Recommendations for load validation of an offshore wind turbine with the use of statistical data: experience from alpha ventus

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Abstract. The present paper provides insight into the validation of computer models used for simulations of offshore wind turbines. The offshore turbines are affected environmental conditions that must be logged during the measurement campaign of the prototype and used for the simulations during the validation.

A simple generic methodology is presented to be used for the comparison of statistical data from the measurement campaign and the simulations. This allows a better analysis of the simulations and helps limit the apparition of outliers in the measurements.

An example of the use of the methodology is provided with the use of the data recorded for the AD5-116 5MW turbine at alpha ventus. For it the turbine power, operational parameters and blade and tower loads are compared.

1. Introduction

The design of an offshore wind turbine (OWEC) requires the simulation of various design load cases according to the IEC–61400–3 [1]. Once a design has been determined appropriate, a prototype can be built. The IEC-61400-13 Guideline - Measurement of Mechanical Loads [2] specifies how a measurement campaign of a full-scale wind turbine system is to be carried out and used as a basis for the validation of computer models, which is exemplified in a general procedure shown in appendix E of the guideline. Despite this, it is still unclear what constitutes a validated simulation model, and furthermore the IEC-61400-13 is based on onshore turbines, providing only a few recommendations for the offshore case.

Early research focused on the verification of the aeroelastic and hydrodynamic codes in projects like OC3 [3] and OC4 [4]. For these projects, a range of different simulation codes are compared to one another with the use of load cases varying in complexity.

The research community has also addressed the issue of computer model validation with measurement data. Zierath et al [5] have shown the validation of an offshore wind energy converter (OWEC) with respect to statistical load data as well as fatigue and fatigue load spectrum. Seidel et al [6] presented a time history comparison of simulation and measurements on the brace of a 5 MW jacket mounted turbine within the research project DOWNVInD. Kaufer [7] has contributed with the validation of an 5 MW offshore jacket mounted turbine by comparing loads on the jacket during a nacelle rotation, as well as frequency domain comparisons of the blade, tower and jacket sensors, and the statistical comparison of 10 minute simulations.

Regarding the general subject of validation, Söker et al. [7] provided a description of the possible comparisons needed between measured data and simulation, outlining important steps to help guide the validation engineer.

Despite these efforts, the question still arises, how to compare measured data from a turbine that is affected by a combination of stochastic meteorological and oceanographic parameters such as: wave height, wave period, wave direction, wind-wave misalignment, wind shear and turbulence intensity. The aim of this work is thus to provide insight regarding the proper validation of an OWEC computer model. The work will as well outline a methodology for the validation of a computational model, with the use of statistical data from a measurement campaign by screening the data that is chosen for comparison. To exemplify the methodology, a validation of the statistics from simulations of a 5 MW tripod mounted turbine installed at the alpha ventus wind park is carried out.

2. On the use of the IEC 61400-13 with regards to offshore model validation

The validation of a simulation model used in the design of a turbine should be carried out with different methods. The aim is that the results of the simulation model need to be accurate enough to be able to obtain a safe design. Söker et al. [8] mentions a number of validation steps which should be required to ensure a good agreement between measurements and model. This includes:

-Consistency of environmental conditions
-Consistency of turbine dynamic behaviour (frequencies)
-Consistency of turbine characteristic curves
-Consistency of behaviour of loads and operational parameters (time series and statistics)
-Consistency of fatigue characteristic behaviour

These validation steps require the analysis of the data in the frequency domain for certain time series, derivation of damage equivalent loads, load cycle spectrums, as well as comparison of statistical parameters such as the minimum, maximum, mean and standard deviation. The comparison of such data is also shortly mentioned in the Annex E of the IEC TS 61400- 13 [2]. These validation steps apply both to onshore and offshore structures. This paper will build on the idea of validation of the statistical data of the simulated load cases for an OWEC within normal power production.

