Predicting Ultimate Loads for Wind Turbine Design

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NOTICE

PREDICTING ULTIMATE LOADS FOR WIND TURBINE DESIGN

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ABSTRACT

This paper addresses the statistical uncertainty of loads prediction using structural dynamics simulation codes and the requirements for the number and duration of simulations for obtaining robust load estimates. Substantial statistical variation is observed in loads data and a statistical model that enables extrapolation and determination of quantiles is presented. Further reduction in the numerical work necessary to determine extreme loads with an acceptable uncertainty is possible using a stochastic process model for the dynamic responses. A procedure allowing for a slightly non-Gaussian response is proposed and satisfactory accuracy is found. Finally, the extreme loads from the revised IEC 61400-1 wind turbine standard on safety requirements are calculated for the turbine, and loads from the gust models and the properly extrapolated simulation extremes are compared.

INTRODUCTION

In general the verification of a wind turbine design comprises investigation of the strength with regard to both fatigue loads and ultimate loads. For several components the design is limited by ultimate loading. Ultimate loading may arise from extreme situations such as extreme wind speeds with a parked rotor, at lower wind speeds during operation where the effect of gusty wind is combined with a significant periodic response, or special events such as start-up, shutdown, or during yawing.

The concept of ultimate loads from extreme wind is very similar to the traditional approach to wind loading adopted in codes for wind action on structures, e.g., ISO 4354.[1] This approach was established by Davenport[2] and was applied to wind turbines in Madsen.[3] This statistical approach forms the basis for the Danish wind turbine design standard.[4] However, in recent years aero-elastic time-domain load prediction codes have been developed and verified, and are now widely used by the industry. These codes are used not only for calculation of operational loads but also for extreme wind loads.

Present design practices and recognized standards for wind turbine loads and safety, e.g., IEC 61400-1,[5] require ultimate loads from the fluctuating wind to be predicted using both discrete gust models and advanced simulations of the 3-D stochastic turbulent wind field as input to comprehensive aero-elastic models. Whereas the gust models give reproducible results, they are a coarse representation of the wind, and are furthermore difficult to adjust to the actual site and wind turbine. On the other hand, simulations using accurate and validated comprehensive turbulence and structural dynamics codes give realistic results but share the difficulties in defining the ultimate load for design with actual full-scale load measurements. The stochastic nature of the turbulent wind input causes the calculated extreme loads to be random quantities with significant variation. Thus, one response simulation will give one realization of the stochastic load extreme, a value furthermore associated with the duration of the simulation rather than of the wind turbine design situation.

Using codes for the aero-elastic response and turbulence developed at Risø, Thomsen et al.[6] investigated the estimation of extreme loads with reference to two load cases from the Danish wind turbine design standard. While the analysis was limited to the flap-wise blade bending moment, a considerable variation in the largest load value was observed, and predicting the mean extreme using the extreme value distribution from a Gaussian process derived by Davenport[7] had some success in terms of less variation.

The present work continues this effort using different models to calculate the primary loads for a different wind turbine. The load cases are chosen with reference to the IEC 61400-1 load cases and focuses on the loads on the parked wind turbine at the extreme wind speed and on the running wind turbine at rated and cut-out wind speed. Additional details can be found in Madsen et al.[8]

THE WIND TURBINE MODEL

For this study a model of the NREL/NWTC Unsteady Aerodynamics Experiment Phase III turbine was used, see Figure 1. The turbine has a rotor diameter of 10 m and nominal rotor speed of 72 rpm. It is a three bladed turbine with a hub height of 17 m and operates in free yaw downwind of the tower. The dimensions, frequencies, and other properties of the turbine are described in detail in Schepers et al.[9] The commercially

Figure 1. National Renewable Energy Laboratory/National Wind Technology Center Unsteady Aerodynamics Experiment Phase III wind turbine

Table 1. Load Cases

Design situation - Load case	Wind speed (10 min aver.)	Power law exponent α	Target turb. intensity I_u*	Reference height
Operation at rated wind speed	14 m/s	0.2	17 %	16.8 m
Operation at cut-out wind speed	20 m/s	0.2	17 %	16.8 m
Parked at extreme wind speed	45 m/s	0.2	17 %	16.8 m

*longitudinal turbulence component

available ADAMS® code linked with the AeroDyn aerodynamic subroutines[10] was used for all simulations.

The ADAMS model was developed from extensive modal tests and system component weights. Modal tests and component weighing were performed for individual components and assemblies. Modal tests were performed on the instrumented blade, one uninstrumented blade, the tower alone, and the nacelle-tower assembly. The nacelle was weighed and the inertia properties were determined from a bi-filar pendulum test. The blades were weighed to determine mass and center of gravity location. The ADAMS model was tuned to match the measured masses, center of masses, and frequencies in the same configurations used in modal tests. The model has 177 degrees of freedom. Six twisted tapered beam elements and one standard beam element model each blade. The tower is modeled with eight beam elements. Other degrees of freedom include the rotor rotational degree of freedom, low speed shaft torsion, and yaw. Nonlinear forces model the tower guy wires. The torque speed relation of the generator was determined from measured data.

The model used in this study is thus considered well validated and is expected to give realistic load predictions.

