

# Load Simulation for Tidal Turbines using Wind Turbine Experience

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## Abstract:

The paper discusses the development of GH Tidal Bladed, a design tool for tidal current turbines. Typical results from a generic turbine simulated with the code are presented, in terms of its power curve and a number of salient load component time histories. The rationale behind the development of the GL draft guideline for Ocean Energy Converters is presented, focussing on its importance in the certification process. The set of load cases to be considered for tidal devices is described. The draft GL-Guideline was implemented by running typical load cases for a generic tidal device using GH Tidal Bladed, resulting in an example set of extreme and fatigue certification loads for the turbine. Finally, some future recommendations for work on tidal device modelling and standards development are discussed.

## Introduction

The development of tidal current turbines has reached the point where prototype systems are now operational. Certification and due-diligence review of tidal current turbines will inevitably be required as part of the commercialisation process and these will demand validated design analyses.

The similarities between horizontal axis wind turbines and tidal turbines suggest that the latter can benefit by transferring experience and modelling tools from the wind industry. To this end, Garrad Hassan (GH) has received partial funding from UK DTI to adapt its wind turbine load and performance simulation code, GH Bladed [1,2], to model horizontal axis tidal devices. The work has resulted in a new design tool specifically for tidal turbine analysis – GH Tidal Bladed. Design tools such as this will allow developers to assess their device with respect to a set of design standards, for example the Germanischer Lloyd draft “Guideline for Ocean Energy Converters” [3].

GH was established in 1984 to answer a growing need for independent expert advice on wind energy. GH now employs over 180 full time engineers working in the wind energy industry around the world and is recognised as the leading independent authority.

GH Bladed is an integrated software package which allows the user to carry out the full range of loading and performance calculations required for the design and certification of wind turbines.

Germanischer Lloyd (GL) was founded 1867 and is one of world's leading ship classification and technical surveillance societies with more than 2000 engineers working worldwide. GL is further one of the leading certification bodies for wind turbines with more than 30 years experience in the wind energy business. From the very beginning GL developed its own rules and guidelines mainly in the maritime sector (1870), or from the very first days of modern wind turbine industry (1979). Nowadays GL has issued rules and guidelines for almost all

sections of maritime industry, wind energy and in 2005 the first draft “Guideline for the Certification of Ocean Energy Converters, Part 1: Ocean Current Turbines” [3].

**Why Tidal Energy?**

The interest in utilising tidal energy has been fuelled by several factors such as fuel prices and environmental issues, and is now being supported by technical development. In an EU funded study, [4] it has been suggested that tidal currents could be used to generate about 50 TWh/year of electrical energy. Energy production from tidal turbines is controlled by the semi-diurnal and diurnal period of the tides and its monthly variations; furthermore, tidal prediction is a well developed science [5, 6] The predictability and regularity of tides compared to offshore wind and wave energy makes the use of tidal energy attractive [9], even if the available resources are relatively limited.

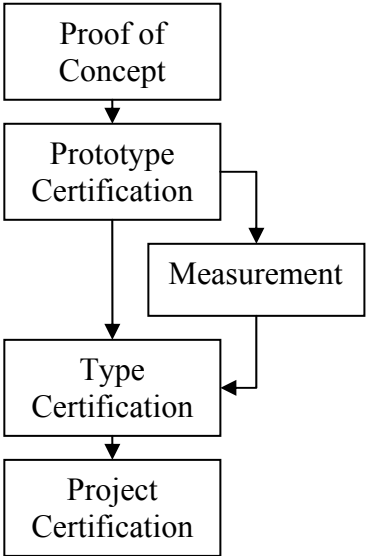
Although different concepts for tidal turbines have been developed – bottom fixed or floating, horizontal or vertical axis, ducted or unducted – several parallels can be drawn with wind turbines. The principle of power extraction is the same, resulting in the same theoretical limitations and hydro- or aerodynamic theories used for analysis. The power output is of the same magnitude and they have a similar machinery design (blades, hub, drive train, electrical installation). The support structure may be of similar design and experiences the same problems regarding soil interaction, scour, marine growth etc as support structures for offshore wind turbines.

The similarities between wind turbine and tidal turbine technologies mean that it is a natural step to adapt tools used in industrial wind turbine analysis to tidal turbines, hence the development of Tidal-Bladed and the use of similar procedures for Certification as those used for offshore wind turbines by GL.

