

Tidal current turbine fatigue loading sensitivity to waves and turbulence – a parametric study.

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Abstract

A parametric study of the sensitivity of fatigue loading experienced by a tidal current turbine to the environment in which it operates is reported. The design tool GH Tidal Bladed is used to model a generic 2MW turbine operating in a range of flow turbulence and sea-state environments representative of the turbine's lifetime. Time histories of the salient load component 'blade root out-of-plane bending moment' are rainflow cycle counted to provide lifetime damage equivalent loads as functions of both mean flow turbulence and significant wave height.

Fatigue load criticality is then assessed by comparing the resulting fatigue damage margins with the ultimate yield stress resulting from the 50-year extreme wave event. Although in this particular study it is found that the selected extreme load case drives the blade root design, fatigue stress margins are observed to fall as low as +8% under certain environmental conditions, suggesting that fatigue loading is still an important consideration in the overall design process -particularly for those projects where the severity of site conditions may exceed those considered in this study.

Generally, strong correlations are observed between turbine fatigue loading and levels of both turbulence and sea-state severity. This indicates the necessity of a detailed description of environmental conditions at a potential tidal turbine site, coupled with sophisticated, validated models of the complex interaction of this environment with the turbine's operational behaviour, if more optimised, cost-effective design solutions are to be achieved in the future.

Keywords: Fatigue loading, turbulence, waves

Nomenclature

<i>CFRP</i>	Carbon fibre reinforced plastic
<i>D</i>	Diameter
<i>H_s</i>	Significant wave height
<i>i</i>	Stress range bin index
<i>I</i>	2 nd moment of area
<i>L</i>	Length of element
<i>L_i</i>	Stress range of <i>i</i> th bin
<i>L_N</i>	Stress range for <i>N</i> cycles
<i>m</i>	Inverse material SN slope
<i>M</i>	Bending moment
<i>MFS</i>	Mean fatigue strength (amplitude)

<i>r_i</i>	Radius (inner)
<i>r_o</i>	Radius (outer)
<i>T</i>	Wall thickness
<i>T_p</i>	Wave period
<i>TI</i>	Turbulence intensity
<i>TSR</i>	Tip speed ratio
<i>U</i>	Mean flow speed
<i>UCS</i>	Ultimate compressive strength
<i>σ_l</i>	Axial stress

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Introduction

The development of tidal current turbines has reached the point where prototypes and pre-commercial devices are now, or are soon to be, operational. To make further progress into a fully-commercial phase it will be important for developers to use more sophisticated modelling techniques, as they seek both optimised design solutions and also certification and due-diligence review of their products.

Sophisticated modelling of tidal current turbines must be able to accurately represent salient characteristics of both the turbine and also the environment in which it operates. As the latter will clearly be of a site-specific nature, an interesting question is, 'how sensitive is a turbine's loading to variations in its operating environment?'

This paper investigates this issue for two characteristics of the flow environment – the sea-state (wave action) and the level of turbulence in the current flow.

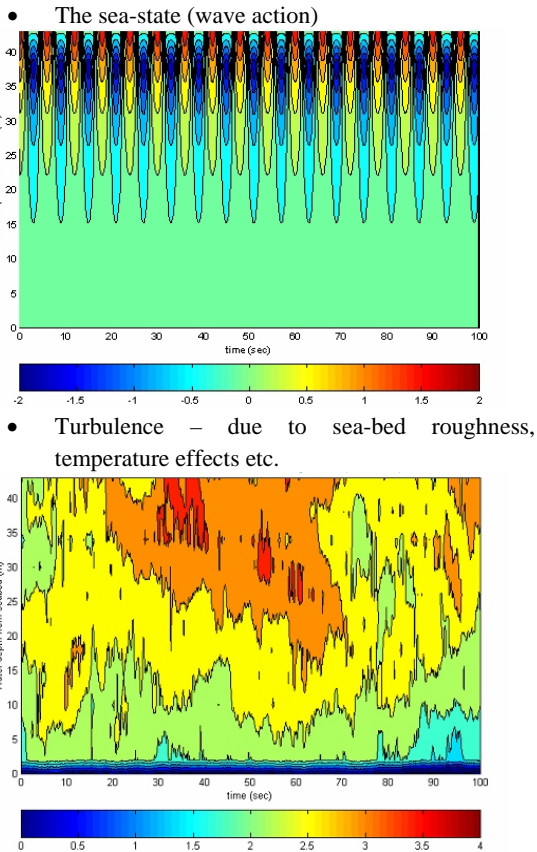
A generic 2MW tidal turbine is used in the simulations, which are performed using the design tool GH Tidal Bladed. Parametric descriptions of the two environmental characteristics are varied and the resulting influence on turbine loading is recorded. Based on the observed fatigue and extreme loads, implications are drawn for the design of certain critical components of the device. Finally, general affects and patterns observed through the study are reported and discussed.

