	0.15	4.44
0.87	0.12	0.15	4.14
0.90	0.11	0.15	3.86
0.93	0.11	0.15	3.62
0.95	0.11	0.15	3.41
0.97	0.10	0.15	3.23
0.98	0.10	0.15	3.10
0.99	0.10	0.15	3.01
1.00	0.10	0.15	2.97

To fully explore the adaptive pitch effect, two sets of adaptive composite blades were compared to a non-adaptive composite set and a set of aluminum blades. One set of adaptive blades was tailored with a pitch to stall bias, such that an increased fluid loading would cause each blade to twist towards stall, decreasing the pitch angle and increasing the effective angle of attack. The other set of adaptive blades was designed to behave in the opposite fashion, pitching to feather and increasing the pitch angle (thus decreasing the angle of attack) under load. The non-adaptive, or neutral, composite blades provided a baseline with identical composite fabrication but no material bend-twist coupling. The aluminum set was assumed to be effectively rigid, allowing further comparison between rigid and flexible blades.

Due to the small scale of the blades required for flume-level testing, it was not feasible to lay up an adaptive composite laminate following the complex blade geometry with sufficient accuracy in either the geometry or the fiber orientation. To address this issue, the composite blades were composed of a flat carbon fiber spar, twisted to follow the chord line of the target blade geometry, and a semi-flexible urethane body cast around the spar to create the hydrodynamic blade shape. The urethane was chosen such that it had adequate hardness to maintain the blade geometry but would not significantly impede the elastic bend-twist deformations. In this way, the adaptive tailoring of the composites could be explicitly controlled in the carbon fiber spar without sacrificing