LOAD CALCULATIONS

In this study two design conditions of the IEC 61400-1 have been considered:

- Power Production
- Parked (standing still or idling).

During the Power Production design condition the wind turbine was modeled as operating in its natural mode, i.e., free yaw and a nearly constant rotation speed of 72 rpm (with small variations due to the generator slip).

Similarly for the Parked design situation the wind turbine was modeled realistically with free yaw and a fixed rotor with blade #1 pointing vertically upwards.

The wind input for the design situations is summarized in Table 1. While the load cases correspond to Design Load Case 1.1 and 6.1 in IEC 61400-1, the wind input is not related to a specific wind turbine class. The wind during the parked situation is modeled as being turbulent at a given mean wind speed rather than by a constant extreme wind.

In all load cases the Kaimal spectral model for the three-dimensional wind turbulence given in IEC 61400-1 annex B has been used. This includes the value for coherence decrements, ratio between velocity component standard deviations, and integral length scales.

Other parameters such as the power law exponent during the parked situation and the turbulence level were given by the turbulence simulation tool and could not be changed without rewriting the code.

For each of the load cases 100 simulation runs were performed. Each simulation had a duration of 610 seconds, of which the first 10 seconds were excluded to eliminate start-up transients.

The following primary signals and loads were retained for further analysis (the wind speed was kept only as a reference):

- Wind speed in m/s   WindSpd
- Blade root out-of-plane bending moment   B1_Moop
- Blade root in-plane bending moment   B1_Mip
- Yaw bearing force in longitudinal direction (thrust)   YB_Fdw
- Yaw bearing force in lateral direction   YB_Fcw
- Yaw bearing pitching moment   YB_Mpitch
- Yaw bearing rolling moment   YB_Mroll

The main statistics of the load calculations are summarized in Tables 2, 3, and 4. The mean, standard deviation, and coefficient of variation (COV) are listed for these main statistical parameters.

Table 2. Statistics – Power Production at 14 m/s

Run statistics		WindSpd m/s	B1_Moop kNm	B1_Mip KNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Mean	Mean	14.10	0.86	0.74	2.35	-0.04	-3.09	-2.89
	St.dev	0.027	0.004	0.004	0.004	0.002	0.017	0.012
	COV	0.2%	0.5%	0.5%	0.2%	-6.2%	-0.6%	-0.4%
Stand Deviat.	Mean	2.18	0.65	0.92	0.50	0.16	1.27	0.32
	St.dev	0.052	0.016	0.002	0.019	0.006	0.046	0.016
	COV	2.4%	2.4%	0.2%	3.8%	3.7%	3.6%	5.2%
Mean cross. freq.	Mean	0.43	3.20	1.28	2.43	2.13	2.37	1.12
	St.dev	0.031	0.053	0.012	0.039	0.022	0.086	0.050
	COV	7.3%	1.6%	0.9%	1.6%	1.0%	3.6%	4.4%
Skewness	Mean	0.14	0.05	0.03	-0.02	0.10	-0.04	0.65
	St.dev	0.159	0.032	0.003	0.069	0.055	0.091	0.320
	COV	114.2%	62.1%	13.1%	-301.7%	56.4%	-237.8%	49.1%
Abs. Maxi-mum	Mean	21.79	4.02	2.91	4.43	0.74	8.48	3.90
	St.dev	0.873	0.330	0.109	0.202	0.105	0.576	0.094
	COV	4.0%	8.2%	3.8%	4.6%	14.1%	6.8%	2.4%

Table 3. Statistics – Power Production at 20 m/s

Run statisticss		WindSpd m/s	B1_Moop kNm	B1_Mip KNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Mean	Mean	20.14	1.25	0.81	2.88	-0.04	-3.50	-3.20
	St.dev	0.035	0.005	0.003	0.006	0.002	0.013	0.012
	COV	0.2%	0.4%	0.4%	0.2%	-4.4%	-0.4%	-0.4%
Stand. Deviat.	Mean	3.11	0.82	0.94	0.79	0.22	1.571	0.53
	St.dev	0.062	0.020	0.002	0.030	0.011	0.057	0.011
	COV	2.0%	2.4%	0.2%	3.8%	4.9%	3.6%	2.0%
Mean cross. freq.	Mean	0.51	3.20	1.40	2.15	2.18	2.53	0.79
	St.dev	0.035	0.053	0.020	0.031	0.018	0.071	0.037
	COV	6.9%	1.6%	1.4%	1.4%	0.8%	2.8%	4.7%
Skewness	Mean	0.137	0.01	0.01	0.79	0.22	0.05	-0.53
	St.dev	0.131	0.046	0.005	0.030	0.011	0.084	0.088
	COV	0.960	466.8%	35.6%	3.8%	4.9%	158.0%	-16.8%
Abs. Maxi-mum	Mean	31.43	5.14	3.35	6.21	1.10	10.23	5.24
	St.dev	1.259	0.498	0.160	0.379	0.161	0.821	0.223
	COV	4.0%	9.7%	4.8%	6.1%	14.7%	8.0%	4.2%