1 Motivation

Assessment and certification of turbines with respect to the structure’s integrity and safety as well as to its power production facilities are applied to mitigate risks and to build confidence in the product’s development and commercialisation. Third party assessment is often required by investors, insurers, operators and authorities and to this end, certification agencies are already drafting guidelines for marine energy device certification [1]. Such guidelines invariably emphasize the need for detailed load analysis.

It is therefore clear that a detailed description of the environment in which tidal turbines are likely to operate, coupled with a sound understanding of how this environment interacts with the device, is required if its loading (and indeed performance) is to be accurately predicted. The application of sophisticated modelling capabilities should thus accelerate the development of more optimised, cost-effective designs and lead to increased confidence in the industry.

Two characteristics of the flow velocity environment likely to bear significant influence on device loading are:



This paper aims to quantify the importance of these two effects, particularly on the fatigue loading experienced by

key selected device components. It also attempts to determine if such fatigue damage over the device lifetime is significant, relative to predicted extreme loads.

The results of this paper will be of interest to device designers concerned with understanding how sensitive their design is to variations in environmental severity. It should also highlight how rigorous, detailed modelling of the device/environment interaction can reduce over-conservatism and facilitate more optimised design solutions.

2 Methodology

2.1 GH Tidal Bladed

The effect of various wave and turbulent current environments on the loading of a generic horizontal axis tidal current turbine is assessed by simulating the device/environment behaviour and interaction in the industrial design tool, GH Tidal Bladed [2].

Tidal Bladed facilitates integrated, time-domain simulations which account for the complexities associated with, for example, unsteady flow fields, turbine structural dynamics, controller dynamics and rotor hydrodynamics. Tidal Bladed shares much of the same computational basis as GH Bladed, which has become an industry standard design tool in the analysis of wind turbines [3]. In addition, Tidal Bladed has undergone its own validation study using data measured by Southampton University [4].

2.2 Fatigue load sensitivity

The paper focuses on assessing the loading sensitivity to variations in flow turbulence intensity (TI) and sea-state severity (characterised by significant wave height H_s and period T_p). The critical turbine component ‘blade root out-of-plane bending moment (denoted blade root M_y)’ is selected for analysis. The environmental variations are prescribed by the following parametric ranges:

CASE 1	TI	0	5	7	10	12
CASE 2	H_s T_p	1.5/7	3.0/14	4.5/21	6.0/28	X

Table 1: Variation of environment parameters in fatigue load sensitivity study

Case 2 will in reality be a function also of the mean water depth. This is because wave orbital velocities are most energetic near the sea surface and decay as depth increases, as depicted in Figure 1.

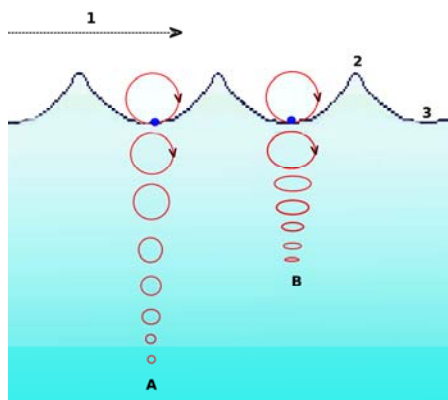


Figure 1: Wave orbital velocities (A – deep water, B – shallow water)

The wave sensitivity study is qualified by the fact that it is performed at 1 mean water depth only – 50m. Further study should focus on quantifying the fatigue load sensitivity as the mean water depth is reduced and increased.

To reduce the number of simulations, the environmental permutations in Table 1 are limited as follows:

- When varying the turbulence intensity (TI), zero sea-state ($0 H_s$) and 50m mean water depth are assumed.
- When varying the sea-state (H_s, T_p), $TI = 10\%$ is assumed.

2.3 Assumptions of the method

A number of assumptions were made in performing the lifetime fatigue load study:

- The range of mean flow speed bins was taken as 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5m/s.
- The TI was assumed to be constant over this flow speed range. I.e for permutation ‘ $TI = 5\%$ ’, 5% turbulence was applied to each mean flow speed representative of the turbine lifetime.
- In the absence of more customised research into spectral representations of tidal flow turbulence, it is assumed that a simple Kolmogorov spectral density description can be used to model flow turbulence [5]. Thus in the analysis performed the standard von Karman spectral density model [2] used to represent atmospheric turbulence was considered.
- The sea-state parameters (H_s/T_p) were assumed constant over the flow speed range, and hence the turbine lifetime. In reality the sea state characteristics would vary over the operational lifetime.
- A JONSWAP wave spectrum was applied in all stochastic sea-state simulations.

- The following flow speed distribution was assumed over the turbine lifetime for all permutations of TI and sea-state:

mean flow speed [m/s]	hours / year
0.5	2717.5
1.0	2191.5
1.5	1577.9
2.0	1008.1
2.5	657.5
3.0	438.3
3.5	175.3

Table 2: Mean current flow speed distribution

- The operational fatigue load simulations were modelled in accordance with the GL guidelines for Ocean Energy Converters [1].
- A generic 2MW pitch regulated, variable speed tidal turbine model was used for all simulations. A description of the model is provided in Section 3.1.