**Certification and Guidelines**

Assessment and certification of products with respect to the structure’s integrity and safety as well as to its capabilities for power production are used to minimise risks and to build confidence in the development and the realisation of the product. Third party assessment is often required by investors, insurers, operators and authorities to qualify a product. The “four-eyes-principle” can help designers to detect inconsistencies and possible sources of damage.

Like wind turbines, significant parts of the structure of tidal devices are site dependent, in particular the support structure. Other essential elements of the tidal turbine, like the rotor, drive train and generator will be designed for generic conditions irrespective of the site where they will be installed. As a result it was decided to follow the same certification strategy [3] as for offshore wind turbines [10]. The generic part of the device (e.g. the machinery) is covered by a “type certification”, performed once, while the site dependent part is included



**Figure 1:** Stages of Certification

in the “project certification”, performed for every new turbine farm. Since tidal turbines are novel devices, a concept study is performed and certified based on plausibility checks in early stages of the design leading to a “proof of concept”.

A special case of design assessment is the certification of the prototype. The behaviour of the system is not really known and the assumptions not verified. The main focus is instead on the safety concept, the safety system and the load assumptions. As a rule, power and load measurements shall be performed on the prototype, after which they shall be compared to the calculated values.

In a new technology it is obvious that no introduced standards may exist. Furthermore the technology is not mature; many new and sometimes unusual designs are developed and tested. To develop the GL Guideline for ocean current turbines, guidelines from other technologies [10-13] have been collected, reviewed and the most appropriate compiled in order to serve as a first basis for design. Experience from certification activity in wind energy as well as oil and gas activities have been used to formulate requirements in excess of the a.m. standards and are collated in the Guideline.

**Requirements for load analysis**

Usually it is assumed that currents will simply reverse in direction every 12 hours with flows dependent on the local bathymetry. Unfortunately this is often not the case. The sea bed, wind, waves, temperature and salinity gradients will influence the loads on the device under consideration. For this reason the requirement for a site assessment is included in the guideline. The main parameters to be considered are shown in Table 1.

Since it is often difficult to predict current profiles or the magnitude of wind induced currents, standard models are given. These consider subsurface (tidal), wind induced and wave induced (surf) currents. Further models for sea state description and for current wave interaction are given.

One point of concern is the fluctuation of the current in time and space and its statistical values. Very few measurements of the turbulence intensity of tidal currents and their spectral distribution are known. Especially for the spectral distribution, no standard models as used in the wind industry or for sea state description exist. It is assumed that a simple Kolmogorov spectral density description can be used. In the first analysis performed the standard von Karman spectral density model [14] used in wind analysis was considered. The main influences to be considered in load analysis are:

- Current including vertical profile and turbulent current fluctuations

Current speeds and directions
Current profile
Current fluctuations
Water level variation
Storm induced currents
Sea states and their directional distribution
Wind speeds and directions
Sea ice
Water temperature range
Water density and salinity
Soil conditions (resistance)
Bathymetry

**Table 1:** Main environmental parameters to be considered in turbine design

- Wave kinematics. Irregular sea states and regular, non-linear waves
- Tidal sea levels
- Rotor hydrodynamics, including stall and wake effects
- Operating behaviour, including control system pitch and rotational speed adjustment
- Hydroelastic coupling, including added mass effects
- Buoyancy
- Non-linear soil structure interaction

Cavitation damage seems not to be problematic since its avoidance can be based on propeller design experience. Standard diagrams are included in the guidelines and can be used for tidal turbines as well.

### **Tidal Bladed – adapted models**

This section details the major modelling changes that have take place in the development of Tidal Bladed.

#### *Water particle kinematics*

Bladed for wind turbines has a comprehensive sea state module which is used to model the wave and current-induced loading on offshore turbine support structures. For the development of Tidal Bladed this module has been extended to apply the full water (wave and current) particle kinematics onto the rotor, nacelle and submerged parts of the support structure.

#### *Water turbulence*

As well as the unsteadiness in the flow due to surface waves, the flow will have a higher frequency unsteadiness resulting from sea bed-generated turbulence. Tidal Bladed combines the current and wave kinematics with the velocity, acceleration and pressure fields due to this roughness-generated turbulence. The properties of the turbulence field can be user defined – future work will focus on the creation of generic models to represent the nature of tidal flow turbulence.

