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The Role of Onset Turbulence on Tidal Turbine Blade Loads

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Abstract

This paper uses a simulation-based approach to investigate the sensitivity of the blade loads for a horizontal-axis tidal turbine to the structure of the turbulent onset flow. The longitudinal turbulence intensity is shown to be the most dominant parameter of those considered. The rotational sampling effects are similar for the two length-scales analysed, however the number of large amplitude, fatigue loading cycles is influenced by the integral length-scale. The predicted extreme and fatigue loads are similar between the von Kármán and Kaimal spectral models. The findings will be of interest to tidal turbine designers for assessing the long-term structural performance of their turbine blades, given the turbulence characteristics at their site.

Introduction

In recent years the tidal stream turbine industry has witnessed considerable development, such that full-scale devices are now being installed. However, due to a lack of confidence in the long term structural performance of critical components such as the blades, which are exposed to a harsh operating environment, there are reports of turbine developers over-engineering their devices by up to 30 percent [8]. If the tidal stream industry is to prove commercially viable, and the turbines optimised, this uncertainty must be reduced.

For a horizontal-axis tidal turbine, the hydrodynamic loads dominate over the gravitational and inertia forces. The hydrodynamic loads are also highly unsteady, with the onset flow turbulence considered to play a significant role [9]. Both temporal and spatial non-uniformities in the turbulent flow induce a load spectrum with a notable once-per-revolution (1P) component due to rotational sampling.

The nature of the turbulence is likely to be site specific and there will therefore be a degree of variability between the turbulence induced loads. This paper aims to highlight the variability and to demonstrate the sensitivity of the loads to a range of turbulence characteristics. The results should be of interest to turbine developers who are attempting to model the long term structural performance of their turbine blades.

Turbulence Descriptors

The single-point longitudinal turbulence intensity is one of the most common predictors of the blade loads for wind and tidal turbines. It is the standard deviation of the turbulent fluctuations divided by the mean velocity (assumed herein as having only a longitudinal u component),

$$TI_u = \frac{\sigma_u}{U}; \qquad (1)$$

The averaging period is typically 10 minutes, during which the mean velocity is considered constant.

Osalusi [14] has shown that the depth-wise turbulence intensity profile for a highly energetic tidal flow at the Fall of Warness, within the European Marine Energy Centre (EMEC), varies from approximately 6 percent near the surface to approximately 13 percent near the seabed, providing an indication of the likely turbulence intensities a tidal turbine may be exposed to.

The integral length-scales offer another means by which to characterise the turbulence. They are a measure of the average size of the turbulent eddies. The integral length-scale of the longitudinal velocity component in the direction parallel to the mean flow is defined as

$$\Lambda = \int_0^\infty R_{uu}(x)dx. \qquad (2)$$

The corresponding auto-correlation function is given by

$$R_{uu} = \frac{\overline{u(x)u(x+\Delta x)}}{\sigma_u^2}, \qquad (3)$$

where Δx is the distance between the two points.

In the wind turbine context, where the longitudinal scales are typically in the order of hundreds of metres, investigations in [11] suggest that they have a secondary role on the blade fatigue loads. In a tidal channel, however, the length-scales will be physically constrained by the seabed and surface, and are likely to be of the order of the channel depth [13]. Since a large tidal turbine is likely to occupy a significant portion of the water column, this would suggest that the integral length-scales may be also much closer to the rotor diameter than for a wind turbine.

Spectral Models

In lieu of a turbulence spectral model specifically available for high velocity tidal streams, the spectral characteristics may be informed from analyses of experimental measurements in literature. Grant et al. [5], whilst not being able to measure the energy-containing region explicitly, have demonstrated the existence of an inertial sub-range for turbulence in a 1.5m/s tidal channel, with a 5/3 slope with wavenumber according to Kolmogoroff theory. Lien and Sanford [7] have also been able to collapse turbulence velocity spectra from measurements of tidal flows of the order of 1m/s to universal forms commonly employed for atmospheric turbulence.

For faster flows, reference [9] indicates that the scales of turbulence at EMEC also agree reasonably well with atmospheric models. However as the analysis was conducted using Acoustic Doppler Current Profiler measurements, which are limited by beam spreading, at mid-way through the water column scales smaller than the rotor diameter were not able to be measured accurately.

