

## A Guide to Design Load Validation

Holger Söker, Martina Damaschke, Deutsches Windenergie-Institut GmbH, Ebertstr. 96,  
D-26382 Wilhelmshaven, Germany, Tel. : +49-4421-4808 –0, Fax: +49-4421-4808-43, h.soeker@dewi.de

Claudia Illig, Jürgen Kröning, DEWI-OCC, Am Seedeich 9, D-27472 Cuxhaven, Germany,  
Tel. : +49-4721-5088 –0, Fax: +49-4721-5088-43, c.illig@dewi-occ.de

Nicolai Cosack, Institut für Flugzeugbau, Stiftungslehrstuhl Windenergie (SWE),  
Universität Stuttgart - Allmandring 5B - 70550 Stuttgart, Germany, Tel. (0711) 685 68273  
Fax ... 68293, cosack@uni-stuttgart.de

### Summary

Data gained in type testing must be evaluated to verify that the intended turbine characteristics are actually implemented in the prototype. To understand structural loads on wind turbines and to validate them against the results of a computer simulation a complex approach must be taken involving statistic analysis, frequency analysis and time history analysis techniques. Dynamic behavior as well as ultimate loading and fatigue loading characteristics are to be investigated on the basis of the measurements and the theoretical design load assumptions. The IEC specifications on design requirements (61400-1) and on load measurements (61400-13) form the basis for a thorough load validation process. Nevertheless, they leave room for interpretations and uncertainty on both ends: the supplier of load validation services and the recipients of such validation reports. DEWI-OCC and DEWI have identified this gap in the existing system of guidelines and have consequently set out to use their strong background to create a „Guide to Load Validation“. The presented paper intends to give a practical guide on how to validate simulated loads for the design of wind turbines by referencing to in-field testing results. In general it is clear that the validation process should be started on rather “good-natured” real world data. Influence of the subjective impression of an individual person can be eliminated if numerical consistency qualifiers are available to establish formal criteria for the assessment of the design loads.

## 1 Introduction

The type certificate of a wind turbine has become a marketing factor of ever increasing importance. Technical due diligence work nowadays requires not only track records of turbine and manufacturing company but also stretches on checking adequacy of the type certificate with respect to the perspective site. Adequacy of the type certificate refers to the parameters relevant for site and turbine classification. On the other hand it requires simply the completeness of the certification components like for example design assessment certificate, type testing reports.

With respect to the latter the data gained in such type testing must be evaluated to verify that the intended turbine characteristics are actually implemented in the prototype. To understand structural loads on wind turbines and to validate them against the results of a computer simulation a multiple layer approach must be taken involving statistic analysis, frequency analysis and time history analysis techniques. Dynamic behavior as well as ultimate loading and fatigue loading characteristics are to be investigated on the basis of the measurements and the theoretical design load assumptions.

The IEC specifications on design requirements (61400-1) and on load measurements (61400-13) are recognized as starting points for a thorough load validation process. Nevertheless, they leave room for interpretations and uncertainty on both ends: the supplier of load validation services and the recipients of such validation reports. DEWI-OCC and DEWI have identified this gap in the existing

system of guidelines and have consequently set out to use their strong background to create a „Guide to Load Validation“.

## 2 General Approach

During the design stage, environmental conditions under which a turbine should be able to perform are defined and serve as the basis for all load calculations with various aeroelastic models and codes. However, very often the overall conditions at the measurement site are benign and by far not as severe as assumed for the turbine design. This makes it difficult to reproduce the predicted turbine loading with enough measured data to ensure statistical reliability in a reasonable period of time. Hence, in most cases the validation process aims mainly at the verification of the applied aeroelastic models and codes for the measured conditions. In this approach the measured site conditions are used as an input for additional simulations with the same codes and models that have been applied for the calculation of the design loads. If the results from the simulations are similar to the measured data, the applied models can be considered to be correct. It is then assumed that the design tools can capture the effect of variations in the environmental conditions with sufficient accuracy and that therefore the predicted loading for the design conditions are valid.