Table 4. Statistics – Parked at 45 m/s

Run statistics		WindSpd m/s	B1_Moop KNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Mean	Mean	45.31	7.90	1.40	8.36	-0.07	-7.86	-5.39
	St.dev	0.061	0.020	0.003	0.022	0.001	0.017	0.012
	COV	0.1%	0.2%	0.2%	0.3%	-1.1%	-0.2%	-0.2%
Stand. Deviat.	Mean	6.99	2.61	0.65	3.89	0.69	3.82	1.59
	St.dev	0.088	0.031	0.005	0.084	0.021	0.073	0.019
	COV	1.3%	1.2%	0.7%	2.2%	3.1%	1.9%	1.2%
Mean cross. freq.	Mean	0.77	1.78	4.48	1.67	2.24	2.21	1.18
	St.dev	0.035	0.053	0.058	0.033	0.017	0.037	0.032
	COV	4.6%	3.0%	1.3%	2.0%	0.8%	1.7%	2.7%
Skewness	Mean	0.13	0.32	0.17	0.22	-0.02	-0.20	-0.40
	St.dev	0.088	0.089	0.037	0.074	0.013	0.063	0.082
	COV	66.5%	27.8%	21.4%	33.7%	-67.0%	-32.0%	-20.5%
Abs. Maxi-mum	Mean	71.81	20.10	4.30	25.38	3.08	25.24	12.61
	St.dev	2.909	1.594	0.302	2.013	0.294	2.014	0.839
	COV	4.1%	7.9%	7.0%	7.9%	9.5%	8.0%	6.7%

The mean crossing frequency is a characteristic frequency for the signal, and is defined as the average frequency with which the signal crosses its mean value from below. In the tables the mean crossing frequency is determined directly from the time series by counting the number of up mean-crossings.

Since the time series represents the load signals sampled at 25 Hz the extremes of the time series may underpredict the extremes of the signal. Therefore, after a local extreme has been identified from three consecutive points in the time series, a 2nd order polynomial is fit to the three points. The data extreme is then replaced by the extreme of the polynomial. The effect is not large, but is believed to give a more accurate estimate of the extremes.

If we assume that the load case under consideration properly reflects a design driving condition two questions immediately come to mind:

- How to determine the characteristic/representative ultimate load for design verification, and
- How many simulations are required for a sufficiently accurate estimate of the ultimate load?

From the summary statistics in Tables 2, 3, and 4, it is seen that although only the seed parameter for the simulation has been changed from run to run, and variability of the wind parameters has not been accounted for, the extremes show a considerable variation.

The variation in calculated extremes is shown in Figure 2 for three of the loads during the parked rotor load case at 45 m/s wind speed. The horizontal axis is simply the simulation run number while the vertical axis is the largest absolute value observed during that run for the load in question.

It is clear from the figures that two arbitrarily selected simulations may give considerably different extreme values and ultimate loads. This means performing a few simulations and selecting the average or the largest extreme load as the ultimate load will neither give reproducible results, nor can the results be extrapolated to a characteristic value defined by a quantile or a different duration of the load case. In general it is doubtful that the uncertainty in extreme value from a few simulations can be properly accounted for with total load safety factors of the order of 1.3.

It is therefore necessary to develop a procedure and rationale for the analysis of the extreme loads from such simulations. With the statistical variation from one time series to the next, a statistical analysis must therefore be performed of the observed extreme or peak loads in order to determine a representative design load.

EXTREME STATISTICS

Under rather weak assumptions (the distribution of the signal is unbounded and approaches zero exponentially for large values, Gumbel[11]) the asymptotic distribution of extremes is the Extreme Value Type 1 (EV1) distribution.

The EV1 distribution function is given by the expression

$$F(x;\alpha,\beta) = \exp(-\exp(-\alpha(x-\beta)))) \qquad (1)$$

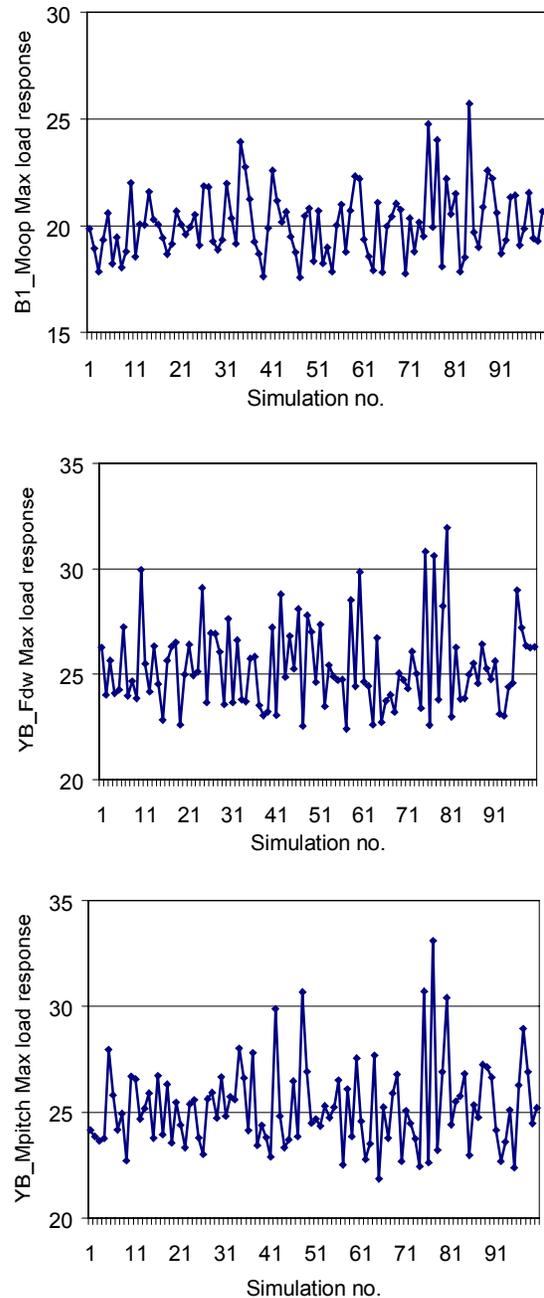Where α and β are the scale and location parameters respectively.