The offshore environment and the complex array of support structures and foundations used by OWECs pose a challenge for a load measurement campaign. When considering the IEC TS 61400- 13 [2], there are several issues that are not discussed that would need to be taken into account for the validation of an OWEC. These include:

1. Hydrodynamic loading needs to be modelled. These parameters involve: waves conditions, wind and wave directionality, sea currents, and water level. The procedure with which one could include such parameters into the capture matrix of a measurement campaign is unclear.
2. Marine growth and scouring could play important roles on the loading of the offshore structure. A quantification of these parameters from the measurement campaign will be needed for the simulation model.
3. Calibration of strain gauges installed in the underwater structures is not possible for most of the cases due to the complexity of the structure (for example a tripod). This severely limits the possibility to compare the magnitude of the loads from simulations for the foundations.

The aforementioned issues have been taken into consideration as much as possible in the following sections, yet as mentioned, the calibration of the strain gauges at the underwater support structure of the modeled turbine was not successful and thus the results section of this paper doesn't show their comparison with the simulation model.

3. Validation of the statistical data

In an ideal measurement campaign, one would be able to know all the environmental parameters that are affecting the turbine during its operation and be able to reproduce these exactly in the simulation. The response of the real turbine and the simulation model could then be easily validated. In reality, we have to simplify these environmental parameters, say for example, generating an artificial wind field for computer simulations based on a mean hub height wind speed measured at a meteorological mast. Due to this fact, an exact time series of a loading signal from a simulation will not be the same as that from the one measured, yet it is still very important for the design and validation process that statistics, such as maximum loads and DELs, are representative of what is really happening to the turbine.

The next section concentrates on how this statistic validation can take place.

3.1. Modelling of the wind turbine in Flex5/Poseidon

The presented results are based on the measurement campaign carried out at the AD5-116 wind turbine from Adwen located in the offshore test field alpha ventus. The bottom fixed wind turbine, mounted on a tripod substructure, has a rated power of 5MW at a wind speed of 12.5 m/s, a rotor diameter of 116m and a hub height of 90m. The wind farm layout and the position of the investigated turbine AV7, which is extensively equipped with measurement devices, are shown in Figure 1. The measurement campaign at the offshore wind park alpha ventus provides statistical data for validation. The turbine is equipped with strain gauges at the tower base and blade root. High resolution 50 Hz data and 10 minute statistical SCADA data of the turbine is available, along with oceanographic and meteorological statistics from the Fino 1 research platform. The data used is taken for 13 months from 01-10-2010 to 31-10-2012.

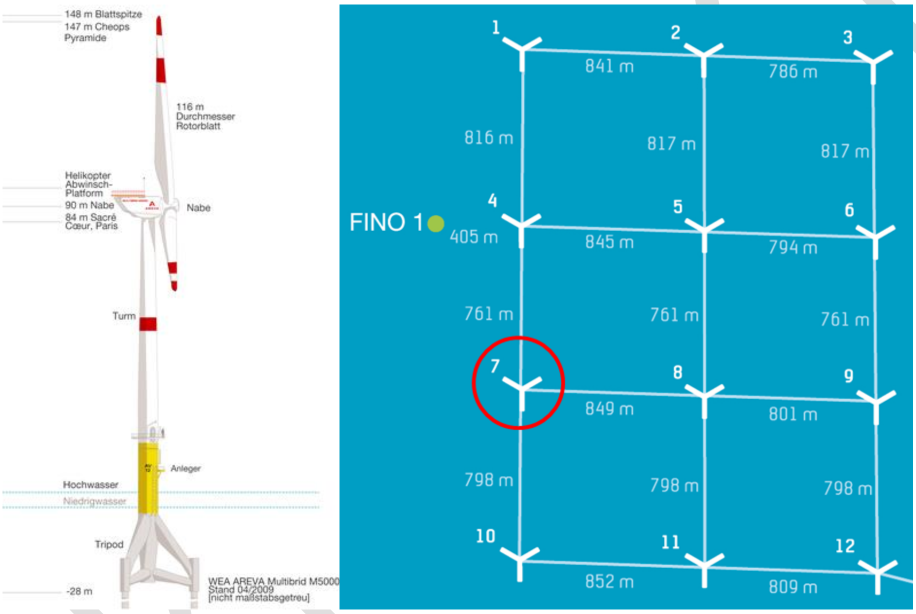

Figure 1: right- Wind farm layout of alpha ventus, left- Sketch of the 5 MW Adwen turbine at alpha ventus [9]