2.4 Fatigue load criticality

The relative criticality of fatigue and extreme loading is a function of the material properties and the safety factors adopted, as well as the actual load levels involved.

To provide a basis for assessing fatigue criticality, a single extreme load case is simulated, corresponding to the 50-year extreme wave event at peak current; see Table 3:

Peak flow speed [m/s]	3.5
Mean flow turbulence intensity [%]	10
Extreme stream fn wave H, T [m, s]	10, 15
Wave, current direction	In line

Table 3: Extreme load case – 50 year wave event

This is simulated in accordance with the GL guidelines for load simulation of ocean energy converters [1]. From this extreme load case, the maximum blade root resultant bending moment M_{xy} is extracted, to which a safety factor of 1.35 is applied.

A simple geometry and material properties are then assigned to the component, such that a zero margin in extreme yield stress results. (Buckling stresses are not considered, but should be in a fuller analysis).

Finally, fatigue failure margins are calculated for the loads predicted from the parametric study described in Sections 2.2 & 2.3 for the same geometry, giving a broad indication of whether fatigue loading for the component is likely to be important, and at what level of wave and turbulence severity it becomes so.

3 Simulations

3.1 Generic tidal turbine model

A 2MW pitch regulated – variable speed generic turbine model is used for all simulations. The salient details of the model are summarised in Table 4.

Rated power [MW]	2.0
Rotor diameter [m]	22.8
Blade length [m]	10.5
Number of blades [.]	3
Rated hub flow speed [m/s]	3.0
Rated rotor speed [rpm]	12.0
TSR below rated [.]	5.8
Hub height above sea-bed [m]	29.0
Control type	Pitch regulated, variable speed
Transmission	Gear-box
Support structure type	Bottom-mounted tripod
Foundation stiffness	rigid

Table 4: Generic turbine specification

Figure 2 shows how the steady power output (MW, black), rotor speed (rad/s, red), rotor thrust (MN, green) and pitch angle (rad, blue) vary with flow speed (range: 0-5m/s).

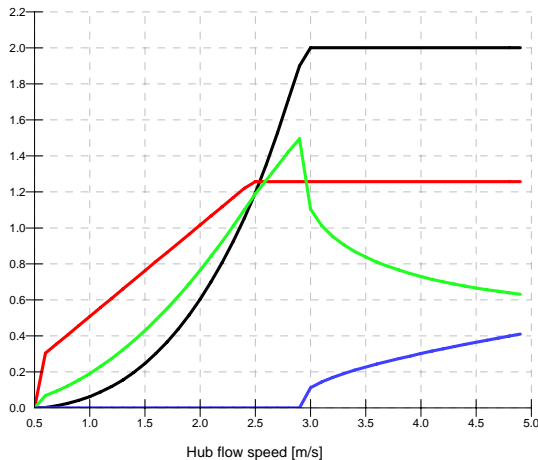


Figure 2: Steady plot as function of flow speed

The turbine is supported by a bottom-mounted steel tripod construction. The nacelle housing the turbine's drive train attaches to the structure 29m above the sea-bed. The structure penetrates the sea-surface by 5m for a mean sea level of 50m (ie. the structure is 55m high). Figure 3 depicts the configuration graphically.

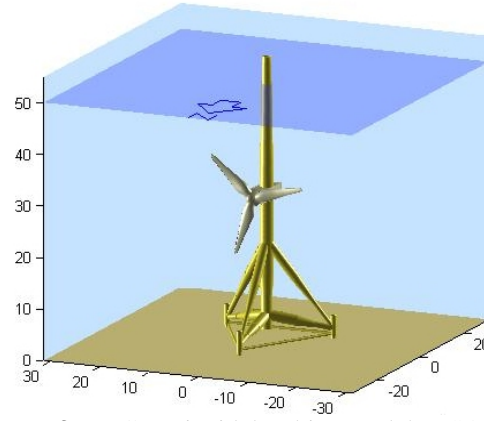


Figure 3: Generic tidal turbine model – ISO view

Structural dynamics of the support structure are included (see Figure 4) but the rotor blades are assumed to be rigid as a first approximation.

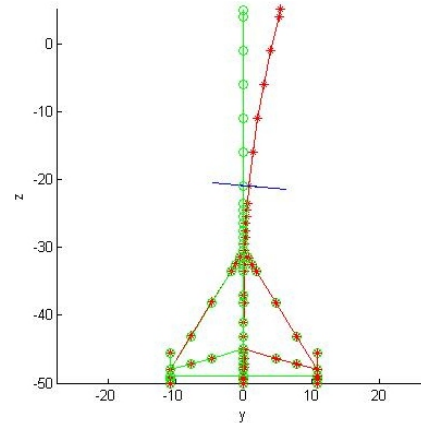


Figure 4: 1st structural mode shape (1.49Hz)

3.3 Simulation set-up

All turbulent flow simulations without wave action (case 1) are run for 10 minutes. For case 2, stochastic sea states are run for 30 minutes. The following models are additionally applied in all simulations:

- current shear (1/7th power law)
- potential flow tower shadow
- rotor mass & geometric imbalance

3.4 Time-history output

Before proceeding to report the final fatigue damage resulting from each environmental permutation, it is instructive to observe the behaviour of the actual simulation time histories. Two characteristics are considered; firstly the turbine performance in terms of electrical power output, and secondly the turbine loading, in terms of the blade root out-of-plane bending moment M_y . Figures 5-16 show how these two quantities vary as functions of both flow turbulence and sea-state action, for a range of mean flow speeds (1.0, 2.0 & 3.0m/s).