#### *Buoyancy of the rotor, nacelle & support structure assembly*

Using the total calculated pressure field described above, and with a detailed description of the turbine geometry, Tidal Bladed is able to compute the resulting applied fluid pressure forces on the structure.

#### *Single/multi member support structures*

Tidal Bladed uses a finite element representation of the support structure, allowing the user to model structures ranging from a simple monopile to an arbitrarily complex multi-member arrangement. Wind loading on surface-piercing members of the structure are accounted for.

#### *Added Mass*

Morison's equation is implemented in Tidal Bladed to model the added mass-related loading on the rotor blades - an extension from Bladed which only needs to consider added mass on the support structure of offshore wind turbines. Flow accelerations, structural vibrations and rotor inertia are all considered in determining the influence of added mass.

### Cavitation

A cavitation index number is calculated by Tidal Bladed at each blade element at each time step, using user-specified  $C_{pmin}$  values, the resultant velocity and dynamic pressure fields, and values for atmospheric pressure and vapour pressure of sea water. If this index exceeds a value of 1 a warning is provided indicating cavitation inception is likely.

### Blockage effect due to sea-bed and sea-surface

A blockage model [15] has been included to account for the presence of the sea-bed and sea-surface.

### Tidal Bladed - model validation

Tidal Bladed has been validated against measurements taken from a scaled tidal turbine model in a cavitation tunnel at Southampton University [16]. The turbine has a rotor diameter of 0.8m. Power and thrust measurements were used to determine  $C_p$  and  $C_t$  values for a range of tip speed ratios (TSR). Comparison between these measured quantities and predictions using Tidal Bladed are provided in Figures 2 and 3.

The code predicts  $C_p$  well around operational TSR values but appears to over-predict for very high TSRs.  $C_t$  is predicted well over the full range of TSR. Further validation studies will be performed whenever full-scale device measurements become available.

### Load cases

Currents and waves are the main sources of loading. In general the known methods from the offshore industry combined with simulation techniques of the wind turbine industry [10] may be applied. For the ultimate load analysis the conditions which have to be analysed can be derived from the load groups shown in Table 2.

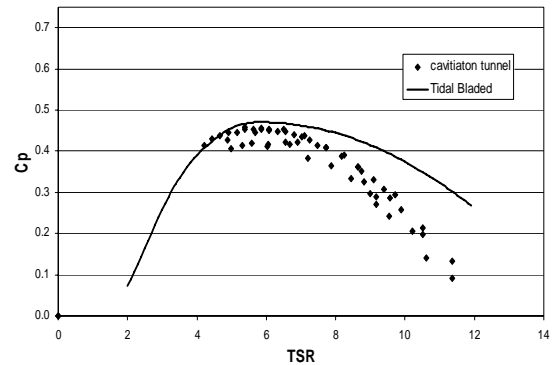


Figure 2: Power coefficient vs tip speed ratio

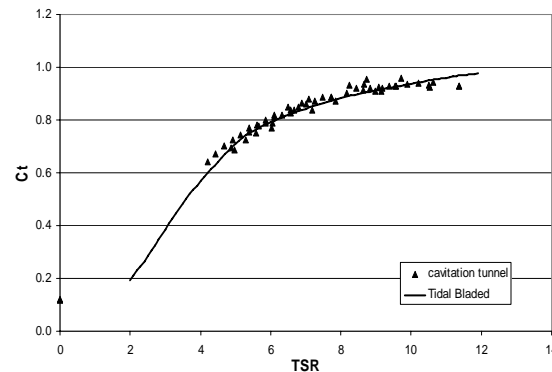


Figure 3: Thrust coefficient vs tip speed ratio

Load Group	Design condition	Environmental conditions	recurrence period
I	Normal operation, parked	Extreme	$\leq 50$ years
II	Operation, emergency stop, fault occurrence, parked after fault	Normal	$\leq 1$ -year
III	Installation and Maintenance	defined by the designer	-
IV	Secured/Parked during installation	Normal	$\leq 1$ -year

Table 2: Load groups to be considered for design of ocean current turbines

The extreme conditions to be considered are based on combined probabilities of the governing environmental conditions (e.g. current speed and wave height). For fatigue analysis only load groups IIA and IV have to be considered. Marine growth, bathymetry and the effects of wakes from neighbouring turbines should also be considered. An example load set is given in Table 3. It is assumed that wind does not influence the device.

