Full-Scale Validation of a Numerical Tool for the Prediction of the Loading and Hydrodynamic Performance of Axial Flow Tidal Turbines

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***Abstract*— Results of performance and loading from numerical simulations performed with GL Garrad Hassan's tidal turbine modelling tool, Tidal Bladed, are compared to measured data from Tidal Generation Limited's 500kW tidal turbine. The mean simulated values of key parameters such as electrical power, rotor speed, pitch angle and blade near-root flapwise bending moment agree well with the measured data. The minimum and maximum values of these indicators are found to be more extreme for simulations than for measured data. This difference is largely attributed to the uncertainty in the definition of the turbulent flow field. Blade root fatigue load predictions by Tidal Bladed are found to be conservative compared to the measured data. The major contributor to measured fatigue load is flow turbulence. Extreme loading under normal power production is also found to be conservative.**

***Keywords*— tidal turbine model, model validation study, Tidal Bladed, ReDAPT, time domain simulation**

I. Introduction

The tidal stream industry is continuing to grow and develop. Full-scale prototypes are demonstrating that tidal turbine technology can survive in the marine environment whilst producing useful amounts of power. In order to develop the technology further an increasing amount of effort is focused upon improving the structural and hydrodynamic efficiency in order to reduce the cost of energy. This design refinement process requires sophisticated design tools that can be trusted to predict the turbine loading and performance.

Tidal Bladed is a commercial software package which can be used to model the performance of, and loading on, tidal stream energy converters in the tidal stream environment. Building on the industry-standard wind turbine design tool Bladed, Tidal Bladed has been developed over the last five years in collaboration with the tidal stream sector.

The Energy Technologies Institute commissioned and funded the Reliable Data Acquisition Project for Tidal (ReDAPT) project with the primary objective of installing a 1MW tidal generator with a comprehensive data collection system at the European Marine Energy Centre (EMEC), Orkney [1].

As part of the ReDAPT project, GL Garrad Hassan (GH) has conducted a comparison between simulations undertaken using Tidal Bladed and performance and loading data collected from Tidal Generation Limited's (TGL) 500kW DEEPGen III tidal turbine installed at EMEC. This is the first public domain reported study to compare Tidal Bladed with a large scale tidal turbine.

II. Pre-processing of Machine and Environmental Data

The comparison between simulation and measured data was conducted using concurrent environmental and machine data collected over a 3 month period in 2011. Environmental data were collected using an Acoustic Doppler Current Profiler (ADCP) sampling at 0.5Hz, placed approximately 50m upstream of the turbine on an ebb tide. The ADCP recorded flow velocity data throughout the water column which was used to infer the inflow conditions on the turbine. Prior to analysis the flow data was filtered based on the error velocity and signal correlation calculated internally by the ADCP.

The ADCP data were gathered into 10 minute samples and were analysed to calculate: mean hub height flow speed, mean flow direction, flow shear profile and acceleration of flow over each sample. The data were also analysed using Teledyne RD Instruments' WAVESMON software to estimate the wave conditions of significant wave height, peak period and wave direction for each sample.

In addition to the ADCP a Single Beam Doppler Profiler (SBD) was mounted on the back of the turbine. The turbine was able to yaw so that the SBD could face the oncoming flow and measure the longitudinal flow velocity with a higher accuracy than the ADCP. The results from the SBD were used to calculate the turbulence intensity.

Both ADCPs and SBDs are known to over-estimate the turbulence intensity due to the presence of Doppler noise in the velocity measurement as described in [2]. The effect of this noise is to increase the amount of fluctuation seen in the velocity value recorded, thus increasing the apparent turbulence intensity. If the particular set up and characteristics of the measuring device are known then it is possible to apply a theoretical correction for the Doppler noise. As the SBDs are at a very early stage of development a theoretical correction was not available.

Additionally, it was not possible to calculate the turbulent length scales from either the ADCP or SBD. A set of turbulence length scales were assumed for the study and were used to calculate the turbulent flow field using the von Karman turbulence model.

The machine data collected consisted of loads calculated from strain gauges on the turbine and information collected from the control system, including electrical power, pitch angle, turbine direction and machine state at frequencies up to 5Hz.

Fibre optic strain gauges were mounted at the inboard section on the blades allowing the instantaneous flapwise bending moment to be measured. The most inboard of these strain gauges that produced consistent measurements reported the load at a position equal to 24% of the blade length from blade root. The most inboard results were used so that comparison could be made between measured and simulated results of the integrated load along the blade.

The machine data were also gathered into 10 minute samples to align with the 10 minute samples of environmental data. The two sets of data were filtered to remove samples inappropriate for comparison; primarily where the ADCP was downstream of the turbine or where the turbine was not operational for the full 10 minutes.

