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Fatigue life of pitch- and stall-regulated composite tidal turbine blades

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ABSTRACT

Tidal turbine blades are subject to harsh loading and environmental conditions, including large thrust and torsional loadings, relative to wind turbine blades, due to the high density of seawater, among other factors. The complex combination of these loadings, as well as water ingress and associated composite laminate saturation, have significant implications for blade design, affecting overall device design, stability, scalability, energy production and cost-effectiveness. This study investigates the effect of seawater ingress on composite material properties, and the associated design and life expectancy of tidal turbine blades in operating conditions. The fatigue properties of dry and water-saturated glass fibre reinforced laminates are experimentally evaluated and incorporated into tidal blade design. The fatigue lives of pitch- and stall-regulated tidal turbine blades are found to be altered by seawater immersion. Water-saturation is shown to reduce blade life about 3 years for stall-regulated blades and by about 1–2 years for pitch-regulated blades. The effect of water ingress can be compensated by increased laminate thickness. The tidal turbine blade design methodology presented here can be used for evaluation of blade life expectancy and tidal device energy production.

1. Introduction

Tidal energy is gaining increased importance as a renewable energy source due to its high predictability over long timescales [1]. However, the tidal force can vary over a small geographical space [2], posing a challenge to the reliable long-term design of cost effective structures. The tidal force can vary locally within distances of tens of meters to tens of kilometres, due to the local bathymetry and seabed conditions. Hence, blade design requires particular attention. Current tidal turbine (TT) blade designs are largely based on wind turbine (WT) blade technology. But increasing appreciation of the specific and unique challenges of the tidal blade environment is leading to specific design evolution for tidal blades [3]. Tidal blades have to withstand the significant forces of seawater and turbulence flows, and must withstand water ingress and saturation during the device employment period [4,5]. The most highly-developed TT technology is the horizontal axis tidal turbine (HATT), which converts the kinetic energy within the tidal stream into mechanical energy, via the hydrodynamic forces acting perpendicular to the rotor plane creating blade lift and rotation [5]. In order to stay within generator capacity, i.e. limit peak power, blade pitching can be used [6,7]. However, blade failures on a number of prototypes emphasise the need for a design that will withstand the significant hydrodynamic loads during expected turbine life.

Composite materials, especially glass fibre reinforced polymers (GFRP), are the most commonly used materials for TT blade design due to their favourable characteristics, e.g. high specific strength and stiffness, resistance to corrosion and reasonable cost [5,8]. The importance of environmental effects on the properties of composite materials has previously been recognised and studied [9,10]. The specific application of composites in structural design of ocean energy structures has triggered studies on immersed performance of composites in seawater [11–13]. Studies show that immersed GFRP becomes moisture-saturated relatively early in its life. Hence, for TT blade design, it is important to understand durability and performance of these materials over the device lifetime.

The polymers normally used in GFRP can absorb up to 5% water by weight when immersed for long periods, changing the mechanical properties (e.g. reducing static tensile strength of the

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material by more than 25%) [14]. Water diffuses into the polymer matrix [13] and the multidirectional nature of laminates complicates the fatigue damage mechanisms. Matrix cracking parallel to the fibres or inter fibre failure (IFF) is first seen in the most off-axis plies under tensile fatigue loading. Most of the IFF cracking takes place in the first 25% of fatigue life and the significant drop in laminate stiffness is complete at this stage, with only a minor reduction in stiffness after this point. However, fatigue strength reductions do not follow the changes in static strength since the damage mechanisms are different in fatigue [15]. There is little test data available on material behaviour under coupled environmental and cycling loading [4]. An extensive review of fatigue modelling in GFRP has divided the work among three broad approaches [16]. First is a testing approach, where life predictions are based on test data of the exact or a similar material; second is a phenomenological approach, where predictions are based on the stiffness and residual strength behaviour; third, a progressive damage approach where damage in the unidirectional (UD) lamina is predicted and incremented until a final failure state is reached, thereby predicting fatigue life. The testing approach to fatigue life estimation is the most widely used [17]. The technique is under continual evolution and refinement to include effects like spectral loading and complex constant life diagram (CLD) results [18]. Strength degrades continuously during fatigue and an early characterization model proposed that it degrades linearly per cycle, in constant amplitude fatigue [19,20]. Key problems with all residual strength methods are the large scatter in the residual strength test results and the complexity of the degradation. The stiffness of GFRP laminates degrades by between 10 and 20% during fatigue cycling. The technique has been used to predict the life of particular WT blade laminates.