Group	Case	Current			Waves		Water Level	remarks
		Tidal	Wind	direction		direction		
I	A	50 year	-	In line	mean	0°, 180°	MSL	Operating or parked
	B	mean	50-year	all	50-year	all	MSL	
	C	-	50-year	all	50-year	all	50-year	
	D	50 year	50 year	In line	mean	±30°	Storm surge	
	E	Daily max	-	In line	1-year	all	MSL	
	F	Max cross flow	-	90°	50 year	all	MSL	
II	A	Daily variation	-	Acc. site	mean	±30°	Acc. current	Operation, stop, failure
	B	mean	-	In line	1-year	all	MSL	
	C	-	-	-	1-year	all	1-year	
III	A	As defined by designer						
IV	A	1-year		all	1-year	all	1-year	Parked, install.

**Table 3:** Typical load case set

### Example simulations

To illustrate the use of Tidal Bladed as a design tool, a number of example simulations have been performed using a generic tidal current turbine model. The turbine is a stall regulated variable speed configuration with a 19m rotor diameter, giving a nominal power rating of 1.5MW. The salient characteristics of the generic device and its operating conditions are provided in Table 4.

power regulation	stall	support structure type	bottom mounted
number of blades	3	Mean sea level (m)	40
rotor diameter (m)	19	current speed range (m/s)	+/- 3.5
rated power (kW)	1500	Mean sea level range (m)	+/- 2.8
rated rotor speed (RPM)	10	Iu turbulence intensity (%)	10
rated flow speed (m/s)	3	irregular sea state spectrum	JONSWAP
rotor orientation (.)	up-flow	sea state characteristics	Hs = 1 / Tp = 5

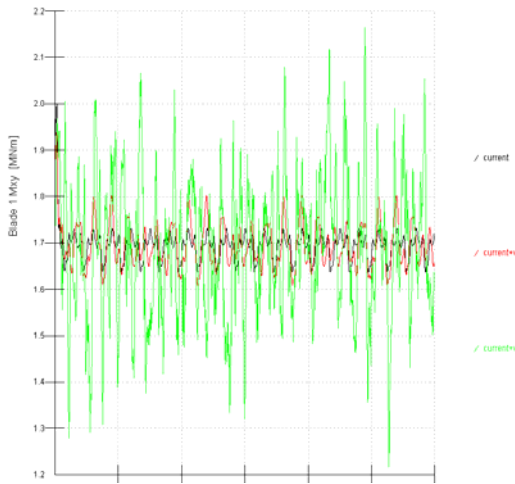
**Table 4:** Generic tidal current turbine characteristics

**Possible analysis**

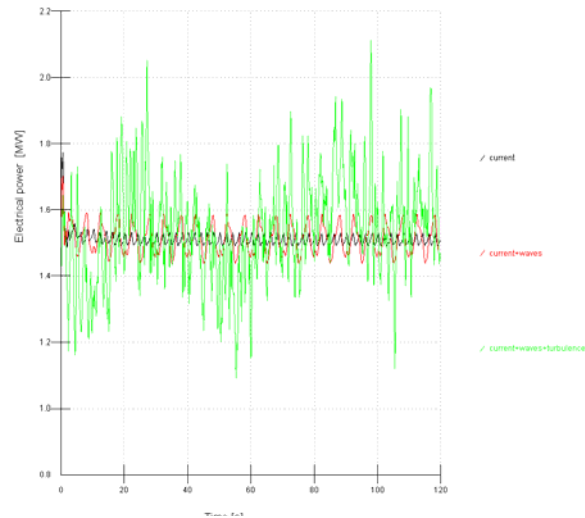
A range of hydroelastic, time-domain example simulations have been run for this model in which the complexity of the flow environment has been incrementally increased to illustrate the effects of waves and flow turbulence on turbine loading and performance:

- Current only (2.5 m/s): black line
- Current and waves (2.5m/s, Hs=1m, Tp=5s): red line
- Current + turbulence + waves(2.5m/s , I = 10%, Hs=1m, Tp=5s): green line

Time histories showing these effects on blade root out-of-plane bending moment and electrical power are provided in Figures 4 and 5.