Two common turbulence spectral models used to describe atmospheric turbulence are the von Kármán and Kaimal models [6]. They are likely to provide a good basis for examining the turbulence induced loads for tidal turbines, although were developed for flat terrain. The auto-spectral density for the longitudinal component of turbulence for the two models are given by equations 4 and 5 respectively, and are plotted in figure 1.

von Kármán:

$$\frac{nS_{uu}(n)}{\sigma_u^2} = \frac{4n_i}{(1+70.8n_u^2)^{5/6}} \; ; \; n_u = \frac{n\Lambda}{U} \qquad (4)$$

Kaimal:

$$\frac{nS_{uu}(n)}{\sigma_u^2} = \frac{4n_i}{(1+6n_u)^{5/3}} \; ; \; n_u = \frac{n\Lambda_1}{U} \qquad (5)$$

Here $\Lambda_1 = 2.329\Lambda$.

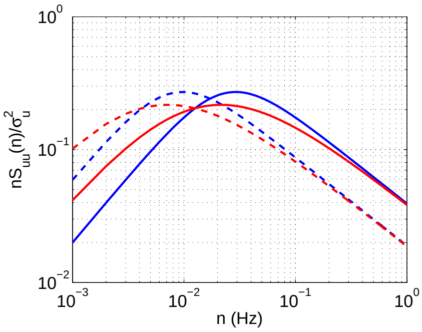

Figure 1: Normalised longitudinal auto-spectra; von Kármán (blue), Kaimal (red), for U_{hub}=2m/s and Λ=10m (solid), Λ=30m (dash)

Expressions for the coherence functions, which differ slightly between the two models, are presented in [3].

Methodology

Parametric Analysis

This analysis investigates the sensitivity of the root out-of-plane bending moment *My* to two turbulence parameters; the turbulence intensity and the integral length-scale, both of the longitudinal component of velocity; and the two aforementioned spectral models, such as is summarised in table 1. For a horizontal mean velocity, the longitudinal turbulent velocity components are considered to have a much greater influence on the blade loads than the lateral and vertical velocity components. Two levels of turbulence intensity are examined which, based on the magnitudes measured at EMEC, are considered to represent both relatively low and extreme levels of turbulence. The two integral length-scales represent a scale of the order of the rotor diameter, and a scale of the order of the channel depth.

The loads are predicted for two mean hub-height flow velocities. At these velocities the turbine will be operating at below rated conditions, for which there is no pitch actuation. The channel depth is 30m and the hub-height is 15m from the seabed and mean-free surface.

Turbine Specifications

The blade loads are predicted for a single 500kW, tri-bladed, horizontal-axis turbine. The rotor diameter is 12.5m and the

Parameter	Range (low,high)
Mean hub-height flow speed, U_{hub}	1.75m/s, 2.25m/s
Turbulence intensity, TI_u	7.5%, 15%
Integral length-scale, Λ	10m, 30m

Table 1: Parameters analysed and their values

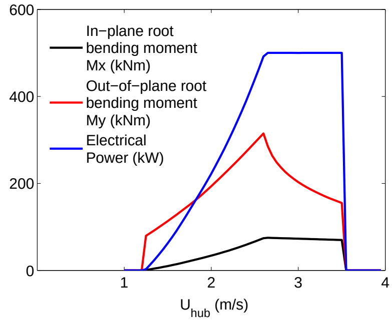

Figure 2: Blade root bending moment and turbine electric power in steady flow

design of the blades is based on those of Tidal Generation Limited [16]. The blades are of variable chord, thickness and twist. For this analysis the airfoil section is based on the NACA 44XX airfoil series, which were recommended for tidal turbines by Myers [12].

The turbine is designed to operate at variable speed, for optimal power output. In this analysis, for the two mean flow cases of 1.75m/s and 2.25m/s, rotor speeds of 12 rpm and 15.5 rpm are respectively selected such that that a mean tip-speed ratio of 4.5 is achieved. The salient performance characteristics of the turbine and blade root bending moments are depicted in figure 2. The in-plane bending moment (*Mx*) acts about an axis parallel to the rotor axis and is predominantly driven by inertial and gravitational forces, whilst the out-of-plane bending moment (*My*) acts about an axis perpendicular to that of the rotor, and is highly sensitive to the hydrodynamic thrust.

Simulation of Turbulence and Blade Loads

The commercially available design code, *Tidal Bladed* by GL-Garrad Hassan [2] is used to simulate both the turbulence and corresponding blade loads. *Tidal Bladed* is an adaption of *Bladed* for wind turbines and has undergone its own experimental validation programme [1].