After filtering there were 57 samples each of 10 minute duration found suitable for comparison. The distribution of flow speeds is shown in Fig. 1. Note that speed bin 11 relates to the rated flow speed of the turbine.

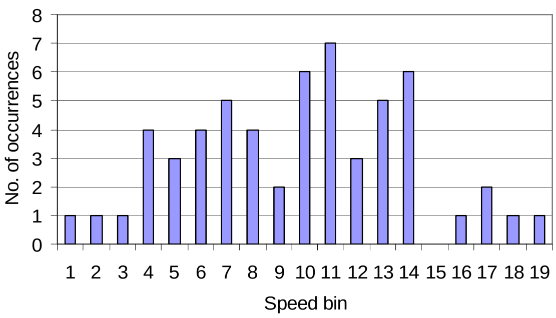

Fig. 1 Distribution of flow speeds

III. Comparison Methodology

To ensure that the model best represented the real turbine, the Tidal Bladed model of TGL's 500kW device was defined by TGL and checked by GH.

For each of the 57 samples identified the environmental conditions of mean hub velocity, flow shear profile, tidal height, wave conditions and turbulence intensity were characterised and then reproduced in Tidal Bladed simulations. The results of the simulations were then compared with the relevant 10 minutes of data. This allowed for a direct comparison of the environmental forcing measured on the real turbine to that calculated from the simulations.

IV. Mean, Minimum and Maximum Load and Performance Parameters

The mean, minimum and maximum of various turbine parameters for both the measured and simulated 10 minute data sets were compared. The variables investigated were electrical power, blade pitch angle, rotor speed and blade near-root flapwise bending moment. As is typical, the data have been normalised due to confidentiality restrictions. In the following text wherever normalised results are presented the parameter used for normalisation is described.

Although 57 ten minute periods were identified for the study and emulated in Tidal Bladed simulations, some of the periods did not have useable data for all of the parameters that were studied. Attempting to find periods where all parameters were useable would have resulted in a far smaller number of viable periods, hence parameter data were only removed if unsuitable rather than removing the complete 10 minute set of data. As a result, fewer than 57 measured data points are seen on each plot.

A. Power

Fig. 2 shows the mean, minimum and maximum electrical power for each 10 minute data (measured and simulation) as a function of mean hub flow speed. Power is normalised by nominal rated power and hub flow speed is normalised by TGL's stated rated flow speed.

The mean values generally match well. The scatter seen in the measured data mean values is distributed fairly evenly above and below the values calculated in Tidal Bladed.

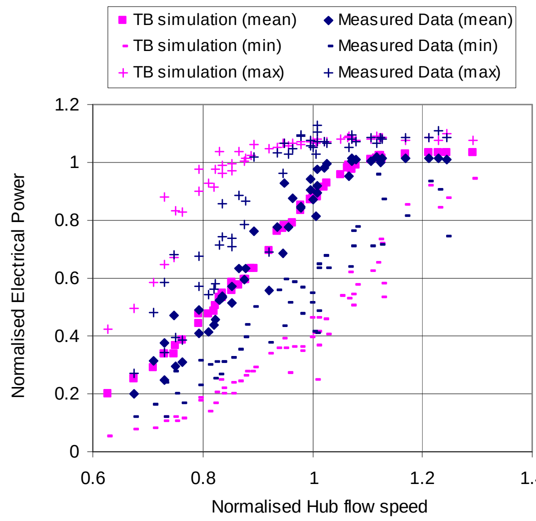

Fig. 2 Comparison of electrical power 10 minute mean, min and max with hub flow speed

The mean power levels-off at a normalised flow speed of about 1.11 in the Tidal Bladed simulations and about 1.07 in the measured data.

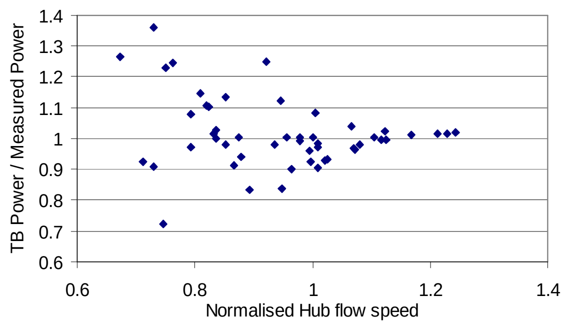

Fig. 3 Ratio of Tidal Bladed and Measured Mean Power

Fig. 3 shows the ratio of Tidal Bladed to measured mean power. It can be seen that the data is generally scattered about a ratio of 1, which suggests that there is no consistent offset for the electrical power prediction. Towards and above rated flow speed, the ratio can be expected to tend towards 1 as rated power is reached in the simulated and measured data. The average ratio of predicted and measured power across all simulations is 1.015 suggesting a relatively small difference between measured and predicted mean power. The range of electrical power within each 10 minute sample is generally greater in Tidal Bladed than in the measured data. This could be due to the increased turbulence intensity calculated from SBD sample data causing greater fluctuations in flow speed in the simulations than in reality.

