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Relative assessment of fatigue loads for offshore wind turbine support structures

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Abstract

Time domain analyses of Offshore Wind Turbines involve a lot of computational effort. In this paper, we present a method for reducing this effort by using results from analyses with shorter simulation lengths to predict the results of the longer simulations lengths required by the standards. This involves using simple statistical treatment of the first 10 minutes of simulation data, and a subsequent linear regression, to predict the damage equivalent load of the full 60 minutes simulation. With some reservations about the general applicability of the method, the results are promising. Some suggestions for further investigations and developments of the presented methods are discussed.

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Keywords: Offshore wind turbines; jacket support structure, fatigue, prediction

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1. Introduction

Reduction of computational effort is one of the major challenges for the analysis of offshore wind turbines (OWTs) in the time domain. Standards [1,2] require simulation lengths of at least 60 minutes, for fatigue estimation (there are other requirements for estimation of extreme values), for each load case and a large amount of such load cases are usually necessary for the certification of an OWT. This makes the investigation of OWTs using a fully integrated aero-servo-hydro-elastic model very time consuming and computationally demanding. In particular, design optimization (see [3] for a review), where each iteration potentially requires new simulations, becomes very

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inefficient. While better hardware can be of great help, finding a solution where the software is more efficiently utilized would be preferable. Consequently, improving the efficiency of these analyses is a primary concern and important for the future success of OWTs.

One way to manage the issues caused by long computation times would be to somehow decrease the required simulation length for a load case. One common alternative is frequency domain methods. These methods are very fast, but, for fatigue estimation, lack the accuracy of the usual time domain methods [4]. It is hence desirable to find methods that maintain a higher level of accuracy, while being significantly faster than a 60 minute time domain analysis. To this end, we propose a method that uses simulations of shorter length to approximate the assessment of the fatigue limit state. Specifically, we have investigated using simulation lengths of 10 minutes rather than the standard 60 minutes. Damage equivalent loads (DELs) are calculated by using a fairly simple statistical treatment of the shorter data segments and a linear regression model. In this way, a shorter load case can be used for predicting for the DEL that would have been estimated from a 60 minute analysis.

The details of the proposed method are presented below, followed by a summary of its strengths and limitations. A discussion of the overall viability of the method and recommendations for further study is presented at the end.

2. Simulation setup and prediction methods

For the simulations carried out in this study, we used an OWT model consisting of the UpWind reference jacket from the OC4 project [5], together with the NREL 5MW turbine [6]. In this model, the jacket has four slightly inclined legs and four levels of X-braces. The transition piece between the tower and the jacket is a modelled as a concrete block and the jacket is modelled clamped at the seabed. For the time domain simulation itself, the simulation tool Fedem Windpower (Version R7.0.4 Fedem Technology AS, Trondheim) [7] was used. The environmental conditions are turbulent wind and an irregular sea state. The turbulent wind is based on the IEC Kaimal model and is generated using Turbsim [8]. The irregular sea state is generated from the Pierson-Moskowitz sea wave spectrum using Fedem. For each wind speed, the lumped scatter diagrams from the K13 Deep Water Site [9] were used to set the values for the significant wave height and peak wave period. The water depth is 50 m. Additionally, parameters like wind shear and marine growth are present, but are kept constant. With this OWT model and these environmental conditions as input, Fedem was run with a typical time step of 0.025 seconds to produce load cases with simulation lengths of 60 minutes after the removal of initial transients.

In order to assess the fatigue limit state, the DEL with a reference number of $6.3 \cdot 10^8$ cycles was calculated for a large selection of members throughout the jacket. This analysis uses a rainflow counting algorithm [10] to extract the number of cycles for constant load ranges from the time history response of axial member forces. Linear summation by the Palmgren-Miner rule is then used to calculate the accumulated damage. A negative inverse slope of the SN-curve of m = 3 was used to match the properties of welded steel. In summary, the following expression is used to calculate the DEL:

$$\mathrm{DEL} = \left(\frac{\sum_i n_i F_i^m}{N_{eq}} \right)^{1/m} \tag{1}$$

Where n_i is the number of cycles in load range i, F_i is the value of load range i, and N_{eq} is the reference number of cycles.