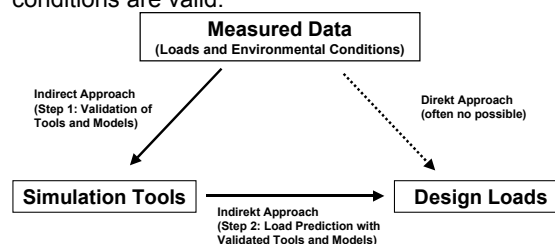


Fig.1 Validation of Design Loads

Consequently, computed and measured time series data of the relevant physical quantities as laid out in IEC61400-13 form the basis of any validation process. It seems intuitively clear that a first focus must be placed on the consistency of these two data pools.

The possible layout and the quality of the load validation process depends very much on the complexity of the measurement campaign, the underlying assumptions of the design process and the used methods and tools. Therefore a universally valid process does not exist. Nevertheless, in the following sections the most important environmental parameters and turbine characteristics are described and a short summary of the major validation steps, according to the authors' experiences, is given.

### 3 Consistency of Environmental Conditions

#### 3.1 General Comments

Beside the categorization of data into operational states of the turbine, the design load cases, a set of external parameters is given in IEC61400-1. In the real world measured data are classified into measurement load cases using a similar set of external parameters. Therefore, in a first step of the validation process consistency of the most characteristic parameters wind speed (distribution), turbulence intensity, air density, wind gradient shall be established.

#### 3.2 Wind Speed and Turbulence Intensity

Wind speeds measured at a met mast or on the wind turbines nacelle shall be representative for the wind speed that the rotor of the wind turbine feels. To ensure compliance with this requirement it is considered necessary to follow the specifications as given in IEC 61400-12 and -13, s.a.

- Use of calibrated anemometers.
- Use of a sensor set-up and boom orientation that ensures minimum disturbance due to mast structure.
- Distance of met mast to turbine within 2 – 4 rotor diameter.
- Position of met mast that ensures free inflow condition to mast and turbine at the same time.

The average wind speed and the turbulence intensity, e.g. the short term fluctuations of wind speed, are without doubt the main load drivers. Hence, consistency of the average wind speed and the turbulence intensity realized in the computer model to the on-site conditions must be established. Therefore these two parameters are the most important when classification of data is required.

Unlike the modeled turbulence being created by a steady mean wind speed with a zero mean variation added on top, the turbulence intensity quantification in measured wind speed time series may be distorted by trends in the wind speed. A trend is given if there is a steady increase, decrease or long periodic variation of the 1-min wind speed averages. To avoid overestimation of the associated

turbulence intensity parameter a de-trending algorithm is to be applied on the wind speed time series. Different approaches are in use at present, hence the de-trending scheme is to be described in the validation report. DEWI is working on the assessment of how de-trending and associated filtering of data sets affects the evaluation of fatigue loading.

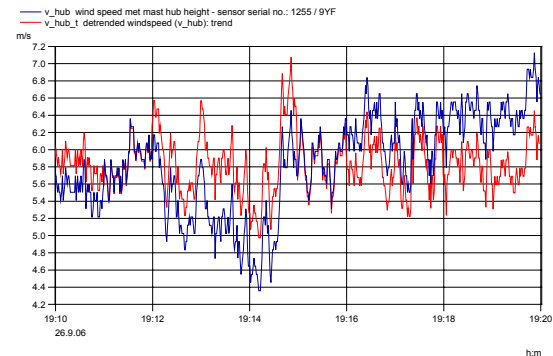


Fig. 2: Example for de-trending wind speed

#### 3.3 Wind Field Stochastic

In numerical simulations a wind turbine is exposed to a three-dimensional wind field with predefined statistics, e.g. mean wind speed and turbulence intensity. The stochastic fluctuations of the wind speed inside the wind field are often based on composition of sinusoidal varying winds. Power spectral density functions are used to define the appropriate distribution of amplitudes with respect to frequency. In addition, coherence functions characterize the spatial dependency of wind speeds in neighboring locations.