B. Rotor Speed

Fig. 4 shows the mean, minimum and maximum rotor speed as a function of mean hub flow speed. Rotor speed is normalised by rated rotor speed and flow speed is normalised by rated hub flow speed.

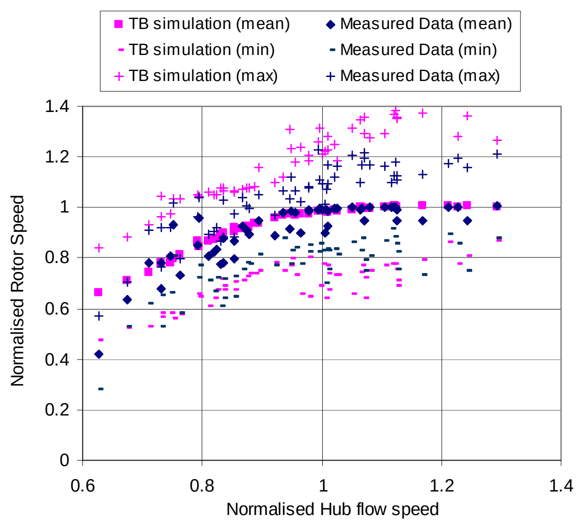

Fig. 4 Mean, Min and Max Rotor Speed vs. Mean Flow Speed

Many of the simulated results of mean rotor speed match well with the measured data, especially around rated, suggesting that the rotor speed is generally well predicted. However, there are a number of measured data points where the mean rotor speed is 5-10% lower than the simulated data. In the region above rated flow speed the rotor should on average operate close to rated rotational speed. As the measured power is at rated for these data points, the measurements are not self-consistent for these cases.

It can be seen that the range of rotor speed within each sample is generally greater in Tidal Bladed than in the measured data. As for the electrical power, this could be due to the increased turbulence intensity calculated from the SBD.

C. Pitch

Fig. 5 shows the mean, min and max pitch angle as a function of mean hub flow speed. Pitch angle is normalised by peak observed pitch angle and flow speed is normalised by rated hub flow speed.

The mean pitch angle generally matches well between the measured data and the Tidal Bladed simulation results. The same patterns are seen as with rotor speed and power, with more scatter in the means for the measured data, but greater variation within each 10 minute sample for the Tidal Bladed data.

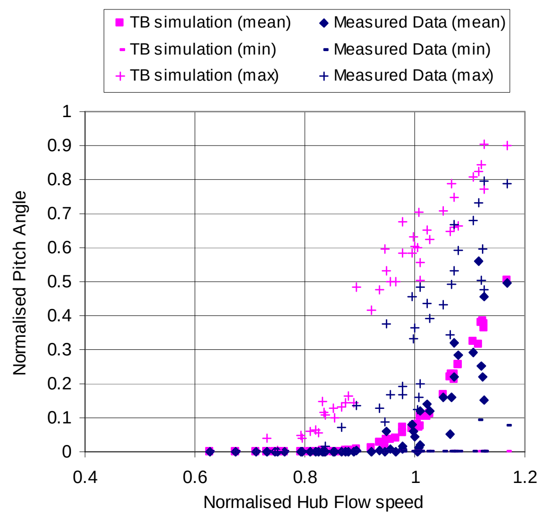

Fig. 5 Mean, Min and Max Pitch Angle vs. Mean Flow Speed

A particular area of interest in Fig. 5 is the region between normalised hub flow speeds of 0.925 and 1.0, i.e. just below rated flow speed. In this region, Tidal Bladed predicts a mean pitch angle greater than zero whereas the measured data suggests that the mean value is zero or very close to zero.

This difference in mean could be caused by larger variation in input flow velocity in the Tidal Bladed simulations than in the measured data. An increase in flow speed above rated causes the pitch angle to rise above zero, but a decrease in flow speed can't cause a pitch angle reduction below zero.

The effect of increased flow speed variation is therefore to increase the mean pitch angle. This effect disappears once the mean pitch angle is consistently above zero, as the pitch angle can respond to increases or decreases in flow speed. The measured and simulated mean pitch angles therefore generally match well above a normalised hub flow speed of 1.0.

D. *Blade Near-root Flapwise Bending Moment*

Fig. 6 shows the mean blade flapwise bending load at a radial location of 24% of the blade length from blade root as a function of mean hub flow speed. The load is normalised against measured peak mean bending moment.