3.2. Modelling of the wind turbine in Flex5/Poseidon

The model data and controller of the 5MW turbine at alpha ventus are kindly made available by the turbine manufacturer, Adwen. For the simulation of the complete offshore wind turbine with substructure under the effects of hydrodynamic and aerodynamic loading, an integrated simulation environment was developed using Flex5 and Poseidon, which allows for a coupled simulation method, as exemplified by Kaufer [8]. The ability to use the coupled programs for OWECs simulations was shown in the OC3 project [2]. The rotor nacelle assembly and tower are simulated in Flex5 whereas the substructure and foundation are modelled in Poseidon.

The pile foundation is modeled as a spring damper at the three connection points of the tripod with the mudline. All tubular elements in Poseidon are modelled as Bernoulli beam elements with 6 degrees of freedom at each node.

For a ten minute simulation, 660 seconds are simulated and the first 60 seconds cut out to try to eliminate the effect of transients during start up. Turbulent wind fields are set up with VindSim. The three dimensional wind vectors at predefined nodes in a polar grid are saved in defined time intervals. This wind field describes the stochastic wind through the use of the Kaimal spectrum as proposed in

[11]. Waves have also been modelled in Poseidon. For it the Jonswap spectrum for waves is utilized, also as proposed in [1].

3.3. Data Screening Methodology

The goal of screening of data is to pick certain events and their measured statistics (from the ten minute time series), and reproduce them with the simulation model. Still, the use of statistics of the measurements from an offshore campaign poses a challenge due to the stochastic behaviour of the wind and wave parameters. The stochastics leads to large scattering of the data points along with the appearance of outliers as exemplified in Figure 2. Thus a comparison of simulation data with the measurements would be more meaningful if the wind and wave parameters have been appropriately chosen to be representative of the conditions simulated, and this is done through a data screening process.

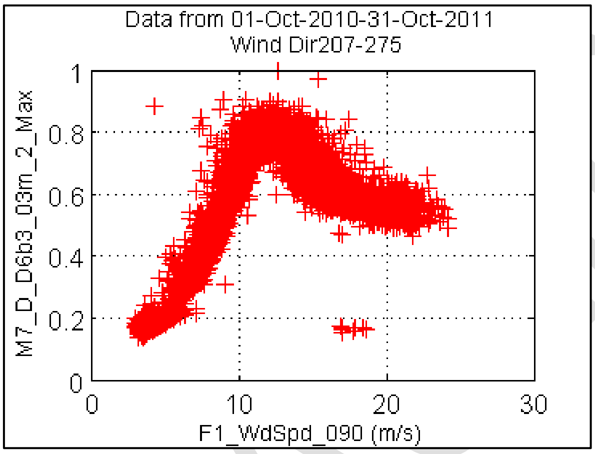

Figure 2: plot showing scattering and outlier in the maximum flapwise loads on the blade root

When screening the data, some parameters will be more important than others since they affect the loads to a greater extent, for example wind speed and turbulence intensity. Furthermore wave height and direction, along with wind/wave correlation and the wave spectrum should be reported by the measurement campaign and included in the screening.

For the validation engineer to be able to carry out the validation procedure of statistical data, the following methodology is recommended for the screening of the data:

1. List all meteorological and oceanographic parameters that are needed for the validation, along with other parameters such as marine growth thickness and density.
2. Define which parameters need to be binned. For example wind speed.
3. Define which parameters will be constrained. For example only data from 5-7% turbulence intensity
4. Define which parameters are, for the purpose of the validation, constants. For example marine growth thickness or mean sea level

Additionally, simulation parameters need to be set based on the filtering of the data. This can be done the following way:

1. Determine a mean value representative of the bin or constraint
2. In the case that a bin or constraint is large, there might be the need to divide the constrained parameter into several different mean values. For example, if the wind wave misalignment is filtered from +60 to -60 degrees, the simulated misalignment can be +45, 0 and -45 degrees.
3. Determine the amount of seeds that are appropriate for each simulation

Using this procedure, the alpha ventus data for the 5MW turbine is screened. An example of the selection and filtering of parameters can be found in Table 1. As is usual, the wind speed is binned.