It is assumed that the power spectral density and the coherency of the wind field are both site and time dependent. This makes it difficult to draw general conclusions with respect to the design loading from the analysis of limited measurement data at a single site.

Furthermore, the coherence inside a wind field is hard to determine and most campaigns do not provide wind speed data at enough spatial locations to allow for such an analysis.

Therefore the validation of aeroelastic models and codes is often performed with data that has been recorded during periods with low turbulence intensities, where inaccuracies in the description of the turbulent wind field have only little influence.

Thus, the quality of the wind fields used for numeric simulation is often not assessable and relies very much on the suitability of the defined density and coherence functions in guidelines.

#### 3.4 Air density

Air density chosen for the simulation must reasonably be the same as in the real world data used for validation. Unfortunately the air density is dependent on the specifics of the site and hence it is most recommended to re-run the design code using the site specific air density. If variations in on-site air density is large (e.g. due to periodic meteorological pattern) it may be necessary to classify measured load data for this parameter.

The load assumptions for the wind turbines are based on an air density of 1.225 kg/m<sup>3</sup> for normal environmental conditions according to the standard wind turbine classes of IEC 61400-1.

The influence of the site specific air density is demonstrated by simulations of a wind turbine at 10 m/s with turbulence intensity 6% and 1.225 kg/m<sup>3</sup> and 1.19 kg/m<sup>3</sup> respectively.

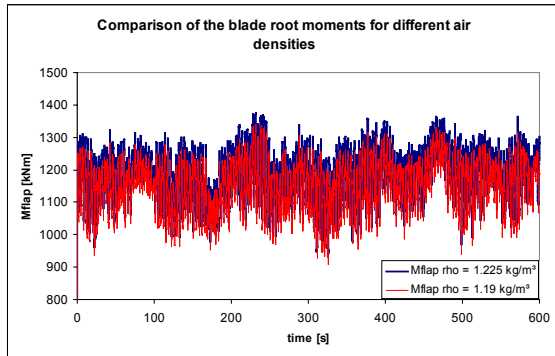


Fig. 2: Effect of Air Density Variation

### 3.5 Wind Profile

With today's large wind turbine rotors stretching over more than 100m in diameter the importance of the wind profile seems to become more important. The assumed wind profile is used to define the average vertical wind shear across the rotor swept area. According to IEC 61400-1 the normal wind speed profile given by the power law shall be used with the standard wind turbine classes:

$$V(z) = V_{hub} (z/z_{hub})^\alpha, \text{ with } \alpha = 0.2$$

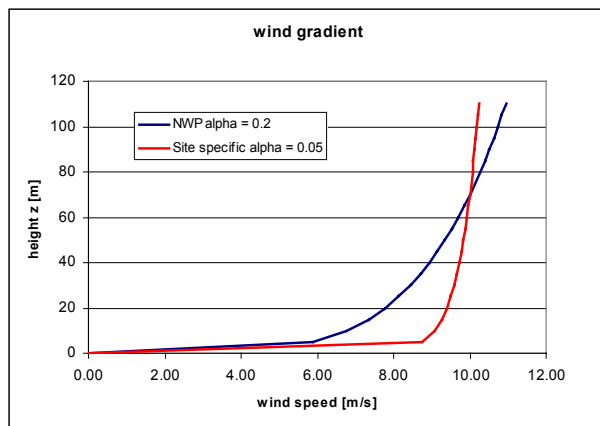


Fig. 3 Example for Wind Profile Check

To validate the wind profile the wind speed measurements at  $z_{hub}$  and  $z_{hub} - \text{rotor radius}$  are to be analyzed. The data shall be transformed to a site specific power law exponent of the wind profile. This shall be used as input parameter for the simulation.

