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Towing tank testing of passively adaptive composite tidal turbine blades and comparison to design tool

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A B S T R A C T

Passively adaptive bend-twist (BT) tidal turbine blades made of non-homogeneous composite materials have the potential to reduce the structural loads on turbines so that smaller more cost effective components can be used. Using BT blades can also moderate the demands on the turbine generator above design conditions. This paper presents experimental towing tank test results for an 828 mm diameter turbine with composite BT blades compared to a turbine with geometrically equivalent rigid aluminum blades. The BT blades were constructed of a graphite-epoxy unidirectional composite material with ply angles of 26.8° to induce BT coupling, and an epoxy foam core. For steady flow conditions the BT blades were found to have up to 11% lower thrust loads compared to rigid blades, with the load reductions varying as a function of flow speed and rotational speed. A coupled finite element model-blade element momentum theory design tool was developed to iterate between the structural (deformation and stresses) and hydrodynamic (power and thrust loads) responses of these adaptive composite blades. When compared to the experimental test results, the design tool predictions were within at least 8% of the experimental results for tip-speed ratios greater than 2.5.

1. Introduction

Marine renewable energy technologies such as horizontal axis tidal turbines (HATTs) have seen increasing interest in recent years due to a global push for increased renewable energy uptake. However, the high capital and maintenance costs associated with operating turbines in hostile subsea environments currently limits the commercial viability of this technology. Reliability and durability of HATTs are therefore primary concerns due to the high cost to retrieve and maintain a device once it has been deployed [1]. With blades being critical components with high failure rates [2–4], there has en significant focus on increasing blade robustness through material selection and appropriate engineering design. Turbine blade performance also has a significant effect on the loads experienced by other turbine components, and hence blade design optimization can lead to increased cost effectiveness of the overall turbine.

Along with reliability and durability, HATTs need to be designed for the deployment site characteristics. At a typical tidal energy site the flow velocities vary sinusoidally with time, hence the flow speeds corresponding to the maximum available power only occur for a small fraction of the time. Therefore, sizing components to meet this peak power leads to oversized and expensive rotor and drivetrain components [5,6]. To maximize the utilization factors of turbine components, developers typically design turbines for flow speeds that are lower than the expected site maximum [7]. Turbine power and loads therefore need to be regulated when the flow velocities at a site exceed design conditions to prevent damage to equipment caused by overloading the turbine blades and structure, and overpowering the generator. Load and power regulation methodologies are dominated in the wind industry by variable pitch (VP) mechanisms, which attach the blade root to the hub and alter the blade pitch (typically feathering the blades to reduce the angle of attack) at high wind speeds. Investigations have shown that VP mechanisms for the tidal energy application can improve power capture by maintaining the optimal angle of attack [8]. However, for subsea applications, VP mechanisms are expensive

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Nomenclature

BEMT	Blade element momentum theory
BT	Bend-twist
FEM	Finite element model
FSI	Fluid structural interaction
HATT	Horizontal axis tidal turbines
TGC	Torque generating current
TSR, λ	Tip speed ratio
VP	Variable pitch

and prone to failure due to problems with sealing and complex mechanical and electrical control systems [9]. Fixed pitch (FP) blades typically have lower capital and operational costs [10], as well as increased reliability, making them better suited to the harsh tidal environment. Although FP blade systems extract overall less energy, the cost of the energy produced is reduced by 10–20% [8]. Perhaps the main disadvantage of FP blades is that they are exposed to high thrust loads at high flow speeds because they lack the ability to adapt to changes in environmental conditions. To avoid this problem, loads can be reduced on FP blades using blade designs that passively alter their angle of attack during operation, for example, using tailored composite materials.