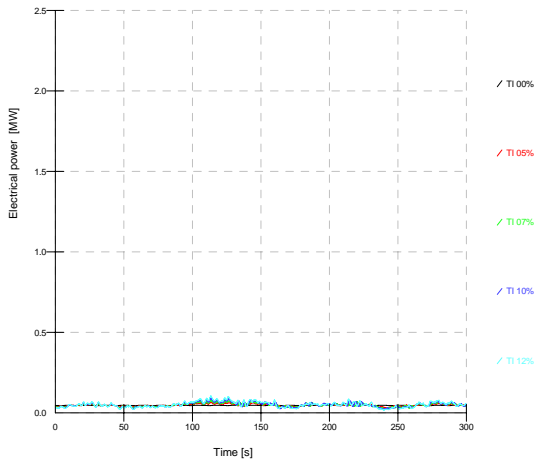


Figure 5: Elec. Power, TI: 0-12% ($U=1.0\text{m/s}$)

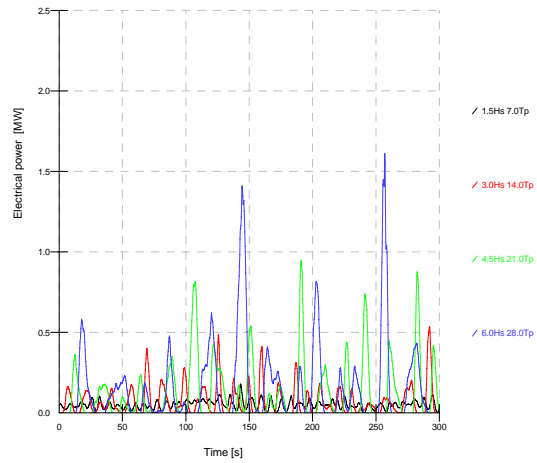


Figure 8: Elec. Power, H_s : 1.5-6.0m ($U=1.0\text{m/s}$)

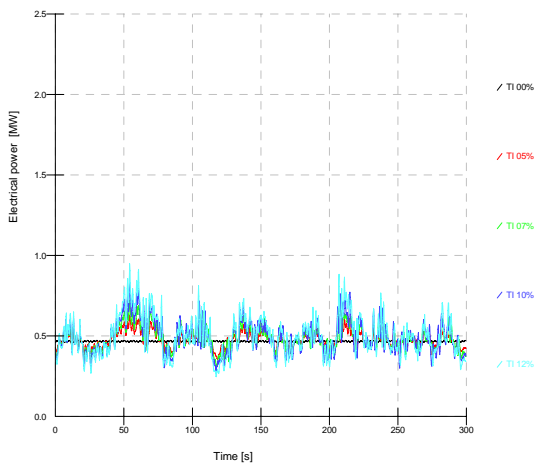


Figure 6: Elec. Power, TI: 0-12% ($U=2.0\text{m/s}$)

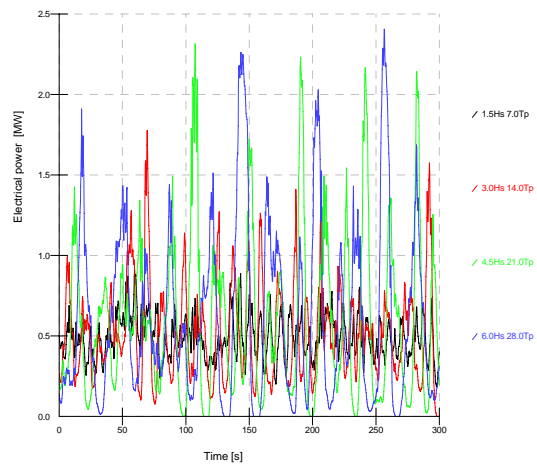


Figure 9: Elec. Power, H_s : 1.5-6.0m ($U=2.0\text{m/s}$)

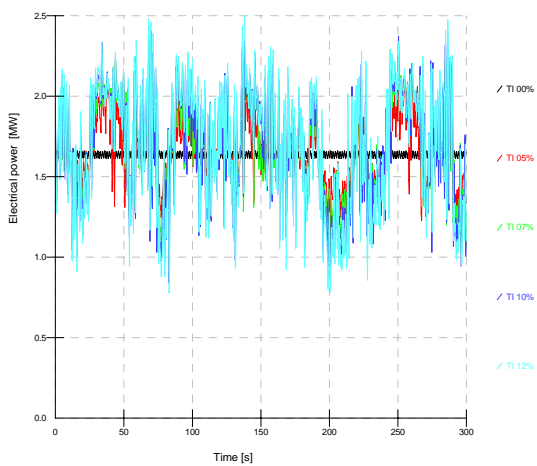


Figure 7: Elec. Power, TI: 0-12% ($U=3.0\text{m/s}$)