Figure 2. Load extremes during 10-minute simulations, parked at 45 m/s

Table 5. Parameters in Fitted Extreme Value Type 1 Distribution for the Load Extremes

EV1-dist. From 100 time series		WindSpd m/s	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Power production - 14 m/s	alfa	1.44	3.69	11.83	6.08	11.99	2.14	14.09
	beta	21.39	3.87	2.86	4.33	0.69	8.21	3.86
	mean	21.79	4.02	2.91	4.43	0.74	8.48	3.90
	st.dev.	0.89	0.35	0.11	0.21	0.11	0.60	0.09
Power production - 20 m/s	alfa	1.01	2.70	8.27	3.40	7.81	1.52	5.72
	beta	30.86	4.93	3.28	6.04	1.02	9.85	5.14
	mean	31.43	5.14	3.35	6.21	1.10	10.23	5.24
	st.dev.	1.27	0.47	0.16	0.38	0.16	0.84	0.22
Parked - 45 m/s	alfa	0.44	0.79	4.10	0.62	4.26	0.64	1.50
	beta	70.50	19.37	4.16	24.46	2.95	24.34	12.22
	mean	71.81	20.10	4.30	25.38	3.08	25.24	12.61
	st.dev.	2.91	1.63	0.31	2.05	0.30	2.01	0.86
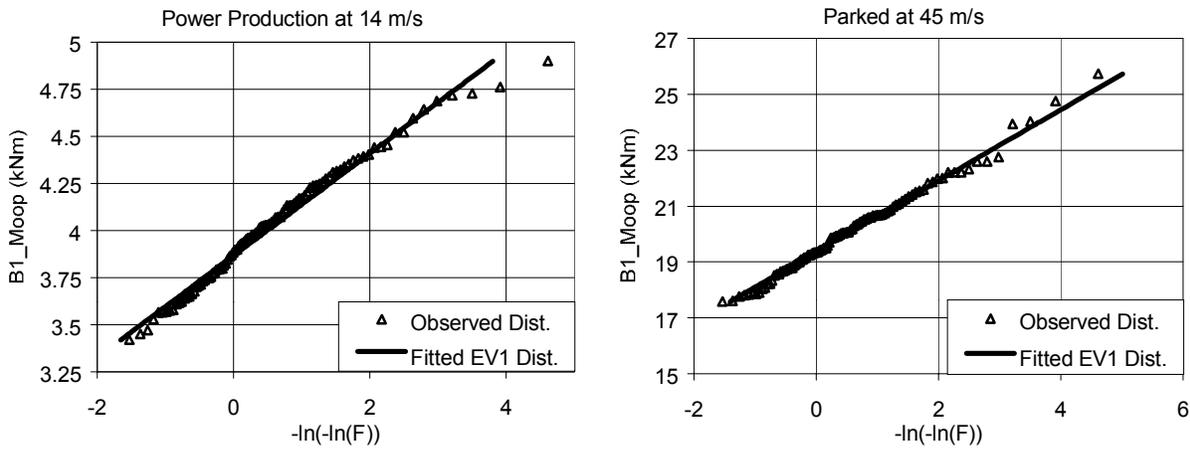
Figure 3. Extreme value fit of maximum out of plane bending moment from each of 100 10-minute runs

For the estimation of parameters in the EV1-distribution, we shall use a simple method called the probability-weighted moment (PWM) procedure, recommended by Abild.[12] Following this approach, the distribution parameters as well as the mean and standard deviation of the fitted EV1-distributions were determined. The resulting values are given in Table 5. In all cases the fit between the data and the EV1-distribution is good. The fit to data is illustrated in Figure 3 for the out-of-plane blade bending moment.

CHARACTERISTIC VALUES

Using the EV1-distribution model for the load extremes, it is now possible to define characteristic/representative values for the load extremes or the ultimate loads for the calculated load cases.

From extreme value statistics, it follows that the larger the sample (either from a longer simulation time or from more simulations) the larger is the expected value of the largest extreme for the sample. For a definition of a characteristic ultimate load we therefore need to define both the duration of the load case and the associated extreme value distribution parameter.