Composite materials have a high fatigue tolerance, high strength-to-weight ratio, are corrosion resistant, and have higher damage tolerance than commonly used metal materials [11], making them of interest for components operating in harsh environments [12]. For tidal turbines, as the weight of the blade decreases, the physical demands on the hub and support structure decrease. The equipment requirements to transport, deploy, and retrieve the blades at the tidal site decrease as well [13], resulting in lower capital and operating expenditures. Composite materials are also of increasing interest in industries where the cost effectiveness of a component can be increased by tailoring the structures' mechanical response [13]. By preferentially orientating fibers, components made of composite materials can be designed to exhibit desirable elastic deformation behavior that is not necessarily proportional to the imposed load. For example, the flap-wise bending of a turbine blade can be coupled with span-wise twisting by exploiting the coupled bending and twisting deformation response of composite materials with off-axis plies (bend-twist coupling). Bend-twist (BT) coupling can decrease turbine loads by reducing the angle of attack of the blade as a function of hydrodynamic loading, causing the blade to passively feather and regulate loads. Decreased blade loads result in decreased loads on turbine components (hub, bearings, drive train, *etc.*) and turbine support structures, hence smaller and less expensive components can be used. BT blades can also potentially regulate power above design conditions, reducing the demands and increasing the utilization factor of the turbine generator.

Research in the tidal energy industry has demonstrated the potential for load reductions and power regulation through appropriate design of BT composite blades. Using a fluid structural interaction (FSI) numerical model, Nicholls-Lee [14] found up to a 12% reduction in thrust loads and up to 5% increase in the power coefficient for an 8 m blade with a BT composite spar with a tip twist of 8.6° toward feather and tip displacement of 1.48 m. Similar outcomes were reported using a modified blade element momentum theory (BEMT) code, however, numerical results were not verified experimentally. Motley and Barber [15] used an iterative boundary element method and finite element method solver to model a two bladed, 20 m diameter, variable speed-VP turbine with BT composite blades. They showed that if the blades were designed to passively twist toward stall the overall power capture increased but the turbine required the use of the VP mechanism at a lower flow speed and had higher blade loads. Blades that passively twisted to feather resulted in decreased power capture but delayed the onset of mechanical pitching and resulted in lower blade loads before the onset of active control. Further studies using the design tool outlined in Ref. [15] showed that passively adaptive BT blades could increase annual power capture by delaying the onset of cavitation, thus enabling the use of larger blades operating at higher rotational speeds, increasing the annual energy capture [16]. SCHOTTEL [17] tested a 4 m diameter rotor on the front of a tug boat and found that BT composite blades had up to 50% lower thrust loads than equivalent rigid blades, however, the composite layup and blade geometry were proprietary. Wada et al. [18] tested two sets of composite blades in a towing tank, one set that were torsionally rigid (fully laminated with carbon fiber composite) and one set that were torsionally elastic (spar and skins made of carbon fiber composite and epoxy resin core) and found that the power coefficient and coefficient of resistance (analogous to the thrust coefficient) both decreased for the more flexible blades. The blade deformation was also calculated by FSI and the simulations were compared to the experimental results. However, there was no mention of composite layups or BT coupling, and the FSI under-predicted the twist angle significantly (experimental pitch angle change of about 2.6° and an FSI prediction of 4°). BT coupling has also been used in both the propulsion and wind energy industries; a full discussion of these applications can be found in Ref. [19].

Although there has been research done in the area, there is currently a lack of experimental data relating the performance of a tidal energy turbine with BT coupled blades to the composite design. Without experimental data enabling sufficient model verification, high safety factors are required for turbine and blade design to compensate for the uncertainty in the turbine performance. The objective of this work was to quantify the performance of an 828 mm diameter three-bladed HATT with BT composite blades in the towing tank at the Kelvin Hydrodynamics Laboratory (University of Strathclyde). The composite blade design and geometry are detailed in Section 2. Performance results of the turbine with composite blades were compared to the same turbine operated with geometrically equivalent rigid aluminum blades. These tests are aimed to increase confidence in turbine performance modelling by providing model verification data for a range of operating conditions. Results of these tests, shown in Section 4, were also used to verify a coupled finite element model (FEM)-BEMT design tool. Design tool verification is an important step in the research and development process as it facilitates investigation into effects of BT composite blades that are not pragmatic to test experimentally. Details of the design tool are given in Section 3, and the final conclusions and remarks of this investigation are presented in Section 5.

2. Experimental setup

A small-scale turbine with aluminum and composite BT blades was tested experimentally, allowing for cost effective design tool verification, as is typically done for early stage tidal energy device development [20]. An 828 mm diameter turbine was chosen to compromise between maximizing the chord-Reynolds number and keeping the towing tank blockage ratio reasonably low. This section outlines the blade and turbine geometry, the composite blade design, and the test program and conditions.

Fig. 1 shows the turbine and support structure designed and manufactured at Cardiff University (details can be found in