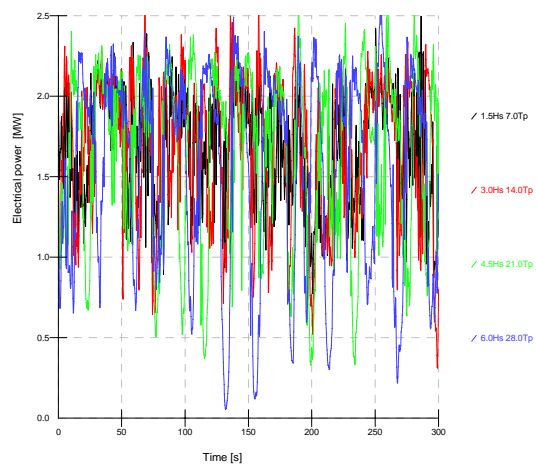


Figure 10: Elec. Power, H_s : 1.5-6.0m ($U=3.0\text{m/s}$)

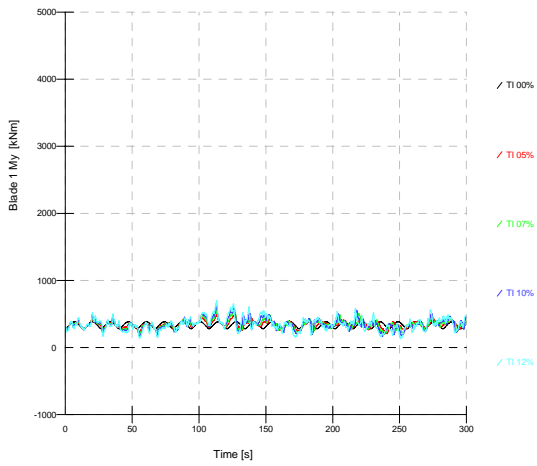


Figure 11: Blade root M_y , TI: 0-12% ($U=1.0\text{m/s}$)

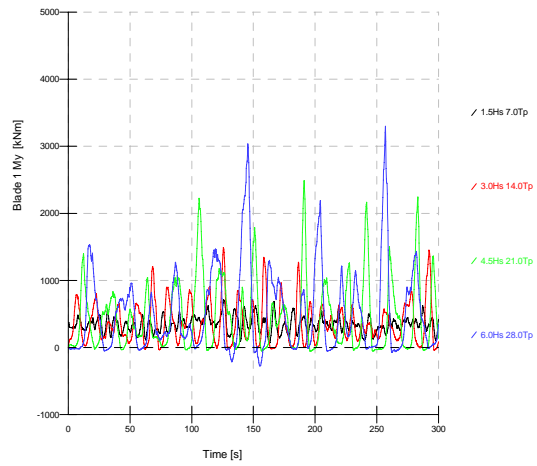


Figure 14: Blade root M_y , H_s :1.5-6.0m ($U=1.0\text{m/s}$)

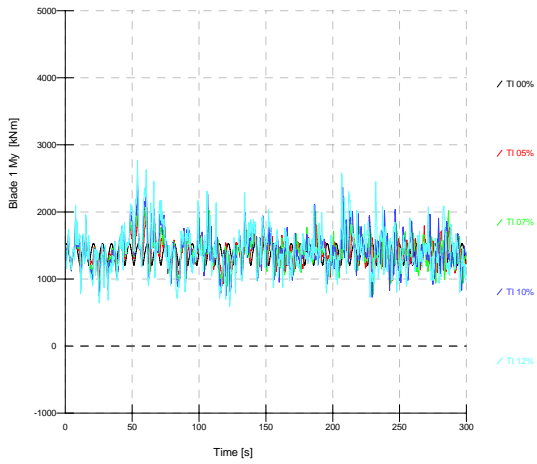


Figure 12: Blade root M_y , TI: 0-12% ($U=2.0\text{m/s}$)

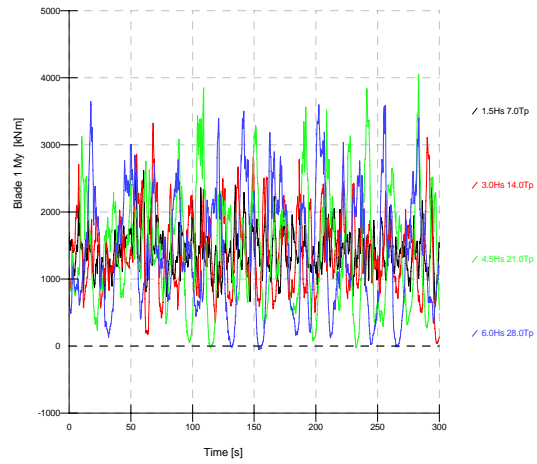


Figure 15: Blade root M_y , H_s :1.5-6.0m ($U=2.0\text{m/s}$)