**Figure 4:** Blade root bending moment



**Figure 5:** Electrical power

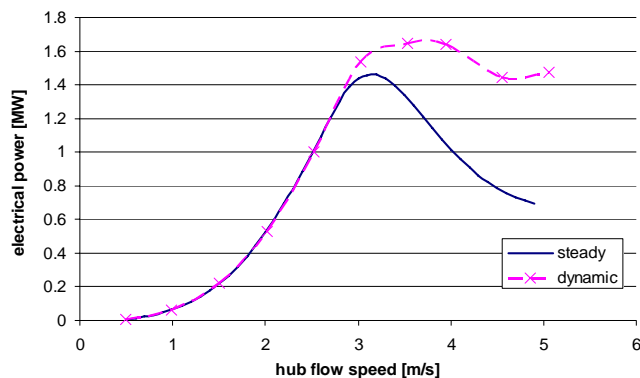
**Power curve (steady vs turbulent)**

A steady power curve is compared with the fully dynamic power curve calculated by simulating a range of flow conditions and including wave and turbulence models to account for unsteadiness in the flow. Figure 6 shows the effect of dynamic stall just beyond the rated point of the device. This behaviour is typical of stall-regulated wind turbines also.

Turbulence Intensity: I = 10%, Hs = 1m, Tp = 5s

Uc [m/s]	WL [m]	Uc [m/s]	WL [m]
0.5	42.8	3	40.8
1	42.4	3.5	40.4
1.5	42	4	40
2	41.6	4.5	39.6
2.5	41.2	5	39.2

**Table 5:** Current velocity and associated mean water level up to rated point



**Figure 6:** Generic tidal turbine power curve (steady and dynamic)

### Extreme Load Analysis

The 50-year return storm design load case, as defined in Section 4.4.2.1 of draft GL guideline [3], has been simulated in Tidal Bladed using the generic model described in Table 4. The environmental conditions associated with the storm case are defined in Table 6. Selected simulated results are provided in Figure 7 (red: tower base Mxy, black: blade root Mxy, green: sea surface elevation, blue: flow velocity at hub height).

Design load case		50-year return storm
U wind		25m/s at 10m height
Wind-induced surface current		0.625m/s
Extreme 50 year regular wave:	Hs	13m
	Tp	10s
Normal current speed at hub height		2.2m/s
Current direction		co-direction with wind and waves
Water level		40m (MWL) + 2m (storm surge)

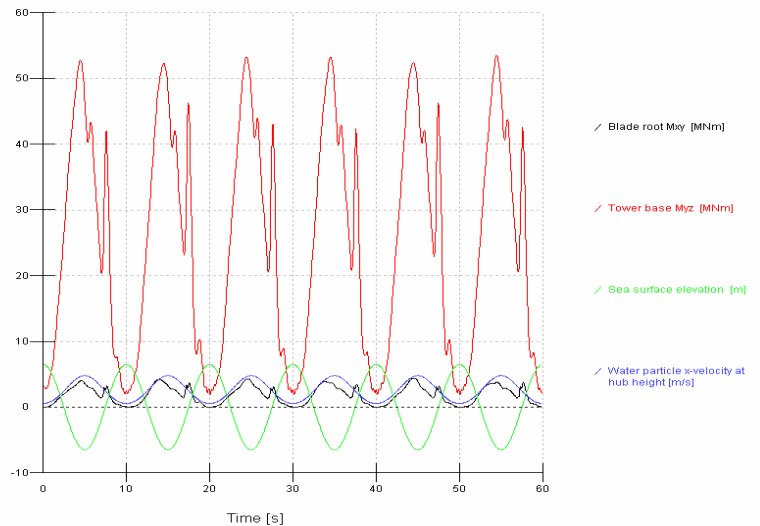
**Table 6:** Extreme 50-year storm design load case conditions

By modelling the complete range of extreme load cases outlined in a design standard (see Table 2) in this manner, it is possible to determine the driving load cases for each turbine component and the maximum load that they are required to withstand.