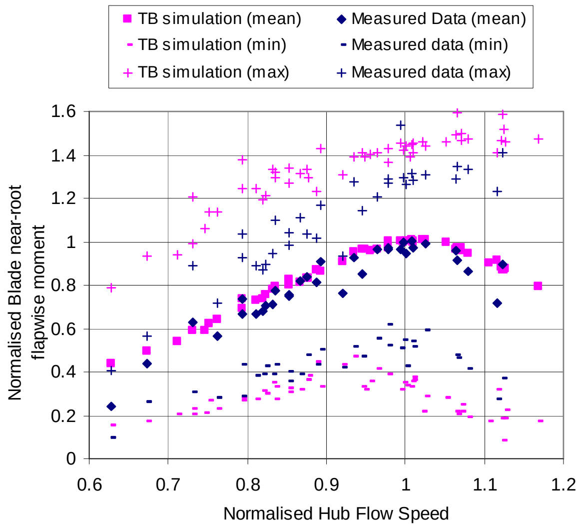

Fig. 6 Mean, Min and Max Blade Flapwise Bending vs. Mean Flow Speed

Generally, a very good match is seen between the mean values for each 10 minute sample. The mean values of blade bending moment have less scatter than any of the previous parameters. The normalised peak mean load agrees well between Tidal Bladed (0.976) and the measured data (1). Also of note is that the peak load occurs at the same normalised hub flow speed of about 1 in the measured and simulated data. This improves confidence that the mean flow speed is matched well between the simulations and measured results.

There is a limited amount of good quality blade load data available above rated flow speed, so it is difficult to comment on the accuracy of load prediction in this region.

As with the other variables, there is greater variation of blade bending moment within each 10 minute sample in the Tidal Bladed simulations than in the measured data.

Fig. 7 shows the ratio of mean blade bending load in Tidal Bladed and in the measured data for each 10 minute sample. The average ratio across all samples is 1.03. The data is distributed fairly evenly above and below this ratio. This suggests that the agreement between mean measured and simulated load is very good, but Tidal Bladed is predicting slightly higher mean blade bending loads than in the measured data.

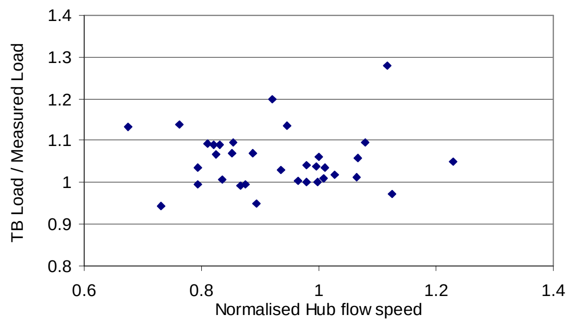

Fig. 7 Ratio of Tidal Bladed and Measured Mean Blade Flapwise Load

E. *Summary*

Generally, a good agreement is seen in the mean values of electrical power, rotor speed, pitch angle and blade near-root flapwise bending load. No significant offset in the mean values between measured and simulated data was observed for these variables. The similarity in operation parameters (power, pitch and rotor speed) show that Tidal Bladed is capturing the time-averaged behaviour of the turbine very well. The good match in blade loading suggests that the mean interaction of the flow with the turbine is well captured in Tidal Bladed.

Some scatter is seen in the 10 minute means of the measured data. This might be explained by poor matching of the mean hub flow speed. However, the correlation between the measured and simulated mean flow speed generally appears good as the peak mean blade bending loads (measured and modelled) occur at the same mean hub flow speed.

In most cases, the difference between the maximum and minimum values of each parameter within each 10 minute sample is larger in Tidal Bladed than in the measured data. Predicted extreme values of operational parameters and blade loading are higher in the Tidal Bladed simulations than in the measured data.

The most significant contributions to the difference between minimum and maximum results are thought to be higher turbulence intensity in the simulations than in reality and uncertainty in the turbulent length scales.

Previous sensitivity studies [3] and [4] have investigated the effect of a number of environmental conditions on unsteady loading in Tidal Bladed including the turbulence model, turbulent length scale, turbulence intensity and significant wave height .

As noted in [3], the maximum blade-root bending loads increase most significantly with increasing turbulence intensity. This is due to greater variation in blade lift. A larger range in blade lift would cause a larger range in the rotor torque, leading to increased variation of rotor speed and pitch angle. Reducing the turbulence intensity used in the simulations would therefore be expected to reduce the magnitude of load fluctuation around the mean.

V. FATIGUE LOADING COMPARISON

A current design driver in tidal turbines is the blade-root bending fatigue load. A simple measure of fatigue loading is the damage equivalent load. The damage equivalent load is derived by decomposing the load time history into its constituent loading cycles, and using a linear damage hypothesis to derive an equivalent load cycle that would cause the same damage when applied a reference number of times.

The method is based on the Miner's rule [5]. The damage equivalent load is given by the formula:

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

Where:

L_N is the equivalent stress for Tf cycles

L_i is the load range bin i.