Furthermore, as in Figure 3, the turbulence intensity is constrained to an area where most of the data points can be found. Similarly, the significant wave height is also plotted in Figure 3 as a function of the wind speed and therefore defined by a fitted curve. The constraint for the filtering is based on this fitted function. The different meteorological and oceanographic parameters would have to be similarly analysed.

After applying the screening of the data, a smaller data pool is obtained which better mirrors the simulated parameters to the measurements and helps limit the appearance of outliers in the data. The advantage of this procedure is that since the simulation parameters are now clearly defined, later it will be easier to compare these simulations with the measurements. This is due to the greater similarity between the simulated parameters and the actual environmental conditions.

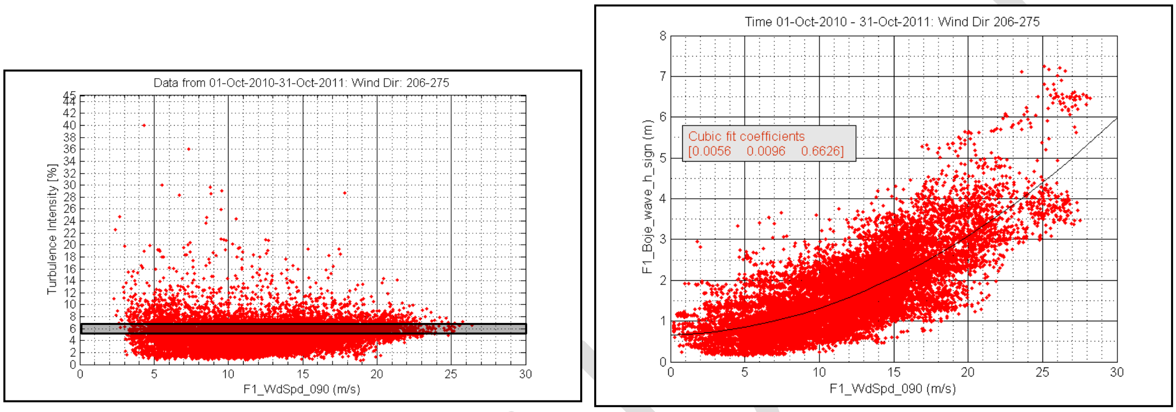

Figure 3: right- scatter plot of the measured turbulence intensity (%) in relation to the 90 meters, 10 minute averaged wind speed at Fino 1. The constraint for data filtering is shown by the shaded area, left -scatter plot of the measured significant wave height (m) in relation to the 90 meters, 10 minute averaged wind speed at Fino 1. The shown curve has been fitted to the data to establish a simulation value

As shown, the method of data filtering and conditioning is not fixed in this case but left open for the measurement and validation engineer due to other factors such as data availability and measurement errors. It also leaves the possibility for the measurement and validation engineer to investigate different effects on the simulation model. For instance, high turbulence intensities or the effects of yaw-wave misalignment could be picked.