The choice of partial safety factors for the ultimate loads will depend on these definitions. These definitions are to some degree arbitrary, but will have consequences for the calibration of safety factors.

The following definitions of the characteristic/representative values for the ultimate loads will be analyzed and discussed:

- The characteristic/representative value is the expected maximum (extreme) value during a 10-minute period.
- The value corresponding to a 0.95 quantile in the distribution of maximum values, where each maximum value is obtained from a 10-minute period.
- The value corresponding to a recurrence interval of a defined period of operation, taking into account the relative duration of the load case.

According to IEC 61400-1, the Parked load case is associated with V_{ref}, which is the 10-minute average wind speed with a 50-year recurrence interval, i.e. the 10-minute average wind speed that, on average, will occur once every 50 years. Definition 1 therefore seems the most appropriate for the parked load case.

Table 6. Characteristic/Representative Load Values

Power production - 14 m/s		Duration hours	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Def 1	10-min mean		4.02	2.91	4.43	0.74	8.48	3.90
Def 2	0.95 quantile		4.67	3.11	4.82	0.94	9.60	4.07
Def 3	Recurrence period	1	4.33	3.00	4.61	0.83	9.01	3.98
""	""	713	6.13	3.57	5.71	1.39	12.12	4.45
""	""	35653	7.19	3.90	6.35	1.72	13.95	4.73

Power production - 20 m/s		Duration hours	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Def 1	10-min mean		5.14	3.35	6.21	1.10	10.23	5.24
Def 2	0.95 quantile		6.03	3.64	6.92	1.40	11.80	5.66
Def 4	Recurrence period	1	5.56	3.49	6.54	1.24	10.97	5.44
""	""	143	7.43	4.10	8.03	1.89	14.29	6.32
""	""	7139	8.87	4.57	9.18	2.39	16.86	7.01

Parked - 45 m/s		Duration hours	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Def 1	10-min mean		20.10	4.30	25.38	3.08	25.24	12.61

The wind conditions for the Power Production load cases in IEC 61400-1 are either the normal wind conditions (frequently occurring during normal operation) with parameters chosen as being representative rather than defined by a certain quantile or recurrence interval, or the extreme wind conditions with recurrence intervals of 1 or 50 years.

However, it is not clear how to interpret this recurrence period in relation to load cases with a given mean wind speed and a relative duration with respect to the lifetime. Consider, for instance, a wind turbine operating in wind conditions characterized by the Rayleigh distribution with mean 9 m/s. In several of the load cases the load shall be calculated at rated and cut-out wind speed, V_r and V_{out}, respectively. Assuming a bin-width of 2 m/s, the relative duration at V_r and V_{out} are

V_r = 14 m/s   P{13 m/s < V < 15 m/s} = 8.14%
V_{out}= 20 m/s   P{19 m/s < V < 21 m/s} = 1.63%

The most reasonable interpretation of a recurrence period of 1 or 50 years for the wind/load conditions at a given wind speed would be to take into account the relative duration. Thus a recurrence period of 1 year at V_r and V_{out} would correspond to a duration of the load case of 713 hours and 143 hours, respectively rather than 8760 hours. Note that the relative duration depends on the bin-width, which then needs to be defined and agreed.

Shown in Table 6 are the load values for the six major wind turbine loads already defined.

The first two definitions may apply for normal wind conditions, while recurrence periods of 1 and 50 years may represent extreme wind conditions. The recurrence intervals shown correspond to 1 hour of operation at the wind speed, and to 1 or 50 years of wind turbine

operation, taking into account the relative duration of the load case.

A similarly important question, namely how to determine the number of simulation runs required for the determination of characteristic value of the ultimate loads, however, remains. Ideally, the uncertainty of the characteristic value due to the numerical scheme for calculation of ultimate loads should be insignificant compared to all other uncertainties in the design verification process.

In order to assess the uncertainty from the simulation scheme, we shall calculate the confidence interval for the already discussed definitions of the characteristic values of the ultimate loads. The approach is described in Madsen et al.[8]

Assume now that the requirement is that the characteristic value of the ultimate load shall be determined such that the 95% confidence interval for all loads (except the rotor force perpendicular to the wind direction) is less than 10% of the characteristic value. The number of necessary simulations of length 10 minutes (necessary sample size) to obtain this confidence interval has been determined and is shown in Table 7. In order to reduce the confidence interval to 5% the sample size shall be four times the values shown.

In the actual design verification situation it is doubtful that more than a few (5) simulations will be made for each load case. We may thus conclude that this direct approach is only feasible for the determination of the 10-minute mean of the extreme value.