The 3-dimensional turbulence is synthesised using a method described by Veers [17], in which separate velocity time histories are computed for several points across the rotor plane. Each point has predefined single point spectral characteristics and each pair of points has predefined coherence characteristics. The turbulence is then superimposed upon the mean velocity, which varies with depth according to the one-seventh power law. No surface waves are simulated.

The blade loads are computed using blade element theory, combined with a dynamic inflow model. The dynamic inflow model introduces a pseudo-inertia term to the momentum equation, as an attempt to model the time which it takes changes in loading at the rotor plane to build up in the far wake. True added mass effects are also accounted for. In this analysis the blades are assumed to be rigid, such that hydro-elastic effects are not present.

Analysis of the Blade Loads

Extreme and Fatigue Loads

The effect of the turbulence parameters on the extreme and fatigue blade loads is shown in figure 3. For the fatigue loads, the damage equivalent load (DEL) is computed from the Rainflow cycle counted load history. The DEL represents the amplitude of a constant frequency f load which would induce the equivalent fatigue damage as the original spectrum, and is expressed as

$$DEL = \left(\frac{\sum_i N_i L_i^m}{T f} \right)^{1/m}, \tag{6}$$

where N_i is the number of load cycles of range L, T is the duration of original time history. For composite blades such as those considered here, the slope of the S-N curve is taken as $m = 10$. The DELs are computed for a frequency of 1Hz.

The dominance of the longitudinal turbulence intensity on both the extreme and fatigue loads reinforces the inclusion of this parameter in load analyses. The effect of the longitudinal length-scales is less pronounced, suggesting that it has a secondary role on the blade loads for the range considered.

Differences in the load predictions with respect to the turbulence spectral model also appear to be relatively minor. This is likely to be attributed to the relatively close match between the longitudinal spectral models over the frequencies of interest.

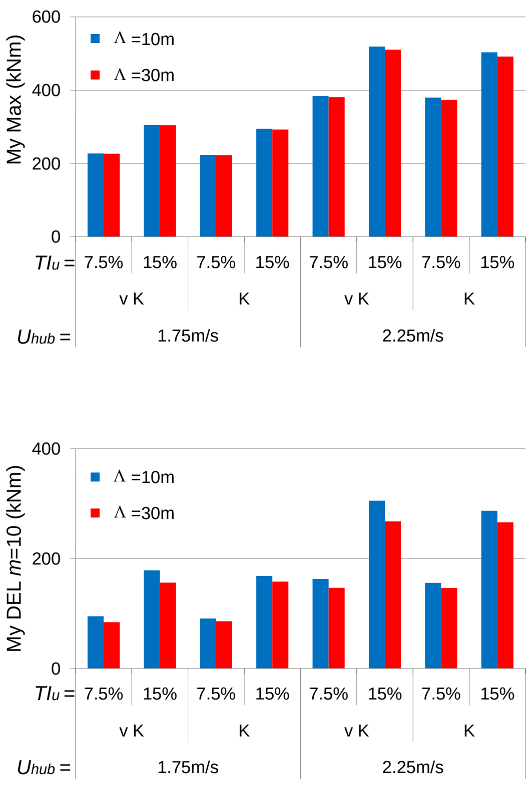

Figure 3: Root out-of-plane bending moment maximum and fatigue loads

A multiple linear regression analysis has been performed to obtain an expression for the maximum and DEL loads, as described by equation 7 and using the coefficients in table 2. The expression provides a useful means of quantifying the relative effect of the mean horizontal velocity and the turbulence intensity. The length-scale parameter has not been included, due to the low statistical confidence of its effect in this analysis.

$$DEL \ or \ My_{max} = b_1 U_{hub} + b_2 T I_u + c \tag{7}$$

	Spectral Model	b_1	b_2	c
DEL	von Karman	185	1397	-330
	Kaimal	176	1163	-319
My_{max}	von Karman	358	1276	-506
	Kaimal	366	1401	-528

Table 2: Regression coefficients

Large Load Events

For materials with inverse S-N slopes in the order of $m = 10$, such as composites, it is the high load-range events which dominate the fatigue damage, even though they have a low probability of occurrence [15, 10]. The blade load time history for one of the simulated cases is shown in figure 4, where large load half-cycles with ranges of approximately 450-500kNm can be observed and which typically have durations much longer than the period of the blade revolution. The corresponding hub-height longitudinal velocity and rotationally observed longitudinal velocity is also presented.