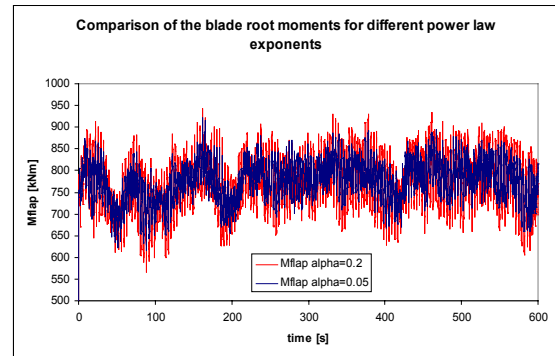


Fig. 4 Effect of Power Law Exponent

## 4 Consistency of Turbine Characteristic Curves

### 4.1 Definition of Characteristic Curves

Characteristic curves describe the operational behavior of the wind turbine on a statistical level. The turbine operation is described in 10-minute averages of crucial operation quantities like electrical power output, rotor speed, generator speed, pitch angle, but also turbine loads like rotor thrust and torque. In general these quantities depend also on the average turbulence intensity and a preceding classification of the measured data is mandatory.

The power characteristics of a wind turbine rotor describe the amount of energy that is put through in a given time interval and converted into mechanical and electrical power. It is intuitively clear that the amount of energy brought into the system is crucial for the loads that it has to bear. Power curve, Cp-lambda characteristics, rotor thrust and power fluctuation coefficient are governed by the rotor aerodynamics, the control algorithm, the pitch angle setting and rotor speed. These parameters can be used to adjust the numerical model of the wind turbine to achieve consistent characteristic behavior.

Hence, before considering the actual loading in various operational states equivalence of the turbine characteristics as described through aeroelastic models and by measurements shall be established.

At least the consideration of the following curves is recommended:

- **Power Curve & Cp-Lambda Characteristic Diagram**
- **Power vs. Rotor Speed**
- **Thrust Coefficient Curve**
- **Power Fluctuation Coefficient Curve**

The PFC indicates how much of the variation in the wind speed is transmitted into the electrical power output

### 4.2 Comparison of Turbine Characteristic Curves

The consistency of the turbine characteristic curves shall be established by visual assessment of:

- differences between the bin averaged values of the measured and simulated 10-min-statistic data (i.e. bin average characteristic curves of 10-min-average, of 10-min-minimum, of 10-min-maximum, of 10-min-standard deviation)
- differences in the min-max-span of the measured and simulated 10-min-statistic data

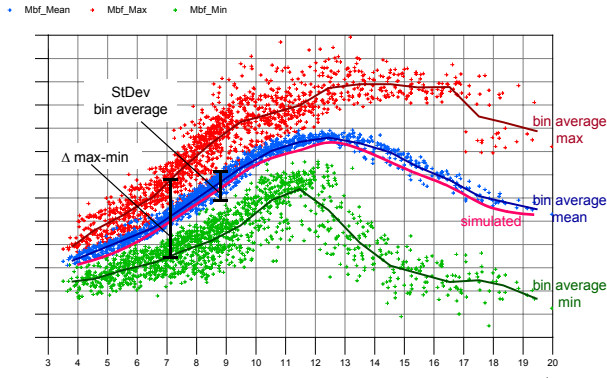


Fig. 5: Characteristic Curve Validation

*Note: The concept of visual assessment / comparison is somewhat dependent on the viewers perception. It would be helpful to define “acceptable” limits of the deviation between measured and simulated characteristics.*

## 5 Consistency of Behavior of Loads and Operational Parameters

### 5.1 Comparison of Statistical Properties

According to IEC61400-13 the characteristic loading of the wind turbine is to be described in terms of:

- characteristic load statistics (i.e. scatter plots of mean-, max-, min- load vs. wind speed characteristics, min-max load difference, standard deviation of the load and equivalent load per 10-min-time series)
- and time series.