The main drawback of the latter models is a lack of flexibility in dealing with different laminate layups and/or loading patterns. Micromechanical approaches that predict the response of the laminate based on damage mechanisms in the individual UD plies offer a potential solution. The simplest approach is to degrade the matrix properties based on observed levels of cracking [21] and use classical laminate theory (CLT) to integrate the results. Others have considered two damage mechanisms, namely matrix cracking and interlaminar delamination [22]. Fracture mechanics approaches have been presented to predict matrix cracking behaviour and fibre failure; energy approaches have been used to model delamination, with stochastic methods used to enhance existing techniques. However, significant ongoing work is focussed on improving the capability for predicting test results and to reduce the amount of testing required to produce reliable fatigue life estimates. In order to fully utilise the TT blade structural material fatigue life, it is necessary to have information on its performance in the marine environment for the full design life of marine renewable energy devices (up to 20 years or so). The literature on fatigue test programs on the use of composite materials in marine renewable energy devices is, however, limited. Consequently, TT device design tends to be conservative, leading to cost penalties. A comprehensive fatigue life model for composite blades, incorporating realistic hydrodynamic loadings, cyclically-varying blade stresses and wet composite material fatigue properties would, therefore, be valuable tool for TT design.

The proposed TT blade fatigue design methodology consists of five modules [23] (Fig. 1). The first module is a tidal model, which predicts the tidal current speed for relevant local tidal velocities measured [5,23]. The output from this tidal model forms an input to a hydrodynamic model, which defines an aerofoil geometry (optimum chord length and pitch angle) and blade loadings (axial and tangential blade forces). The third module is a structural model. Based on the hydrodynamic module output, a finite element model of the blade is developed and factored forces are applied in order to determine the strain distribution in the turbine blade. The fatigue model determines the maximum strain in the blade for each rotation cycle. The maximum strains are compared to an experimentally-determined strain-life curve for the material and a damage fraction for that cycle is obtained. Summation of the damage fractions using Miner's rule gives an estimate for the life of the TT blade (TTB) [24]. In this paper, we adopt this design approach in the context of the water ingression effect on the performance of stall- and pitch-regulated tidal turbine, in order to integrate fatigue life expectancy of water-immersed composites into blade design.

2. Design methodology

2.1. Tidal model

It is assumed here that the tidal phenomenon occurs twice within each period of 24 h, 50 min and 28 s, consisting of two high and two low tides [25]. The highest tides, spring tides, occur when the sun and the moon line up with the earth. The lowest tides, neap tides, occur when the sun and moon are at 90° to each other. The current speed depends on the local topography. However, if the spring and neap maximum velocities are measured, the full cycle can be approximated by combining a semi-diurnal sinusoid and a fortnightly sinusoidal function [26]. The tidal current velocity, V_t, is:

$$V_t = \cos(\omega_d t)[v_{ave} + v_{alt}\cos(\omega_m t)] \tag{1}$$

where v_{ave} is the average of the peak tidal velocities, v_{alt} is half the range of peak tidal velocities, ω_d is angular frequency of the tides, ω_m is angular frequency of the spring-neap (14.7 day) cycle, and t is time.

2.2. Hydrodynamic model (HDM)

The design of the aerofoil is dependent on the turbine type and met-ocean condition. The blade element momentum theory (BEMT) code adopted here for blade design and to predict performance of HATT blades is based on previous work [27–29]. A stream-tube model (Fig. 2) based on BEMT is employed to calculate steady loads on the turbine blades and the thrust and power of the rotor for varying fluid velocities, rotational speeds and pitch angles. Optimised chord and pitch angle distributions can be defined along the span of the blade for a given set of input parameters (Table 1) [5].

The stream tube model examines a series of concentric tubes, dividing the blade into a number of sections, within which momentum is conserved, as it is transferred from the water to the blade. The BEMT-related mathematical formulation of the forces acting on the blade is given in Appendix 1. The input data for the HDM in this study is given in Table 1.

The design of the aerofoil, viz. chord and twist distribution along the blade, is intended to achieve optimum performance over turbine lifetime. The design code of this paper performs adjustments to the chord length until moment balance is achieved, after which the process is repeated for all remaining stream tubes. The outputs at each radial increment are chord length, aerofoil pitch angle, the axial and tangential force on the blade at particular radial increment, torque, and power.

In order to regulate the turbine power during high water velocity, control systems are used to manage forces and moments on the tidal blade. The HDM is used to simulate the two options for controlling power, pitch- (PR) and stall-regulation (SR). PR is a system which modifies the lift coefficient (C_L), i.e. the forces on the blade, by rotating the entire blade about its axis. SR blades are