Table 1: Meteorological and Oceanographic parameters

	Parameters	**Constraint or Binning**	**Values for data screening**	**Value for simulations**	**Seeds**
Wind condition	Wind direction	Free stream	207-275 degrees	270 degrees	-
	Mean hub wind speed	1m/s bins	3.5-23.5m/s	4-23m/s	-
	Turbulence intensity	Constrained	5.5%-6.5%	6%	9 turbulent seeds per wind bin
	Wind shear	Constant	none	0.14 power law exponent	-
Wave conditions	Significant wave height	Constrained as function of wind speed	Bin is defined as a function of the fitting curve. This gives the relationship between the significant wave height and the binned wind	For each wind speed bin, a significant wave height	-

			speed. The bin will be +/- 0.5 m of the fitted significant wave height value for a given wind speed	value is given by the best fit curve	
	Peak spectral period	Constrained	6-8 seconds	7 seconds	-
Wind and wave	Misalignment	Constrained	-30 to +30 degrees	-30,0, +30 degrees	3
Sea currents	Current velocity	Not binned or constrained.	None	0 m/s	-
	Direction	Not binned or constrained.	None	-	-
Water level	Mean sea level	Not binned or constrained	None	27m design basis	-
Air Properties	Density	Constant	None	1.225 kg/m^3	- -
Marine growth	Thickness	Constant	None	0.05 m	-
	Density	Constant	None	1325 kg/m^3	-
Wind/Yaw	Misalignment		None	-5,0,+5 degrees	3
Soil parameters	Scour	Constant	Not available	None	-
	Stiffness and Damping	Constant	Not available	Provided by manufacturer	-

4. Comparison of results from measurements and Simulations

To validate a computer model, different sensors or measured quantities have to be compared. Examples are shown in the following section. Here, the methodology for selection of data leads to a better representation of the measurements with simulation and thus higher certainty in the validation of the model.

Since 3 seeds for wind and wave misalignment as well as 3 seed for wind- yaw misalignment have been chosen, their combination leads to 9 different seeds per wind bin, and a total of 180 simulations. Simple statistical values such as the mean, minimum, maximum and standard deviation can be compared. As well, for the case of the loads, the damage equivalent loads (DEL) can be computed in order to get a better understanding of the fatigue loading of the simulations and measurements. The following equation has been used to calculate the DEL,

$$S_{r,eq} = \left(\sum_{i=1}^{n} \frac{S_{r,i}^{m}}{N_{eq}} \right)^{1/m}$$

where S_r is the range of a load cycle and $-1/m$ is the slope of the S-N line on log-log scale for the material of the measured component, N_{eq} is the number of equivalent cycles. This simplified equation does not carry a correction for the mean value of the load data.

4.1. Turbine characteristic curve

Before considering actual loads on the turbine, operational characteristics of the turbine, such as the power produced can be compared.

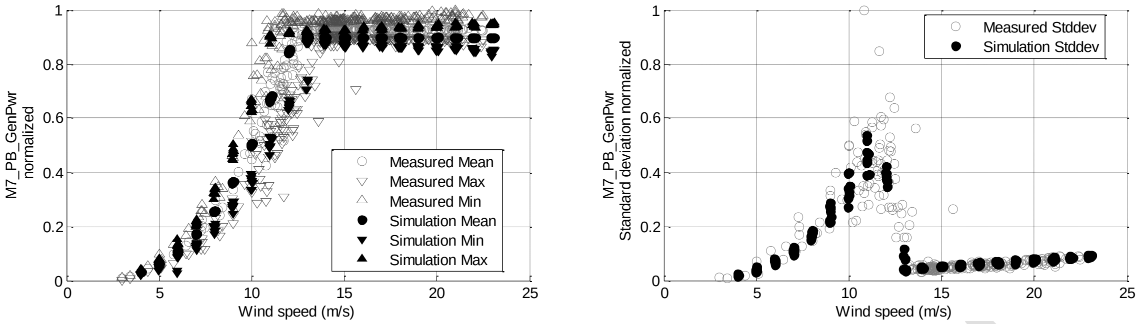

Figure 4: minimum, maximum and mean, right-standard deviation of the ten minute statistics for the power production

Figure 4-left shows good agreement in the simulations for the underrated region when compared to the measurements. Nevertheless, the simulations slightly under-predict the produced power for the region above rated. This can be explained due to the fact that the simulation model take into account further losses, which are not measured by the exact positioning of the sensor in the alpha ventus turbine since the measurement point is directly at the generator. On the other hand, the standard deviation of the 10 minute measured generator power seems to fit very well above the rated wind speed, while at around rated wind speed there seems to be larger scattering of the measured data meaning more fluctuations of the produced power.