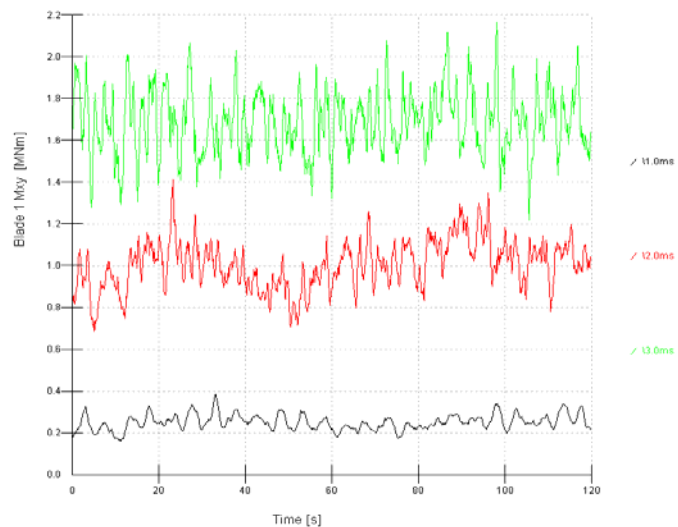
### Fatigue Load Analysis

The range of operational load cases representing a turbine lifetime of 20 years has been simulated in accordance with Section 4.4.2.2 of the draft GL guideline [3]. The load cases take account of the tidal fluctuations, namely the current velocity and sea level variations. A stochastic sea state is applied and sea-bed generated turbulence is also modelled. For the purposes of this example, wind, waves and currents are assumed co-directional. The environmental parameters of the model are again outlined in Table 4.

For the purpose of illustration, we concentrate on one load component; blade root resultant



**Figure 7:** 50-year extreme storm example time histories



**Figure 8:** Blade root resultant My time histories

bending moment ( $M_{xy}$ ). 10 minute time histories of this load are shown for 3 mean flow speeds in Figure 8 (black: 1m/s, red: 2m/s, green: 3m/s). By rainflow cycle counting the complete set of load time histories and integrating over the turbine lifetime, fatigue load spectra may be determined, as shown in Figure 9.

Load time histories and spectra such as this, available for all major components of the turbine (rotor blades, hub, support structure etc), can be used as input to stress analysis tools, allowing the designer to assess structural integrity and determine the location of structural ‘stress hot-spots’. They can also be processed within Tidal Bladed to determine ‘lifetime damage equivalent loads’ experienced by the turbine.

### Conclusion

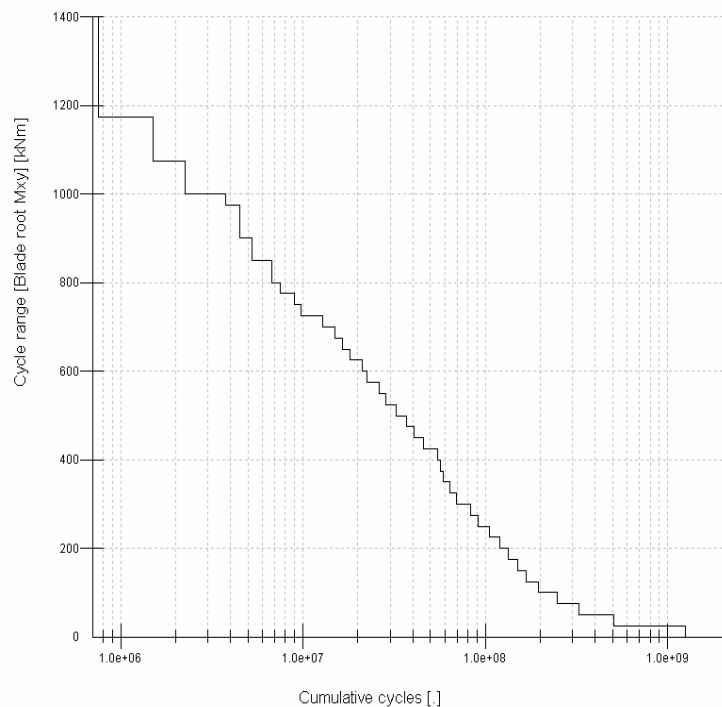
The necessity of standardised requirements for the design of tidal turbines is considered by the Guideline developed by Germanischer Lloyd. Based on experience with wind turbines and propellers a comprehensive set of load cases has been determined, considering all governing environmental conditions. The parameters to be considered during load analysis are defined.

A tool has been developed considering all parameters required for the load analysis of tidal turbines, drawing upon Garrad Hassan’s experience of turbine modelling in the wind industry. The use of this tool for the design and certification of tidal turbines has been demonstrated.

Finally, the need for more fundamental research into the influence of the sea-surface/sea-bed boundaries on turbine performance and loading, as well as the development of suitable spectral models for current turbulence, is emphasised by the authors.

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**Figure 9:** Blade root bending resultant moment fatigue spectrum

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