For each load case, the DEL of a 60 minutes simulation was calculated to serve as a reference, or “true”, value for the prediction methods. Each of the methods investigated represents a different scheme for utilizing the first 10 minutes of simulation time to predict what the 60 minute simulation would yield. In total four different schemes were used. In all the schemes, the DEL for two or more subintervals was calculated. Then, the possibility of a power law relation between DEL and simulation time was investigated by a logarithmic transformation of both quantities. A subsequent linear regression analysis led to an extrapolated value for the DEL at 60 minutes. Specifically, the following linear relationship between the logarithm of the DEL and the logarithm of the simulation length was established:

$$\log_{10}(\mathrm{DEL}) = a \cdot \log_{10}(t) + b \tag{2}$$

Where t is the simulation length and a and b are parameters determined by a linear regression of the shorter segment (10 minutes or less) DEL values. While the values for a and b are different for each element, this is a simple post processing task which still saves time compared to doing the actual 60 minute analysis. A prediction at 60 minutes (or $t = 3600$) for the DEL can then be extrapolated from this relation. It is important to note the difference between this approach and a more straightforward scaling of the DEL after 10 minutes. The latter case would simply mean that the DEL after 10 minutes is assumed to be representative of the entire stochastic process and that a value for a longer simulation length could be obtained by multiplying with the ratio of the two lengths. That is, the DEL at 60 minutes would be six times the DEL at 10 minutes. If this were the case, then the standard 60 minute simulation length would not be necessary at all. In general, such a scaling is assumed when extrapolating the damage for a period close to the lifetime of the OWT, e.g., 20 years. The assumption being that 60 minutes is a sufficient simulation length for such a scaling, but that 10 minutes is not. The methods presented here operate under this assumption. Another way to analyze the problem would be to scale the DEL of each segment up to 60 minutes in the simplified manner and then model the deviation. This makes sense since the difference between the DEL of the shorter segments and the DEL at 60 minutes can be split into two parts: A simple scaling with time and the correction for the bias caused by using a simulation length that is too short to be representative. In the methods used in this study, both of these aspects are instead combined into the (logarithmic) linear relationship to be found.

In addition to creating a bias, there are other potential issues with using shorter time series. Firstly, there is a possibility that some of the smaller frequencies may not be resolved. If important modes are not captured in the first 10 minutes, then they would not be included in the prediction for 60 minutes. Secondly, there is the chance that the shorter simulation time is unable to capture sufficient information about wave loading. However, for fatigue loading of jackets the wave loads have been shown to be of lesser importance [11]. A third issue is the variance caused by different seeds. While important for wind, this has also been shown to be less of an issue for the wave loading [12]. In general, the idea is that, while the above issues could cause some amount of error in the predictions, the method presented in this paper is able to use the information obtained in the first 10 minutes to yield reasonable estimates. In particular, the method is an attempt to handle exactly these kinds of challenges.

The four schemes are as follows: The first simply uses the DEL calculated after the first 5 and 10 minutes, referred to as DEL5 and DEL10, respectively. The second scheme divides the first 10 minutes into five non-overlapping segments of 2 minutes each and then uses the mean of these (5DEL2) together with DEL10 to determine a regression line. The third method divides the first 10 minutes into two non-overlapping segments of 5 minutes each and uses the mean of these (2DEL5) in conjunction with DEL10. Finally, the fourth scheme combines 5DEL2, 2DEL5 and DEL10. A summary of the four different methods and their descriptions is shown in Table 1. The idea of the latter three methods is to reduce the inherent bias in using only the first 10 minutes by averaging subsets of this segment, thereby including more of the variability from the environmental processes in the regression analysis. The underlying assumption is that it is possible to extrapolate from local (2, 5 and 10 minutes) to global (60 minutes) behavior. The fourth method tries to gain an additional advantage by using a third point in the regression. The overall intention of this procedure is to investigate whether simple statistical treatment of a subset of the 60 minute time series can yield a sufficiently accurate prediction for the behavior of the complete time series.