4.2. Operational data

A good way of quickly checking the behaviour of the model is with the use of the operational parameters.

4.2.1. Generator Speed. The generator speed comparison shows the behaviour of the controller with regards to the wind speed.

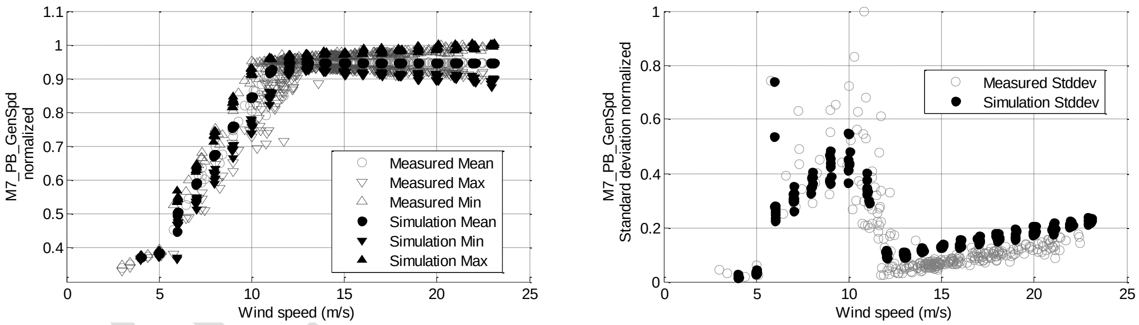

Figure 5: left-minimum, maximum and mean, right-standard deviation, of the ten minute statistics for the generator speed

The minimum, maximum and mean from the statistics in Figure 5-left show very good agreement. The standard deviation above rated shows however that the fluctuations in the rotor speed are higher for the simulations. Also, the transition region programmed into the controller which tries to avoid the first excitation frequency of the tower is visible in the 6m/s wind speed simulation bin. In this case the screening of the data is too thorough and therefore at low wind there are few data points available for comparison.

In this case the validation engineer might decide to change some of the screening criteria in order to obtain more data for analysis. As an example the screening of the peak spectral period has been, which in hindsight should not have a large effect on the rotational speed of the rotor, is removed for the data plotted in Figure **1**Figure 6. Here it is seen that the simulations do behave as the real turbine does at wind speeds around 6m/s.

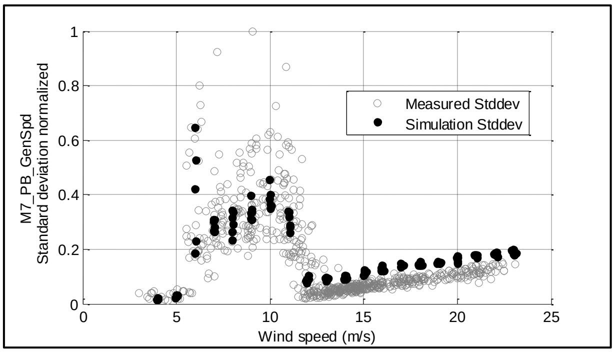

Figure 6: standard deviation of the ten minute statistics for the generator speed when wave spectral period screening criteria has been removed from the screening procedure

4.2.2. Pitch Angle. The pitch angle comparison also helps show the behaviour of the controller, especially at the region above rated wind speed. Figure 7 left shows again good agreement between measurements and simulations for the mean, minimum and maximums.