T is the length of the simulation in seconds

f is the reference cycle frequency

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 inverse S-N curve slope).

Calculations of damage equivalent load were performed using an inverse S-N curve slope of 10, which is appropriate for composite materials. It was found in a study as part of this work that inverse S-N slopes of 6-14 gave very similar damage equivalent loads across all simulations. A reference frequency (f) of 0.015844 Hz was chosen. This is a standard assumption that corresponds to 10 million cycles in a 20 year turbine lifetime.

A. Blade Near-root Flapwise Bending Moment

The load time histories for both the measured and simulated data were post-processed to produce damage equivalent loads (DEL). Fig. 8 shows the comparison of DEL between the measured data and the simulated results, both normalised by the measured DEL at rated flow speed. Fig. 9 shows the ratio of Tidal Bladed DELs to the measured data DELs.

The Tidal Bladed predictions of damage equivalent load are consistently higher than the measured data results. The average ratio between the results is 1.58.

This difference in damage equivalent load can be explained by comparing the size and number of loading cycles present in the simulated and measured load signals.

Fig. **10** shows the rainflow cycle exceedance plot for the blade near-root flapwise load for a typical single 10 minute sample, with the cycle normalised by mean measured blade flapwise bending moment at rated flow speed. It can be seen that the Tidal Bladed simulation contains larger loading cycles, leading directly to the higher damage equivalent loads calculated for Tidal Bladed than for the measured data.

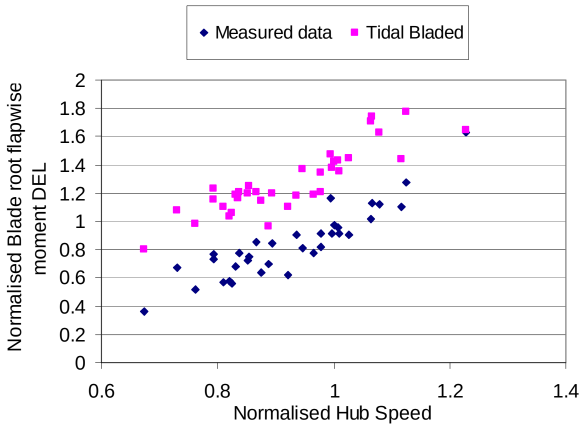

Fig. 8 Blade Near-root Flapwise Damage Equivalent Load vs Mean Hub Flow Speed (Inv. SN Slope = 10)

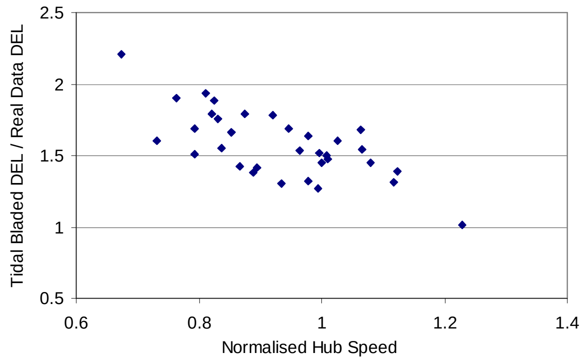

Fig. 9 Ratio of Tidal Bladed to Measured Data Damage Equivalent Load

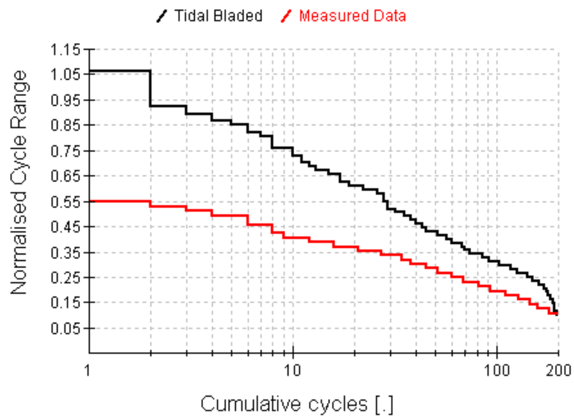

Fig. 10 Typical Rainflow Cycle Exceedance for Blade Flapwise Bending load

B. Azimuth Dependant Loading and Stochastic Loading

The difference in blade flapwise bending damage equivalent load was investigated further by decomposing the signal into load that was dependent on the azimuthal position of the rotor and that which was not.

In this paper the term "periodic" refers to load contributions that depend on rotor azimuth and occur (on average) with every complete rotor revolution. For example, each blade travels through the average flow shear profile once per revolution, leading to a fixed change in the load every revolution.

"Stochastic" loads come from flow turbulence or waves. Turbulence and waves do cause loading at harmonics of the rotor frequency due to rotational sampling, so the resulting loading is not only stochastic. However, as the source of this loading is stochastic, the load contributions derived from waves and turbulence are referred to as the stochastic loads.