To verify the applicability of these methods, four different wind speeds (8 m/s, 12 m/s, 18 m/s and 22 m/s), with corresponding significant wave height (1.31, 1.7, 2.47, 3.09) and peak period (5.67, 5.88, 6.71, 7.4), were used as input. Furthermore, two additional models for the jacket were considered, in order to study how the method generalizes to an assessment of related designs. In these models all outer diameter of legs and braces were increased by 10% and 20%, respectively, compared to the base OC4 model, while the thickness was held constant.

Table 1: Prediction schemes.

Names	Description
PS1	DEL5 + DEL10
PS2	5DEL2 + DEL10
PS3	2DEL5 + DEL10
PS4	5DEL2 + 2DEL5 + DEL10

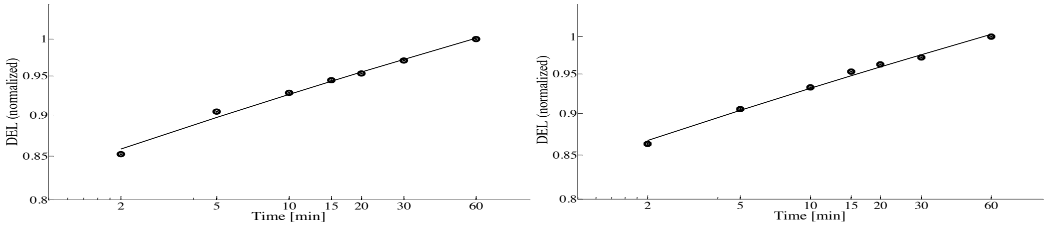

Figure 1: Left: Normalized damage equivalent load (DEL) for axial force in a brace at water level, wind speed 12 m/s. Right: Results for axial force in a leg at lowest level, wind speed 8 m/s.

3. Results

Initially, a straightforward analysis of the time dependence of the DEL was performed. This was done in order to verify that the assumed power law behavior, required by the logarithmic linear regression, was valid. Some results from this analysis are shown in Figure 1. All locations in the jacket and all wind speeds show a similar linear behavior after a logarithmic transform, with a coefficient of determination (R^2 value) for the linear regression very close to the maximum value of 1. There does not seem to be any pattern in how the slope changes for different locations and wind speeds. Consequently, it does not seem possible to identify any general behavior for the jacket members from this, other than that the assumption of power law behavior holds. It should be noted that this analysis includes DEL values calculated from much longer time segments (15, 20 and 30 minutes) than that which is used in the four different prediction schemes. It is therefore no indication of the overall performance of the prediction schemes. The analysis simply confirms that the main ideas of the methods make sense. From this, it would also seem that simply scaling DEL10 by six to estimate DEL60 would not work very well. Since in that case the relationship between DEL and simulation length would be linear rather than a power law. Indeed, comparing such an estimate with the true DEL60 value gives an error of more than 200% for all cases. This is because the assumption of such a purely linear relation consistently overestimates the actual value, since the actual evolution with time flattens out to an extent which is far below a straight line.

An example of the first prediction scheme applied to six different stochastic representations of the wind speed for a brace at water level is shown on the left in Figure 2. Evidently, this scheme struggles to make an accurate prediction. Not only do all six predictions miss the region covered by the true values, the scatter for these predictions is quite large compared to the scatter in the true values. In other words, the variability in the result caused by different realizations of the turbulent wind is greatly amplified when trying to predict the DEL calculated for the entire 60 minute segment (DEL60) with method PS1. The second scheme, PS2, applied to the same setup is shown on the right in Figure 2. Already, this is a clear improvement on the first method. Not only are the predictions fairly close to the true DEL60 values, the scatter in the predictions is also significantly lower, if not quite as low as the scatter in the true DEL60.