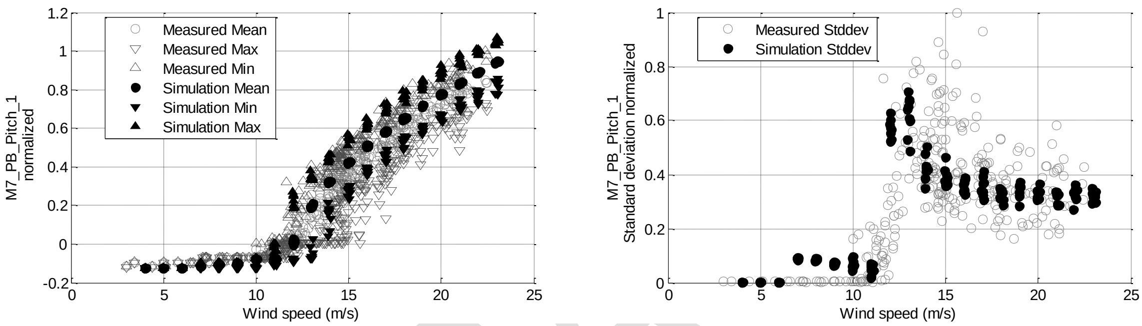

Figure 7: left- minimum, maximum and mean, right- standard deviation, of the ten minute statistics for the pitch of blade 1

When taking a look at the results from the standard deviation, it is apparent that the pitch activity of the real turbine has a slightly different behaviour than that given by the simulations. At around 7 m/s wind speed there is some small amounts of pitch activity in the simulations and above the rated wind speed the pitch activity of the real turbine can be more or less than that of the simulations. In this particular case, since the controller has been obtained by the manufacturer and is encrypted, a closer look at these results is not analysed.

4.3. Loads

The most important part of the whole validation process is to show that the loads of the simulations are representative of the real loads seen by the turbine.

4.3.1. Fore-aft bending moment. The thrust of the rotor plays an important role on the fore-aft loading. Also, the wave loading on the underwater structure influences the dynamics of the tower and substructure. Figure 8 shows that the simulations can reproduce the minimum, maximum and mean of the measurements very well, even though there is still some deviation at the region between 14-16 meters per second wind speed, which is clearly seen from the plot of the standard deviation.

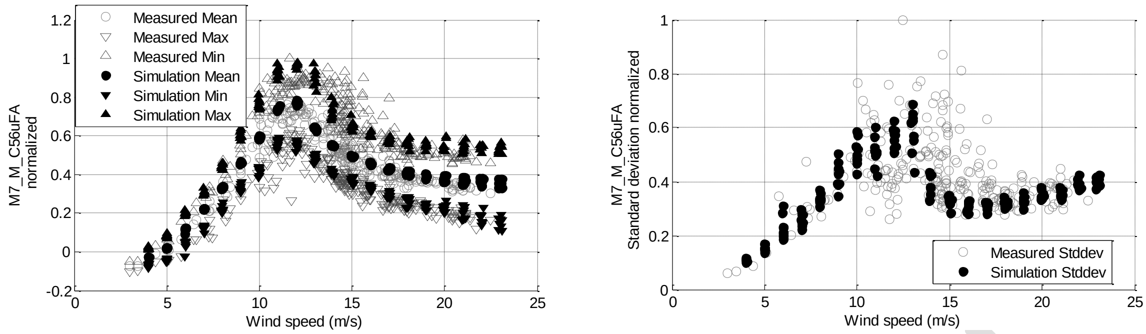

Figure 8: left- minimum, maximum and mean, right- standard deviation, of the ten minute statistics for the tower fore-aft bending moment

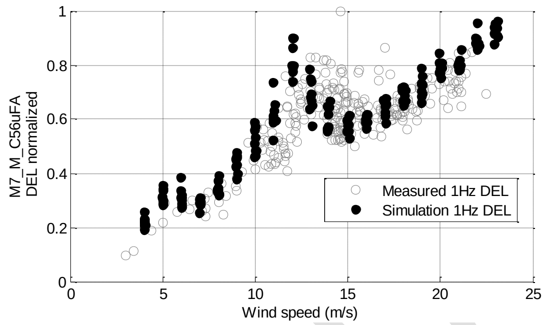

Figure 9: DEL of the ten minute statistics for the tower fore-aft bending moment

The damage equivalent load for the fore-aft bending moment of the tower seem to agree well, with a slight over prediction of the DEL at rated wind speed and an under-prediction for the 14-16 meter per second wind speeds.