To identify the periodic loading, all of the load data from a 10 minute simulation is binned by azimuth angle. An average of all of the loads at each azimuth angle is taken. This average is different for each azimuth angle, giving rise to a periodic load that depends on rotor azimuth. This mean cyclic load is then subtracted from the original time history, leaving only the stochastic component of loading.

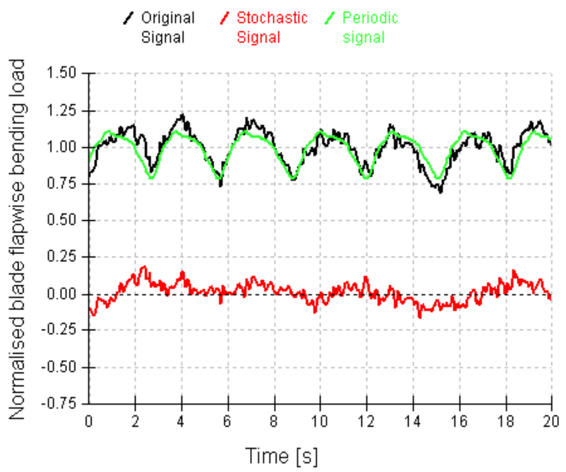

Fig. 11 Total, Stochastic and Periodic Load Components vs. Time

Fig. 11 shows an example of this decomposition for a sample of measured data. It can be seen that the periodic load is the same with every rotor rotation. The difference between the original and the periodic load is the stochastic load. Decomposing the signal in this way allows the loading contributions to be analysed separately.

C. Comparison of Periodic Loading

Fig. 12 shows the ratio of the periodic cycle size in Tidal Bladed to that in the measured data. The Tidal Bladed cycle size is on average 2.25 times larger than the measured data.

To investigate the reason for this difference in cycle range, the measured and simulated periodic cycles for a typical sample are shown in Fig. 13. The load data presented is normalised by the mean flapwise bending moment at rated. The solid lines show the total measured and simulated periodic cycle ranges, while the dashed lines show the various contributions to periodic load in Tidal Bladed. In this case, the measured data cycle range is 1 and the cycle range in Tidal Bladed is 2.13, when both are normalised against the measured cycle range.

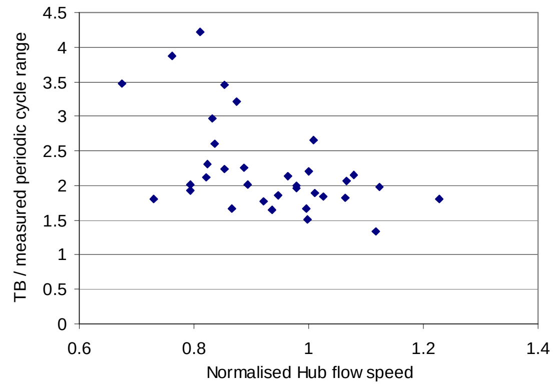

Fig. 12 Ratio of Tidal Bladed to Measured Periodic Cycle Range

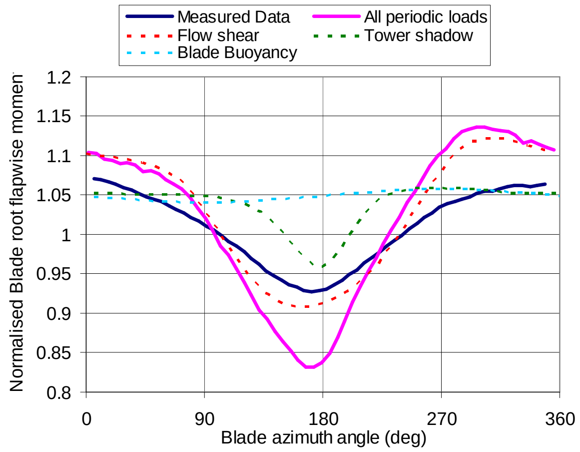

Fig. 13 Periodic Cycle Range in Simulated and Measured Data

In the simulated data, the most significant contributions are (cycle range in brackets, normalised against measured cycle range)

- Flow shear (1.33)
- Tower shadow (0.7)
- Blade buoyancy (0.1)

The shear profile gives the largest contribution to periodic load. The shear profiles used in the Tidal Bladed simulations are based on ADCP data collected by TGL (as stated in Section 2). Although there is confidence in the ADCP measurements to produce representative mean shear profiles, it is possible for the mean shear profiles to change significantly over relatively short distances. The shear profile can change in both cross-stream and streamwise directions due to the local bathymetry as discussed in [6]. Hence there is some uncertainty around whether the shear profiles measured 50m from the turbine are actually representative of those at the rotor location. During the study it was found that removing flow shear lead to a reduction of between 15-35% in DEL. Given the significant impact that sheared flow can have on the loading it is important that the subsequent ReDAPT measurements address this uncertainty.