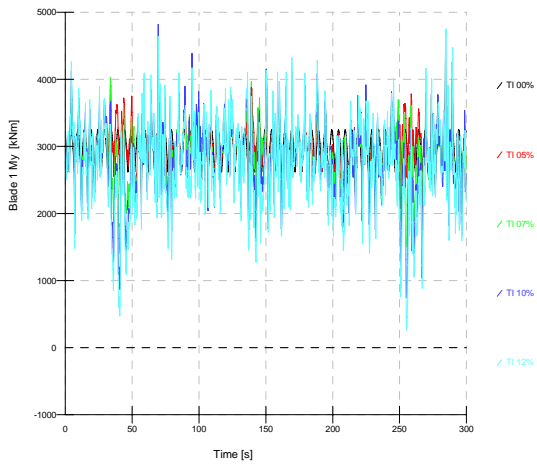


Figure 13: Blade root M_y , TI: 0-12% ($U=3.0\text{m/s}$)

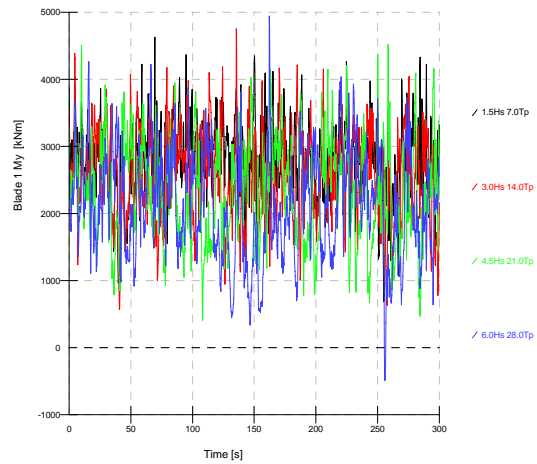


Figure 16: Blade root M_y , H_s :1.5-6.0m ($U=3.0\text{m/s}$)

4 Fatigue load processing

For each state of environmental conditions shown in Table 1, the range of representative flow speeds detailed in Table 2 are simulated and then integrated over the turbine lifetime to provide lifetime damage equivalent loads.

Damage equivalent loads (DELs) are used to equate the fatigue damage represented by rain flow cycle counted data to that caused by a single stress range repeating at a single frequency. The damage equivalent stress is given by the following formula:

$$L_N = \sqrt[m]{\frac{\sum L_i^m n_i}{N}}$$

where L_N is the equivalent stress for N cycles L_i is the stress range bin i . n_i is the number of rain flow cycles at stress range bin i . m is the negative inverse of the slope on the material's Wöhler curve (m is also referred to as the S-N curve slope). N is the number of cycle repetitions in the turbine lifetime.

The stress, L_i , depends upon the geometry of the structure under consideration. It is assumed that stress is proportional to load, therefore it is quite acceptable to use load instead of stress in the above equation.

Tables 5 and 6 present the integrated lifetime DELs (for selected component blade root out-of-plane bending moment M_y) as functions of mean turbulence and significant wave height respectively. The equivalent load frequency equates to $10e7$ cycles in 20 years (0.158Hz).

m	Turbulence Intensity [%]				
	0	5	7	10	12
4	384.4	708.8	957.9	1219.2	1468.5
6	445.0	885.5	1238.9	1626.9	1978.7
8	483.2	1025.0	1481.3	1988.3	2439.3
10	509.5	1136.5	1682.6	2283.2	2813.6
14	543.3	1300.2	1979.4	2705.4	3348.1

Table 5: Blade root M_y DEL [kNm] vs TI ($H_s=0m$)

m	Significant wave height [m]			
	1.5	3.0	4.5	6.0
4	1234.1	1580.6	1849.9	2033.8
6	1602.8	1966.2	2272.6	2472.0
8	1929.1	2278.0	2597.1	2792.3
10	2205.7	2539.9	2860.9	3049.7
14	2627.9	2961.9	3273.2	3467.7

Table 6: Blade root M_y DEL [kNm] vs H_s (TI=10%)

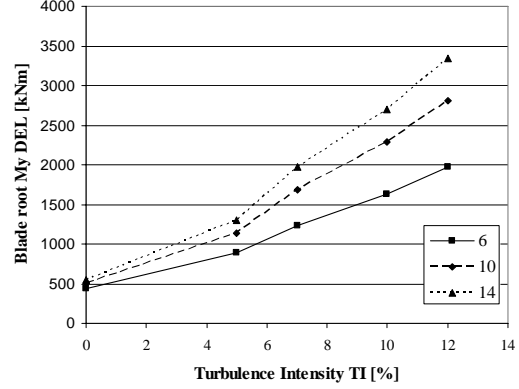


Figure 17: Blade root M_y DEL v TI ($H_s=0m$)