If another model for the determination of the characteristic ultimate loads, which would require a smaller sample size or number of simulation runs, could be derived, this would have beneficial consequences for the verification process and the size of the partial-load

Table 7. Sample Size Requirements for a 10% Confidence Interval

Load case	Definition of ultimate value	Duration hours	Sample size 10 min run
Power production - 14 m/s	10-min mean		3
	0.95 quantile		15
	Recurr. period	1	7
	""	713	60
	""	35653	92
Power production - 20 m/s	10-min mean		4
	0.95 quantile		17
	Recurr. period	1	8
	""	143	50
	""	7139	84
Parked - 45 m/s	10-min mean		3

Figure 4. Comparison of actual occurrences and the Gaussian probability density function

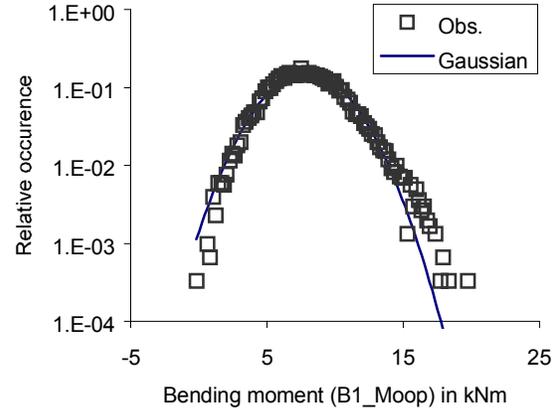safety factors. Such a model will be presented in the next section.

The choice of definition of the characteristic ultimate load together with the choice of partial load safety factors is to some degree a political one, to be taken by standards committees or similar bodies. For the Power Production load cases the definitions determined from a recurrence period based on the assumed operational modes of the wind turbine seems to be the most conceptually satisfying. The values, however, are based on extrapolation far beyond the observed extreme values from the simulations, which hardly can be justified without experimental verification. A better way could be to define the characteristic load as the mean extreme during a 10-minute simulation, using a turbulence intensity of the recurrence period in question.

Finally, it is noted that apart from the in-plane blade bending moments, the ultimate loads are found for the parked rotor load case at the 50-year wind speed. The blade points vertically upward in the simulations, and gravity does not contribute to the in-plane blade bending moment.

SEMI-ANALYTICAL PREDICTION OF EXTREMES

In the following we shall attempt to reduce the statistical uncertainty associated with the distribution of extremes by introducing further assumptions on the nature of the turbulence response simulations. We shall only look at the parked load case, where the mean and the standard deviation are constant with time. In Madsen[8] it is shown, how the approach can be extended to the operation load cases, taking into account the periodic variation of the signal mean and standard deviation.

The approach is inspired by Davenport.[7] He assumed that the structural response to wind turbulence was a stationary Gaussian process, and derived an

asymptotic solution for the distribution of the largest extreme during the period T. Before presenting a semi-analytical method for the prediction of the distribution of extremes we will take a closer look at the characteristics of the turbulence response signal for one of the simulation runs and the validity of the assumptions.

The statistics shown in Tables 2-4 show a definite skewness in several of the response realizations. Except for the wind speed signal and the tower force perpendicular to the wind direction, the probability densities are definitely skewed with a significant effect in the tails. The histogram for the out-of-plane blade bending moment for a 10-minute run in the form of the relative number of occurrences is shown in Figure 4 together with the Gaussian probability density functions with the same first two moments. Note that the skewness causes the number of occurrences in the tail with the largest absolute value of the load to be higher than the Gaussian assumption would predict.

Therefore we will develop an analytical solution to the distribution of extremes taking into account that the signal generating the extremes is skewed. Since a Gaussian stochastic process does not have skewness, we shall instead assume that the generated response signals Z(t) are of the form

$$Z(t) = \zeta(t) + \eta(t)(X(t) + \varepsilon X(t)^2); \quad \varepsilon << 1 \qquad (2)$$

where X(t) is a normalized Gaussian process, and ζ and η are parameters that determine the mean and standard deviation. In this section ζ and η shall be considered constants, i.e., independent of time.

Assuming that we know the mean, variance, and skewness of the response process Z(t), the first order approximation of the parameter ε, ζ, η, and ν_{0X}, see Madsen,[8] are

$$\varepsilon \cong \frac{\gamma}{6} \qquad (3)$$

$$\eta \cong \sigma_Z \tag{4}$$

$$\varsigma \cong \mu_Z - \varepsilon\, \sigma_Z \tag{5}$$

$$\nu^Z_{\mu_Z}(t) \cong \nu_0^X \tag{6}$$

The resulting mean and variance of the asymptotic EV1 distribution of the process Z(t) becomes

$$
\begin{aligned}
E\{Z_T^{\max}\} &= \beta + \frac{\gamma_E}{\alpha} = \\
&\mu_Z + \sigma_Z\left(\sqrt{2\ln(\nu_0 T)} + \varepsilon\left(2\ln(\nu_0 T) - 1\right)\right) + \\
&\frac{0.5772\,\sigma_Z\left(1 + 2\varepsilon\sqrt{2\ln(\nu_0 T)}\right)}{\sqrt{2\ln(\nu_0 T)}}
\end{aligned}
\tag{7}
$$

$$Var\{Z_T^{\max}\} = \frac{\pi^2}{6\alpha^2} = \frac{\pi^2\sigma_Z^2\left(1 + 2\varepsilon\sqrt{2\ln(\nu_0 T)}\right)^2}{12\ln(\nu_0 T)} \tag{8}$$

The prediction of the mean value and the standard deviation of the largest extreme during the parked load case at 45 m/s, using the Gaussian assumption and using the non-linearity correction described above, are compared in Table 8 to the mean and standard deviation calculated directly from the observed extremes.