The next greatest contribution arises from the tower shadow model. The tower shadow flow deficit is derived from potential flow methods so should be a good estimate of reduced velocity for an upstream device. However, the strong tower shadow effect over a narrow range of azimuth angles seen in the simulated data is not seen in the measured data. It is possible that tuning of the potential flow deficit model in Tidal Bladed could improve this matching between simulated and measured data.

The contribution of buoyancy force was relatively small so this was not investigated further.

A further possible cause of mismatch between measured and simulated data could be inaccuracy in mean flow speed measurement. However, the close match of flow speed that gives the peak blade load (as seen in Fig. 6) suggests high confidence in the measured mean flow speed.

D. Comparison of Stochastic Loading

Fig. 14 shows the damage equivalent loads calculated for the stochastic part of the load signals from Tidal Bladed and the measured data. The stochastic DEL is seen to be consistently higher in Tidal Bladed than in the measured data. On average, the Tidal Bladed stochastic signal DELs are higher than those measured by 35%.

The higher stochastic loading seen in Tidal Bladed could be due to the definition of the turbulent flow for the simulations. It is likely that the simulation turbulence intensity is higher than in reality (as mentioned in Section II) and there is also uncertainty over the choice of turbulent length scales. Both of these parameters affect the DEL [3].

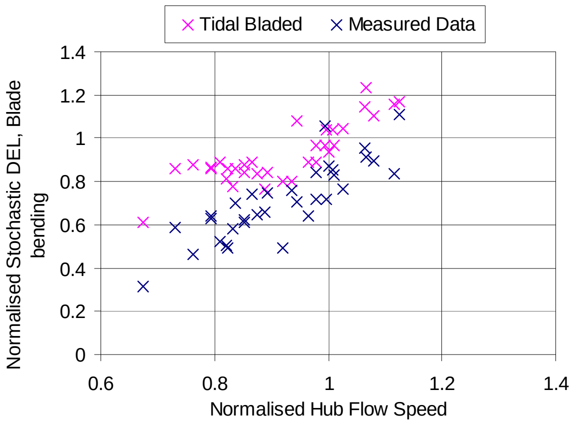

Fig. 14 Blade Flapwise Stochastic Load Component DEL vs. Mean Hub Flow Speed

E. Damage Contribution of Stochastic Loads

Fig. 15 shows the stochastic contribution of DEL and the total DEL for Tidal Bladed, while Fig. 16 shows the same results for the measured data.

The Tidal Bladed stochastic DEL is on average 0.77 times the total simulated DEL, whereas the measured data stochastic DEL is on average 0.93 of the total measured DEL.

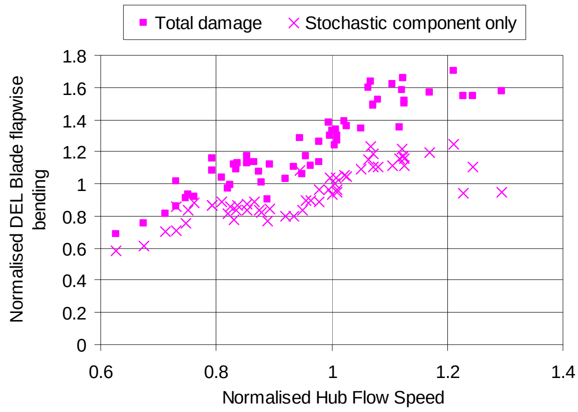

Fig. 15 Tidal Bladed: Total and Stochastic Blade Flapwise Damage Equivalent Loads

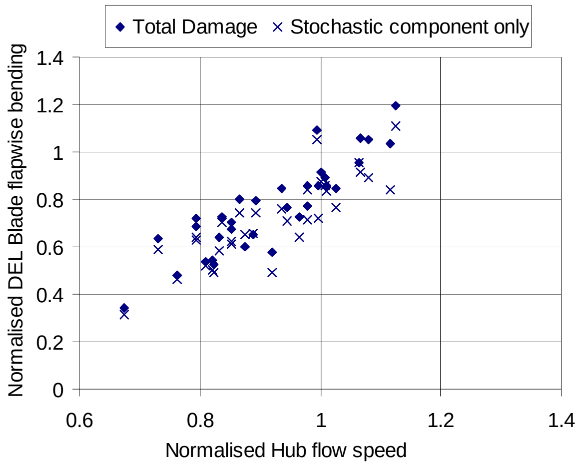

Fig. 16 Measured Data: Total and stochastic Blade Flapwise Damage Equivalent Loads

This suggests that the relative contribution of the stochastic loads (compared to periodic load) is greater in the measured data than in the simulated data. In the measured data, the stochastic loading is the dominant source of loading.