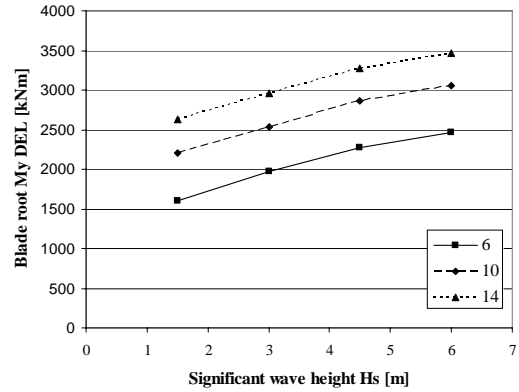


Figure 18: Blade root M_y DEL v H_s (TI=10%)

Figures 17 and 18 graphically present the variation of blade root out-of-plane M_y DEL with TI and sea-state H_s respectively, for 3 values of material inverse-SN slope, m (6, 10 and 14).

5 Fatigue load criticality

5.1 Extreme load benchmark

As described in Section 2.4, an ultimate load case corresponding to the 50-year extreme wave event coinciding with peak current flow is simulated to provide a benchmark for establishing fatigue load criticality. Table 3 provides details of the simulation.

In Figure 19 we observe the resulting simulation time-history, in terms of the following salient variables:

- Hub flow speed – m/s (black)
- Sea surface elevation – m (red)
- Blade 1 pitch angle – rad (green)
- Blade 1 root out-of-plane bending moment, M_y – MNm (blue)
- Rotor thrust, F_x – MN (light-blue)

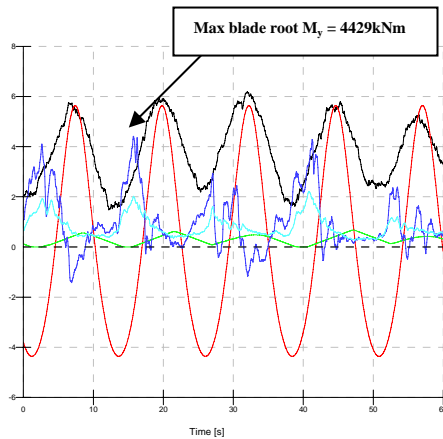


Figure 19: Extreme load simulation time series

From the results of the simulation we can extract the maximum blade root out-of-plane bending moment M_y , in this case corresponding to a value of 4429kNm (before the application of safety factor).

5.2 Extreme yield analysis

To facilitate a simple case for comparison of extreme and fatigue loading, the blade root component is modeled as a simple cylindrical section of constant wall thickness. It has been assumed that the component is constructed from CFRP, with the following material properties [6]:

Property	Unit	Value
Specific gravity	n/a	1.58
Young's Modulus	GPa	142
UCS	MPa	1105
MFS* (10e7 cycles)	MPa	350

* corresponding to a material inverse-SN slope = 14

Table 7: Material properties of CFRP

The geometry of the component is represented by Figure 20 (not to scale), where L is the nominal blade root length, r_0 is the outer radius and r_i is the inner radius.

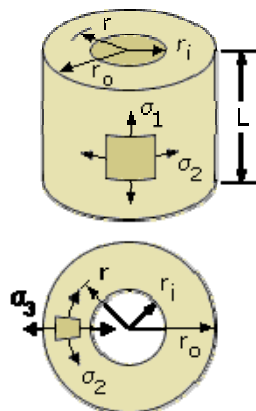


Figure 20: Simple representative geometry of blade root

The following relationships can thus be stated:

$$D = 2.r_0 \quad \{eqn 1.1\}$$

$$T = r_0 - r_i \quad \{eqn 1.2\}$$

$$I = \pi.[D^4 - (D-2.T)^4]/64 \quad \{eqn 1.3\}$$

$$\sigma_1 = M.r_0/I \quad \{eqn 1.4\}$$

To assess fatigue load criticality, the component is firstly dimensioned such that a zero reserve margin in *extreme* yield stress is achieved when applying a safety factor of 1.35 to the maximum value of M from Section 5.1, ie:

$$1.35.\sigma_1/\sigma_{UCS} = 1 \quad \{eqn 1.5\}$$

(Note, Equation 1.5 has been satisfied purely on the basis of axial yield stress – a rigorous design process would include consideration of extreme buckling failure in addition).

5.3 Fatigue stress margins

It is now possible to calculate fatigue stress reserve margins for the simplified blade root component, based upon the fatigue loads derived in Section 4 and the component's geometric and material properties determined in Section 5.2. A positive margin indicates that fatigue failure is *not* predicted to occur within the lifetime of the component.