4.3.2. Flapwise bending moment. The lift and drag caused by the aerodynamic profile of the blade influence the flapwise loading at the blade root. As the blade is pitched these force are changed and also the loading. Furthermore, turbulence also strongly influences the flapwise bending moment fluctuations.

The analysis of the flapwise bending moment shows the example of a situation where the validation engineer would have to carefully look at the simulation model to find the source of the discrepancies. In Figure 10- left there is a slight under-prediction of the statistics from the simulation at the region above rated wind speed, which could be linked to the slightly higher pitch angles of the simulations. The standard deviation also is over-predicted and does not show the scattering that is obtained in the measurements. This is also mirrored in the DELs, where the simulations cannot reproduce the scatter of the measurements in Figure 10-right.

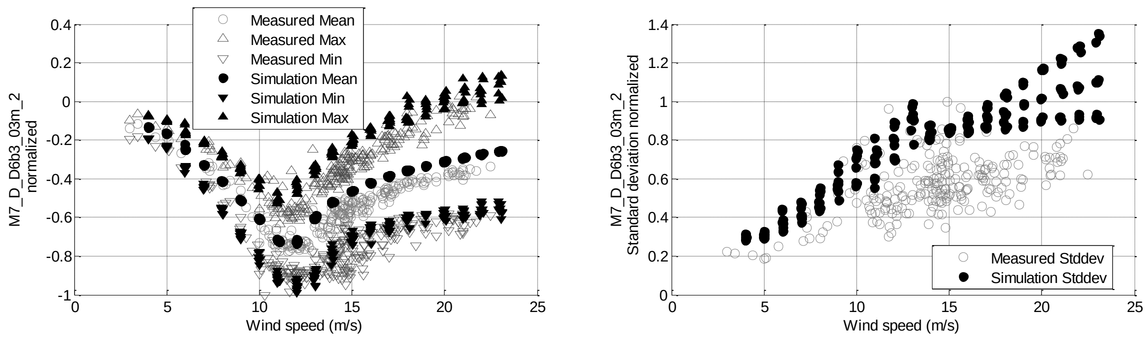

Figure 10: left - minimum, maximum and mean, right- standard deviation, of the ten minute statistics for the flapwise root bending moment

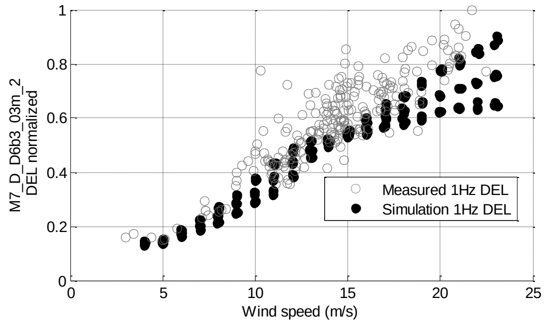

Figure 11: DEL of the ten minute statistics for the flapwise root bending moment

5. Conclusions

Model validation of offshore wind turbines presents specific challenges which have to be addressed. Oceanographic parameters add complexity to the loading of the turbines and need to be properly modelled by the simulations tools. The work thus described the necessary meteorological and oceanographic parameters that are needed from an offshore measurement campaign. These are then used to implement a methodology of data screening for the statistical comparison of measurements and simulations. The methodology is shown to be helpful to define the simulation parameters that will be used and limits the influence of measured outliers as well as limits the spreading of the measured data created by the stochastic environment. The methodology itself is a flexible procedure since not all offshore turbines prototypes will be the same, and their measurement campaigns will not capture the same environmental conditions since these vary from location to location.

The Flex5-Poseidon coupled model of the alpha ventus 5 MW tripod mounted turbine agrees well with the measurement data, and serves as an example of the use of the methodology. The process thus shows how better management of the available data and data screening helps improve the validation process. The plotting of the screened statistics from the turbine data help the validation engineer determines the strengths and weaknesses of the simulation model.

6. Acknowledgments

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