In the simulated data, the periodic loading makes a larger contribution to the overall damage than in the measured data. This is due to the observed larger periodic cycle range as seen in Section C.

To achieve good agreement of overall DEL between the simulated and measured data it is therefore necessary to accurately match both the stochastic and periodic loading.

F. Summary of Fatigue Loading Comparison

The Tidal Bladed predictions of damage equivalent load are consistently higher than the measured data results. The average ratio between the results is 1.58.

The average ratio of simulated to measured periodic load cycle size was found to be 2.25. In the simulated data, the shear profile makes the largest contribution and there is uncertainty over whether the measured shear profile is in fact seen by the rotor. The strong simulated effect of the tower shadow model is not observed in the measured data periodic load.

The average ratio of simulated to measured stochastic component DEL was found to be 1.35. This is thought to be caused largely by uncertainty in specification of the turbulence intensity and turbulent length scales.

In the measured data, stochastic loading has been found to contribute 93% of the DEL, compared to 77% in the simulated results. Clearly, accurate characterisation of the turbulent flow is required to accurately predict the stochastic loading. It is also important to refine the periodic load component modelling as these make a significant contribution to the simulated DEL.

VI. Future Work

Accurate characterisation of the marine environment has been identified as a main priority to improve blade root DEL prediction in Tidal Bladed. The planned further actions are summarised in Table 1.

TABLE I

Principal uncertainties in Tidal Bladed modelling and planned investigations

Area	**Comment and Plan of Action**
Shear profile	The form of the shear profile can have a strong influence on turbine blade loading. Although some measurements have been made in the vicinity of the turbine, further measurement campaigns planned under ReDAPT are required to better characterise the flow incident upon the rotor in both ebb and flood tides.
Turbulent length scales and turbulence intensity	Turbulent length scales and turbulence intensity have a strong influence on turbine blade dynamic loading. Under the ReDAPT project more suitable flow data will be obtained and analysed to provide a better estimate of turbulent length scales and turbulence intensity.
Tower Shadow Model	The contribution of the tower shadow model to the periodic blade load was much greater in Tidal Bladed than in the measured data. Investigation of the validity of this model could involve tank tests or CFD modelling.
Effect of waves	Time samples where large waves were recorded were excluded from this study. The effect of large waves on turbine fatigue loading has not yet been evaluated. The ReDAPT project is aiming to validate the wave kinematics models used within Tidal Bladed.

VII. Summary

Tidal Bladed has shown good prediction of the mean values of blade near-root flapwise bending loads, rotor speed, electrical power and pitch angle. This suggests that the mean environmental characteristics and the resulting turbine performance and loading are captured well. The extreme values of each of these parameters are generally larger within each 10 minute sample in the Tidal Bladed simulations than in the measured data.

Tidal Bladed prediction of damage equivalent load is more conservative than the measured results and predicts on average a damage equivalent load 1.58 times that of the measured data. In the measured data, stochastic loading was shown to dominate the fatigue loading. Periodic cycle size was on average 2.25 times greater in the simulated data. This led to stochastic loading being less dominant in the simulated data.

The method of environmental data analysis and the environmental models used within Tidal Bladed are to be reviewed in depth as part of future work under the ReDAPT project. Areas arising particularly from this work are the flow shear profiles, the significance of turbulence intensity measurement and characterisation of the turbulent flow structure through the definition of turbulent length scales, as well as other models such as the tower shadow.

References

[1] Energy Technologies Institute (2013) *Marine.* [Online] Available from: http://www.eti.co.uk/technology_programmes/marine [Accessed 19th July 2013].

[2] E Nystrom, K Oberg, C Rehmann. (2002): "Measurement of Turbulence with Acoustic Doppler Current Profilers – Sources of Error and Laboratory Results". *American Society of Civil Engineers, Specialty Conference on Hydraulic Measurements and Experimental Methods*

[3] I A Milne et al. (2010) "The Role of Onset Turbulence on Tidal Turbine Blade Loading", *Proc. 14th Australasian Fluid Mechanics Conference,* Auckland, New Zealand, 2010

[4] G N McCann (2007) "Tidal Current Turbine Fatigue Loading Sensitivity to Waves and Turbulence – A Parametric Study", in *Proc. 7th European Wave and Tidal Energy Conference*. Porto, Portugal, 2007

[5] Miner, M.A., "Cumulative Damage in Fatigue,"Journal of Applied Mechanics, Vol.12, No. 3, September 1945 (Transactions of the American Society of Mechanical Engineers, Vol. 67, A159-A164, 1945.

[6] Way S and Thomson M (2011): *Site Characterisation and Design Basis Report*, MA1001 ReDAPT MD6.1.