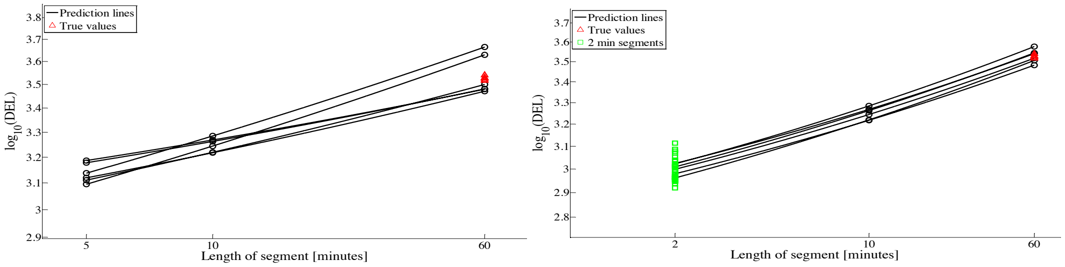

Figure 2: Calculated and predicted damage equivalent loads (DEL) for six different stochastic realizations of the wind speed, for axial forces in a brace at water level, 8 m/s wind speed. Left: Prediction method PS1. Right: Prediction method PS2.

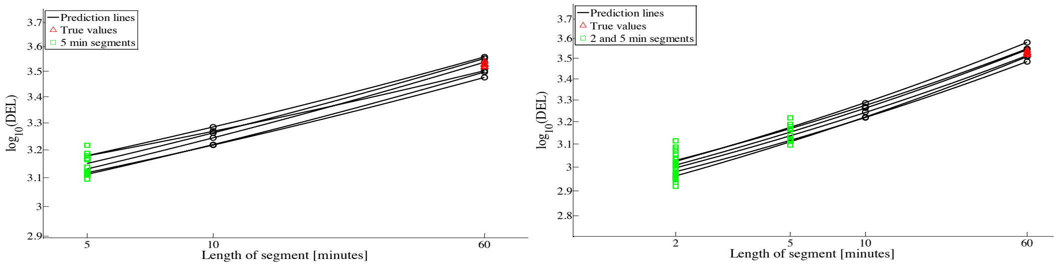

Figure 3: Left: Prediction method PS3, same setup as in Figure 2. Right: Prediction method PS4.

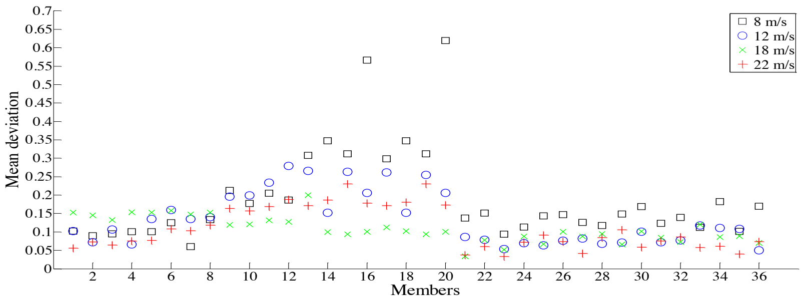

Figure 4: Mean deviation from true values, for prediction method PS1. Legs are members no. 1-20, braces are members no. 21-36. Vertical position is increasing from left to right.

In Figure 3, similar performance is shown for schemes PS3 and PS4. Though the latter three methods significantly outperform the first, it is difficult to explicitly rank their performance against each other. An important result to note here is that there seems to be no consistent bias in any of the prediction schemes. That is, they do not consistently under- or overestimate the true value. An explanation for this might be that the average loading that occurs during the first 10 minutes can be both higher and lower than the loading that is characteristic for the whole simulation.

To quantify this last point a bit more, the mean deviation of the predictions from the true DEL60 values was calculated for all members and wind speeds. This is shown in Figures 4-6. These results also give some insight into the overall accuracy of the prediction schemes. They essentially show the expected error for the various schemes. Again, it is clear that PS2-PS4 are much more accurate than PS1.