The uncertainty has been considerably reduced as can be seen in Table 9, showing the 95% confidence interval for the expected value of the largest extreme during 10 minutes for the parked load case. The confidence interval is given as a percentage of the mean

value. The parameter n is the sample size, i.e., the number of simulation runs. Using the semi-analytical approach with the non-linearity correction based on statistics from two runs gives the same width of the confidence interval as 15 runs combined with the direct estimate of the expected value of the largest extreme.

The use of the semi-analytical approach with the non-linearity correction is recommended to provide a reasonably small uncertainty with a feasible number of simulation runs.

COMPARISON WITH IEC

The latest revision of IEC 61400-1 requires the ultimate loads to be determined using both turbulence simulations and extreme wind events/gusts during power production and using an extreme wind determined as a short-term-average wind speed for the parked load case. In the following we shall compare the ultimate loads using the standard directly with the ultimate loads based on turbulence response simulations.

The IEC ultimate loads were calculated[13] using the same ADAMS-model as was used for the turbulence response simulations. Load cases without any internal or external faults were analyzed for the design situations Power Production (DLC 1.3, 1.6, 1.7, 1.8 and 1.9) and Parked (DLC 6.1) for the defined gust models and assuming wind turbine Class IA. The analyzed load cases assume the parameters in Table 10.

The IEC 61400-1 does not specify the turbulence

Table 8. Comparison of Prediction Methods

Estimates from all runs		WindSpd m/s	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
EV1-dist. From 100 time series	alfa	0.44	0.79	4.10	0.62	4.26	0.64	1.50
	beta	70.50	19.37	4.16	24.46	2.95	24.34	12.22
	mean	71.81	20.10	4.30	25.38	3.08	25.24	12.61
	st.dev.	2.91	1.63	0.31	2.05	0.30	2.01	0.86
Simple Daven-port	Peak factor	3.67	3.89	4.12	3.87	3.95	3.94	3.78
	Est max mean	70.96	18.03	4.07	23.42	2.77	22.92	11.40
	Est max st.dev	2.56	0.89	0.21	1.34	0.23	1.29	0.56
Non-linearity correction	Peak factor	3.94	4.64	4.58	4.38	3.99	4.42	4.67
	Eps	0.00	0.05	0.03	0.04	0.00	0.03	0.07
	Est max mean	72.23	19.99	4.37	25.40	2.80	24.73	12.80
	Est max st.dev.	2.95	1.25	0.26	1.70	0.24	1.61	0.83

Table 9. Comparison of Confidence Interval at Different Sample Sizes

95% confidence intervals		WindSpd m/s	B1_Moop kNm	B1_Mip kNm	YB_Fdw kN	YB_Fcw kN	YB_Mpitch kNm	YB_Mroll kNm
Semi-analytical prediction	Est. max mean	72.23	19.99	4.37	25.40	2.80	24.73	12.80
	St. error	1.33	0.57	0.07	0.78	0.09	0.68	0.31
	Interval +/- n=1	3.6%	5.6%	3.1%	6.1%	6.1%	5.4%	4.7%
	Interval +/- n=2	2.6%	4.0%	2.2%	4.3%	4.3%	3.8%	3.3%
Statistics from 100 time series	Est. max mean	71.81	20.10	4.30	25.38	3.08	25.24	12.61
	St. error	2.91	1.63	0.31	2.05	0.30	2.01	0.86
	Interval +/- n=1	7.9%	15.9%	14.3%	15.9%	19.1%	15.6%	13.3%
	Interval +/- n=15	2.1%	4.1%	3.7%	4.1%	4.9%	4.0%	3.4%

Table 10. Load Case Parameters

Design situation – Load case	Wind speed (10 min aver.)	Power law exponent α	Turbulence intensity I_u*	Turbulence standard deviation σ_1*
Power Production (DLC 1.3, 1.6, 1.7, 1.8 and 1.9)	14 m/s	0.2	18.4 %	2.58 m/s
Power Production (DLC 1.6, 1.7 and 1.8)	20 m/s	0.2	16.5 %	3.30 m/s
Parked (DLC 6.1)	50 m/s	0.11	(11 %)	(5.5 m/s)

*longitudinal turbulence component

Table 11. Comparison of Scaled Extreme Loads from Turbulence Response Simulations and IEC Power Production Load Cases

Load	Scaled simulation extreme - 14 m/s		Scaled simulation extreme - 20 m/s		IEC extreme
	10-min mean	0.95 quant.	10-min mean	0.95 quant.	
B1_Moop (kNm)	4.32	5.04	5.12	6.01	3.90
B1_Mip (kNm)	3.01	3.23	3.34	3.63	2.83
YB_Fdw (kN)	4.66	5.09	6.19	6.90	5.74
YB_Fcw (kN)	0.82	1.05	1.09	1.39	0.33
YB_Mpitch (kNm)	9.73	10.98	10.15	11.71	7.49
YB_Mroll (kNm)	4.64	4.82	5.19	5.61	5.54

parameters for load case 6.1, but simply requires the quasi-static loads to be calculated for a short-term average wind speed of $1.4*V_{ref} = 70$ m/s. However, assuming that the wind profile power law has been fitted at hub height and that we have neutral atmospheric stratification with both the wind profile and the turbulence intensity determined by the surface roughness z_0, see ISO4354.[1]

$$V(z) = k\ln(z/z_0) \qquad (9)$$

$$I_u = \frac{1}{\ln(z/z_0)} \qquad (10)$$

A power law exponent $\alpha=0.11$ corresponds to the listed turbulence.