The validation process has two consider both representations of the turbine loading. This comparison should also be performed for important operational parameters, like for example rotational speed, power output and pitch angle.

### 5.2 Comparison of Load Quantity Time Series

Individual measured and simulated 10-min time series of the turbine’s characteristic load quantities may be compared:

- visually,
- investigating statistical parameters like minimum, maximum, standard deviation, variation intensity,
- applying differentiation i.e. slopes
- applying frequency analysis techniques,
- investigating number and size of load cycles, level crossings, time at level,
- derivation of the damage equivalent load (Rainflow counting + S-N curve of material + linear damage accumulation).

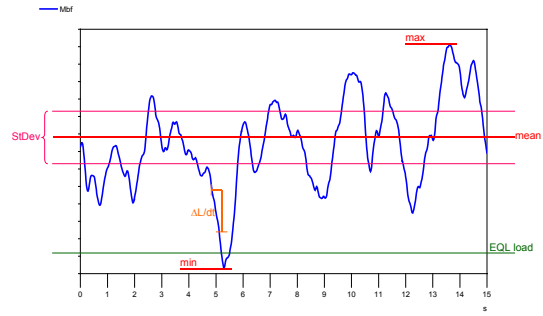


Fig.6: Time Series Validation

## 6 Consistency of Turbine Dynamic Behavior

The dynamic behavior of a wind turbine mainly depends on aerodynamic, structural and control characteristics. While the steady state properties of wind turbine model can be assessed in good quality by comparison of the above described measured and simulated characteristic curves, the dynamic behavior is more difficult to verify.

The simulation codes calculate the natural frequencies of the system and of specific components by using modal analysis under consideration of masses and stiffness. These input parameters are delivered and investigated by the turbine designer. For the natural frequency of the tower its restraint at the tower bottom has a big influence. These input parameters depend on the properties of the soil which differ from site to site and have to be adjusted for site specific calculation and comparability.

Relevant parameters in wind turbine dynamics that can be used to assess and to improve the computational model are structural, aerodynamic damping, natural frequencies of blades, drive train and tower.

### 6.1 Comparison of Turbine Dynamic Behavior

Time series of various operational states with suitable excitations shall be examined in time and frequency domain. Where ever possible special focus shall be placed on system identification tests for analysis of natural frequencies and decay rates of component oscillations caused by stopping procedures, or step-input excitations (e.g. start of yawing, grid coupling). A mode shape analysis is also recommended, if enough measured data is available to do so.

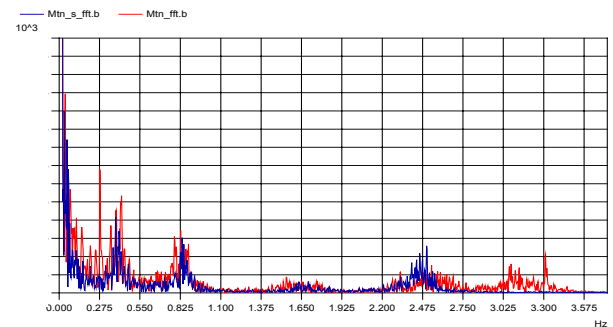


Fig. 7: Frequency Content Validation of Tower Thrust Moment

The evaluated system natural frequencies from measurements as well as from simulations shall be summed up in a table and presented in a Campbell diagram.

## 7 Consistency of Fatigue Characteristic Behavior

For characterization of the fatigue loads subsets of the validated simulated and measured database shall be chosen for further evaluation according to the provisions of IEC61400-13. The wind speed distribution for fatigue load analysis shall be modeled by a Weibull distribution with intensity parameter A and shape parameter k corresponding to the IEC standard wind turbine classes. A service life of 20 years shall be chosen for the fatigue analysis. No data for starts, stops or idling nor low cycle fatigue shall be considered. It is recommended to carry out this analysis for two different turbulence levels that are kept constant throughout the considered wind speed range. The wind speed range shall be restricted to the range covered by a sufficient number of measurements as given in IEC61400-13 (capture matrix for normal power production operation).