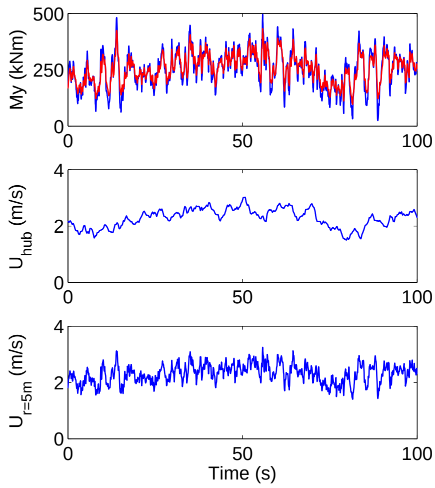

Figure 4: Time history of My (blue=DI, red=BEM), U_{hub} and $U_{r=5m}$

The large loading events observed here are typically correlated with large scale turbulent eddies. As the integral length-scale is reduced, the number of large load events will tend to increase, and hence so too will the fatigue damage sustained. However, the magnitude of these large scale fluctuations is dependent on the 1-P velocity fluctuations. These 1-P fluctuations are themselves a function of the integral length-scale and the depth-wise mean shear profile.

It should also be noted that the 1-P fluctuations occur over a time-scale in which the effects of dynamic inflow are apparent. Figure 4 attempts to highlight the increase in the magnitudes of the loads over the quasi-steady BEM model. It is therefore critical that the dynamic response of the wake is included when simulating the load response.

Analytical Models for Rotationally Sampled Turbulence

The role of the integral length-scales on the blade loads can be explored further by considering the auto-spectra and cross-spectra as observed by a rotating blade. Connell [4] and Burton et al. [3] provide a theoretical model developed from a homogeneous and isotropic von Kármán model, and provide expressions for the corresponding auto and cross correlation functions.

The rotationally sampled turbulence auto-spectra observed at a

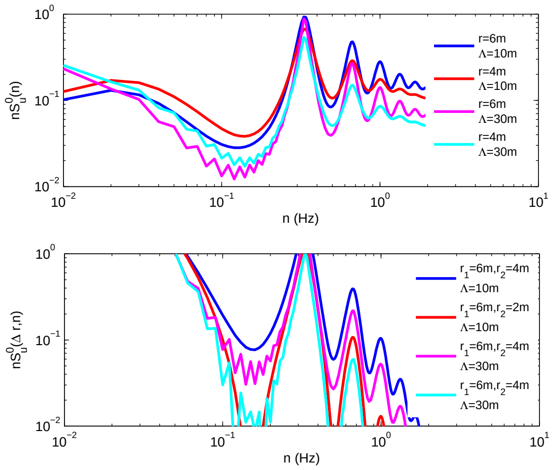

Figure 5: Rotationally sampled auto-spectra and cross-spectra of longitudinal component of turbulence

blade radius of $r = 6m$ and $r = 3m$, and cross-spectra between radii pairs of $r = 6m, 4m$ and $r = 6m, 2m$ are shown in figure 5, where pronounced peaks at frequencies corresponding to the blade passing frequency and multiples of it can be observed.

Connell [4] points out that peaks corresponding to rotational frequencies diminish as the blade radius decreases and the ratio of the radius to tip-speed-ratio (r/λ) is held constant. As the size of eddies become large relative to the radius of the blade the rotor is effectively spatially enveloped. However, since in this instance r/λ is not constant, the characteristics of the auto-spectra are similar for both integral length-scales examined. This implies that the 1-P velocity contributions are likely to be relatively similar between the two length-scales, and hence that the magnitudes of the large loads are likely to also be similar. This agrees with the very similar loads in figure 3. The peak in the cross-spectra at 1-P suggests that there is a relatively high degree of coherency across the blade, and hence implies that the 1-P velocity fluctuations are a significant source of loading.

As the aforementioned spectral descriptions for rotationally sampled turbulence do not include the velocity variation induced by the depth-wise mean velocity profile, it would be expected that the total energy of the velocity fluctuations observed by the blade at 1-P would be even greater than that indicated by figure 5.

Conclusions

The analysis has demonstrated that, like wind turbines, the longitudinal turbulence intensity is a primary fatigue load driver for horizontal-axis tidal turbines. The blade extreme and fatigue root bending moments are likely to be similar for the integral length-scales of interest, though the number of large amplitude, fatigue inducing cycles is likely to increase with a reduction in length-scale. No pronounced difference in the loads between simulations using the von Kármán and Kaimal turbulence models was predicted. These results will be of interest to tidal turbine designers in assessing the long term structural performance of their blades.

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