	Turbulence Intensity [%]				
	0	5	7	10	12
Load [kNm] (SN=14)	543.3	1300.2	1979.4	2705.4	3348.1
Stress margin [%]	+85.6	+65.5	+47.5	+28.2	+11.2

Table 8: Fatigue stress margins for blade root component vs TI

	Significant wave height H_s [m]			
	1.5	3.0	4.5	6.0
Load [kNm] (SN=14)	2627.9	2961.9	3273.2	3467.7
Stress margin [%]	+30.3	+21.4	+13.1	+8.0

Table 9: Fatigue stress margins for blade root component vs H_s

We observe immediately from Tables 8 and 9 that in this particular example, the blade root component design is governed by extreme loading, for all permutations of flow turbulence and sea-state severity considered. The lowest fatigue stress margin is +8%, resulting from the stochastic sea-state characterized by a 6.0m significant wave height and 28.0s period, combined with a flow turbulence of 10%. Figures 21 and 22 help visualize the fatigue stress margin sensitivity to turbulence and sea-state severity.

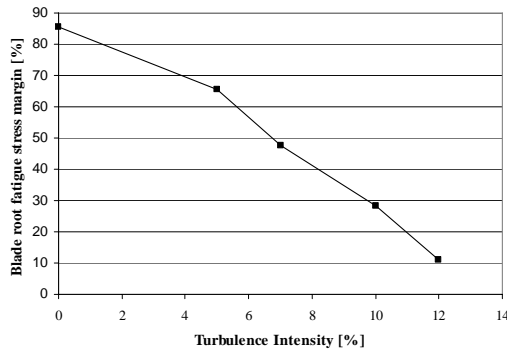


Figure 21: Fatigue stress margin vs TI

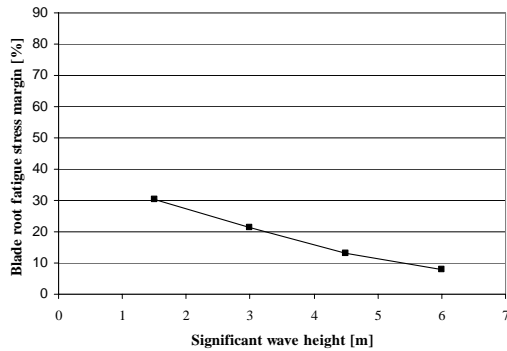


Figure 22: Fatigue stress margin vs H_s

6 Discussion

A number of further observations follow:

- The study shows that fatigue loading, although not driving in this particular example, is still an important design consideration and cannot be neglected.
- A strong correlation is observed between fatigue damage and flow turbulence. Figure 21 suggests that at TI=14%, fatigue could begin to drive the design of our simple blade root component. One may conclude that, even in the absence of any waves, the structure may still be sensitive to fatigue damage due to unsteady flow.
- Figure 22 shows that fatigue damage is also sensitive to wave action. It is true that a number of real devices will operate at depths likely to take them outside the wave-affected zone. However, many others *are* likely to share similar rotor diameters and water depths as used in this study (22.8m and 50.0m respectively), suggesting that they would benefit from a consideration of sea-state effects in their fatigue analysis.
- In reality, for the generic turbine considered, the blade root component design of Section 5.2 may be driven by buckling, which would increase the wall thickness and therefore reduce fatigue margins further.

- The selection of H_{max} for the extreme load case is critical, and the results of this paper are qualified by the fact that they consider just one value (10m) in determining the extreme load. In reality, an actual site may experience a more benign H_{max}, and fatigue loading criticality may increase as a result.
- An exhaustive list of environmental permutations for the fatigue load simulations has not been performed and so higher fatigue loads could in reality result. At a given site, it is likely that flow turbulence would vary as a function of mean flow speed, and the sea-state would be defined by a scatter matrix of H_s and T_p, not just single values as in this study. The conclusion of the study remains that the fatigue loading mechanisms due to a combination of flow turbulence and waves are a necessary consideration in the overall design process.
- We have only considered one component of the turbine in this study. Designers are encouraged to consider the conclusions of the study applied to such components as, for example, the transmission and support structure.
- The potential importance of flow turbulence underlines the requirement for detailed flow measurement studies, followed by the development of validated spectral models of tidal current flow. These will indicate whether the assumptions applied to the modelling of turbulent tidal flow in this study are applicable and how they could be refined in future studies.
- The importance of turbulence and wave-driven fatigue damage suggests a benefit in researching the mitigation of such loading mechanisms through the use of sophisticated control strategies – such as is presently occurring in the wind turbine industry (eg. individual blade pitch control).

7 Conclusions

A parametric study of the sensitivity of fatigue loading experienced by a tidal current turbine to the environment in which it operates has been performed. A number of conclusions results:

- Fatigue loading has been shown to vary appreciably as a function of mean flow turbulence.
- Fatigue loading is similarly shown to be sensitive to wave action
- The fatigue loading mechanisms of flow turbulence and waves are a vital consideration in the overall design process.
- The potential importance of flow turbulence in turbine loading underlines the requirement for detailed tidal flow

measurement studies, followed by the development of validated spectral models of tidal current flow.

- Further research could build on the findings of this study by investigating the mitigation of the identified loading mechanisms through the use of sophisticated control strategies eg. individual blade pitch control.

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