The turbulence response simulations for the power production load cases were calculated for a wind-profile power-law exponent of 0.2 and turbulence intensity for the longitudinal component of 16.6%. The 14 and 20 m/s wind speeds correspond to the rated and the cut-out wind speeds. Only the turbulence level is different, and assuming that the stochastic part of the response is proportional to the turbulence level (expressed as the standard deviation of the longitudinal component), we shall use the expression:

$$S_{extreme}^{scaled} = \hat{S} + (S_{extreme} - \hat{S})\gamma_1 \qquad (11)$$

$\hat{S}$ is the average absolute max of the azimuth averaged signal for the blade bending moments (1.29 and 1.98 kNm for B1_Moop at 14 and 20 m/s, respectively and 1.98 and 2.10 kNm for B1_Mip at 14 and 20 m/s, respectively) and the mean value for the rest of the loads. The latter approximation is reasonable, since their azimuth-averaged variation is only a few percent of the mean. γ_1 is the ratio of the turbulence intensities, which is 1.11 and 0.99 at 14 and 20 m/s, respectively.

Similarly, the turbulence-response simulations for the parked load case were calculated for a wind profile power law exponent of 0.2 and a turbulence intensity for the longitudinal component of 0.17, resulting in a

grid-point standard deviation of 7.47 m/s. The 10 minute average wind speed was 45 m/s. Hence, we need to adjust for the mean wind speed, the profile, and the turbulence level.

As for the power production load cases, we shall scale the simulation results for the comparison. As the basis for the scaling we shall choose the velocity pressure

$$p(y,z,t) = \tfrac{1}{2}\rho V^2 = \tfrac{1}{2}\rho(V_0 + V(y,z) + u + v + w)^2 \\ \cong \tfrac{1}{2}\rho V_0^2 + \rho V_0(V(y,z) + u + v + w) \qquad (12)$$

We shall therefore use the expression

$$S_{extreme}^{scaled} = S_{gravity} + (\bar{S} - S_{gravity})\gamma_1 + (S_{extreme} - \bar{S})\gamma_2 \qquad (13)$$

in which the gravity component to the rotor moments are excluded from the scaling (-0.98 kNm and –0.43 kNm for the pitching and the rolling moment, respectively), γ_1 is the ratio of the 10-minute average wind speeds squared except for the pitching moment, where γ_1 is the ratio of the power law exponent times the 10-minute average wind speeds squared and γ_2 is the ratio of the turbulence standard deviation times the ratio of the average wind speeds.

In the comparison of the power production load cases, only the extremes corresponding to the mean extreme during 10 minutes and the 0.95 quantile for the 10 minute extreme are shown in Table 11.

Note that the blade bending moments and especially the rotor pitching moment are larger from the simulations than for the extreme wind gusts of the IEC standard. This suggests that for this wind turbine, these IEC ultimate load cases are very benign and not critical.

The results of the comparison for the parked load case are shown in Table 12. All loads based on the turbulence response simulations, except for the rolling moment, are larger than those obtained from the IEC requirements.

Table 12. Comparison of Scaled Extreme Loads from Turbulence Response Simulations and IEC for Parked Load Case

Load	Scaled simulation extreme	IEC extreme
B1_Moop (kNm)	17.51	14.97
B1_Mip (kNm)	3.63	3.03
YB_Fdw (kN)	21.46	17.93
YB_Fcw (kN)	2.39	0.27
YB_Mpitch (kNm)	19.28	14.83
YB_Mroll (kNm)	10.30	10.67

CONCLUSIONS

The results presented demonstrate a significant statistical variation in ultimate loads predicted by an aeroelastic code with simulated turbulence input. Depending on the definition of the characteristic load a high number of simulations are necessary for a precise estimate.

It is concluded that prediction of ultimate loads using turbulence response simulations must be combined with statistical methods. Basic extreme value statistics have been applied for possible definition of characteristic load values. A semi-analytical model for the extremes from a non-Gaussian process has been derived, and good accuracy and efficiency demonstrated.

Although the comparison with the IEC loads is valid only for this or similar wind turbines, it raises some questions. During power production the ultimate loads are determined by load case 1.1, with normal turbulence model at rated and cut-out wind speeds. Extrapolation to extreme 1 and 50 year events will give much higher ultimate loads than the IEC extreme wind gusts from the load cases DLC 1.3, 1.6, 1.7, 1.8 and 1.9.

The ultimate loads during the parked load case, DLC 6.1, seem to be under-predicted using the quasi-static extreme wind model in the IEC standard. While the effect of averaging the turbulent wind field is much smaller for a wind turbine of this size than for a large turbine, the comparison indicates that the extreme wind model is unsatisfactory, especially for asymmetrical loads. A requirement for turbulence simulations is recommended.

ACKNOWLEDGEMENTS

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