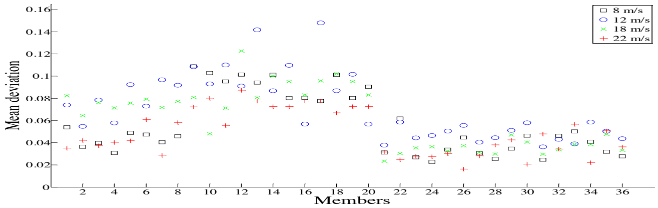

Figure 5: Mean deviation from true values, for prediction method PS2. Legs are members no. 1-20, braces are members no. 21-36. Vertical position is increasing from left to right.

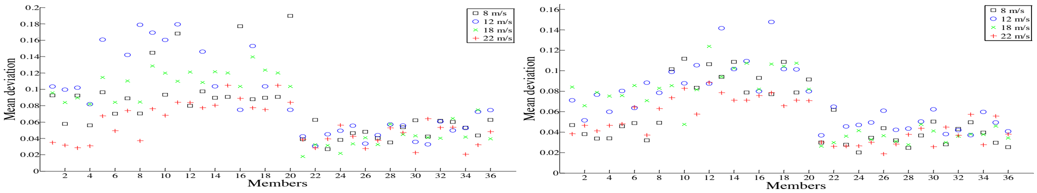

Figure 6: Mean deviation, prediction method PS3 (left) and prediction method PS4 (right).

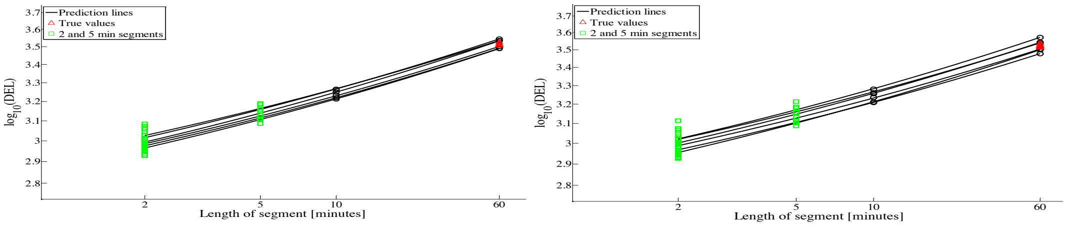

Figure 7: PS4, same setup as in Figures 2-3. Left: All member outer diameters increased by 10%. Right: All member outer diameters increased by 20%.

There are two notable effects. Firstly, for schemes PS2-PS4 the accuracy is higher for the braces than for the legs. An explanation for this could be that the legs, being the primary load carrier of the turbine, are more sensitive to variations in the loading from the turbine. The second effect to note is that, for the legs, there is an increase in inaccuracy as one moves upwards in the jacket. One possible cause for this is the fact that only higher positions in the jacket feel the impact of wave loading directly. Another cause could be that since the legs at the bottom of the jacket carries the weight of the entire structure, the mean loading amplitude here is higher. This means that the impact of variations in the loading is smaller for the legs at the bottom than the ones higher up in the structure, though it is hard to quantify this exactly.

Finally, the two models with changed outer diameter for all members were investigated. Results for the scheme PS4 are shown in Figure 7 and Figure 8. There appears to be no significant difference in behavior for either of the two changed models when compared with the original model. This is also true for the other methods. Additionally, by assuming the prediction error to be constant when changing the diameter, corrected predictions for the two changed models could be found based on the results for the base model. Averaging over all elements, this yields an improvement of about 40% (more than 50% for the braces only). Some numerical values for the brace at waterline is summarized in Table 2. One additional fact shown here is the high variance in the prediction compared with the actual variance caused by different seeds.

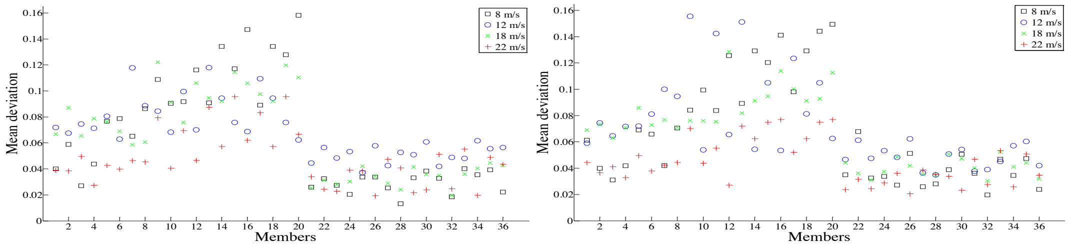

Figure 8: Mean deviation, PS4, 10 % increased outer diameter (left) and 20 % increased outer diameter (right).