For each of the characteristic load quantities the cumulative Rainflow count of all load realizations in a given wind speed bin shall be linearly extrapolated in time to meet the requirements as formulated through the chosen Weibull wind speed distribution. The extrapolation factor is found by evaluating the equation:

$$\text{Factor} = \frac{\text{requested operation time per wind speed bin as per Weibull distribution}}{\text{Measured or simulated operation time in the wind speed bin}}$$

Next the resulting Rainflow counts of each wind speed bin are cumulated into an overall Rainflow cycle distribution representing 20 years of operation time. This representation of the turbine's fatigue loading shall be validated by comparison of the measured and simulated:

- load cycle transition matrix itself,
- amplitude spectra,
- load duration distribution (time at level distribution),
- 1-Hz-damage equivalent load analysis.

## 8 Main Steps of Validation Process

As mentioned before, the input to the validation process of the aeroelastic models and codes comes from two data pools. On one hand there are measurement data, which have been categorized according to the above described main environmental conditions, while on the other hand there are simulated data for the same categories. With these data, a number of validation steps are required to ensure a good agreement between the real turbine and the numerical model and therefore allow for a reliable calculation of design loads. These steps are listed in the table below, together with examples for the applied methods and the main purpose of the individual validation step.

It is recommended to use only measured data with low or medium underlying turbulence intensity for the model validation. This helps to reduce possible uncertainties in the analysis which can result from different wind field stochastics in simulated and measured data.

## 9 Conclusion

The presented paper intends to give a practical guide on how to validate simulated loads for the design of wind turbines by referencing to the in-field testing results. The work is of course not complete and a number of questions are yet to be answered. In general it is clear that the validation process should be started on rather "good-natured" real world data to avoid getting lost in the specifics of a given test site. Accordingly the test site and the test set-up shall be chosen with care.

It is very important, that the evaluation of the comparison between design loads and measured loads is not based solely on the subjective impression of an individual person. This can be achieved if numerical consistency qualifiers are available and can be used to establish formal criteria for the assessment of the design loads.

step	Quantity to Check	Example for Methods	Objective of Validation Step
1	<ul style="list-style-type: none"> <li>Documentation</li> <li>Selected Time Series</li> </ul>	<ul style="list-style-type: none"> <li>Comparison of model data against weighing log</li> <li>Spectral analysis of selected time series for various operational states (e.g. in partial and full load)</li> </ul>	<ul style="list-style-type: none"> <li>Main structural properties like masses, stiffnesses, eigenfrequencies and coupled modes</li> </ul>
2	Characteristic Curves	<ul style="list-style-type: none"> <li>Visual comparison of curves of operational parameters (e.g. speed, power) and loading for several environmental conditions</li> </ul>	<ul style="list-style-type: none"> <li>Validation of basic control characteristics and rotor aerodynamics as well as mechanical and electrical parameters (e.g. losses)</li> </ul>
3	Time Series of various operational states, like <ul style="list-style-type: none"> <li>power production</li> <li>start</li> <li>stop</li> <li>emergency stop</li> </ul>	<ul style="list-style-type: none"> <li>Visual comparison of data in time and frequency domain</li> <li>Check of statistical properties of data</li> <li>Analysis of decay rates of oscillations during stopping procedures</li> </ul>	<ul style="list-style-type: none"> <li>Dynamic behaviour all important and assessable operational states with focus on aerodynamic mode, controller model and actuator models</li> <li>Structural and aerodynamic damping</li> </ul>
4	Post-Processed Data	Comparison of loading spectra like <ul style="list-style-type: none"> <li>rainflow distribution</li> <li>load duration distributions</li> <li>damage equivalent loads</li> </ul>	<ul style="list-style-type: none"> <li>Final check of turbine behaviour and dynamic properties</li> <li>Check of all previously performed validation steps</li> </ul>

Table 1: Main Design Load Validation Steps