Table 2: Selected results for brace at water level, wind speed 22 m/s, using different prediction schemes and models.

Model, scheme	True mean [N]	Predicted mean [N]	Coefficient of variation true (%)	Coefficient of variation predicted (%)	Mean deviation (% of true value)
Base model, simple scaling of DEL10	5806	18683	0.8	1.0	222
Base model, PS1	5806	5974	0.8	6.9	5.8
Base model, PS2	5806	5849	0.8	2.6	2.1
Base model, PS3	5806	5827	0.8	2.4	2.3
Base mode, PS4	5806	5854	0.8	3.2	2.6
10% increased outer diameter, PS4	5911	6011	1.1	2.4	2.4
20% increased outer diameter, PS4	5684	5710	0.8	2.8	2.3
10% increase, PS4, corrected	5911	5963	1.1	1.8	1.8
20% increase, PS4, corrected	5684	5663	0.8	1.1	0.8

4. Discussion

In general, the results show that with a fairly simple procedure, reasonably accurate predictions can be made for the fatigue damage of the jacket without the need to run the simulation length required by the standard. However, there are limitations on the accuracy of the approach, especially for the legs, and there is a significantly increased variance compared with the variation caused by different seeds alone. The question then becomes how useful this procedure is and how and where it can be applied. In terms of a full analysis of the jacket, there is little applicability if only the braces can be handled with sufficient accuracy, since an assessment of all jacket members is usually needed. Therefore, in this case only a very preliminary analysis, possibly as part of an optimization procedure where high accuracy is not required, can be performed. An aspect which make these methods very suitable in an optimization context is the stability with respect to changes in the structure. The fact that this does not seem to have a significant effect on the accuracy of the predictions, and the possibility of using this to correct the predictions by using information from a more thorough analysis of an initial model, should be noted.

Care should be taken such that the level of accuracy required matches the application. For the braces the error seems to be 6-5 % or less. Whereas for the legs the error can be as much as 16 %. If such errors are acceptable in a given context, the methods presented herein should be very suitable to speed up the analysis in question.

One interesting result of this study is that there seems to be such little difference between the accuracy of schemes PS2, PS3 and PS4. In fact, schemes PS2 and PS4 are remarkably similar and cannot really be distinguished when displayed here. The choice between the other three schemes then becomes a matter of convenience.

Finally, there are aspects of the presented framework that have not been explored in this study. For example, only the axial force DEL has been considered in this analysis. It would be interesting to see whether the in- and out-of-plane bending moment behave in a similar way. Secondly, there are other ways in which the stability of the methods with respect to structural changes could be tested. One might decrease the outer diameters in similar ways as they have been increased here, though that should not have a significant effect on the accuracy. More interestingly, one might make changes in a non-uniform manner and see if the predictions remain equally stable. Since the systematic changes do not affect the accuracy of the prediction schemes, one would expect the same behavior for the non-uniform changes. This is because the eigenfrequencies do not change significantly when such non-uniform changes are made, while they do change significantly when the changes are made systematically. However, this expectation should be verified. Exploring some or all of these remaining issues could be an interesting future endeavor.

5. Conclusion

In this paper, we have presented a way to speed up the assessment of the fatigue limit state of OWTs in the time domain. The method is based on simple statistical treatment of the first 10 minutes and linear regression and extrapolation to 60 minutes. The results are promising, though there are certain limitations on the accuracy for the lower wind speeds and the leg elements. While the method as it is can be used for certain investigations, further work exploring robustness and optimal segment length is required before an overall recommendation can be made.

Acknowledgments

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