

## **INCREASED RELIABILITY OF SERVICE LIFE EXTENSION THROUGH FIELD MEASUREMENTS AT THE INDIVIDUAL WIND TURBINE**

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### **Summary**

At present, the mandatory assessment for service life extension of wind turbines (WT) is performed, in Germany, according to the guideline for the civil building authority to prove operational safety. A detailed inspection and an in-depth simulation of the WT with the site's individual wind regime are combined to determine the remaining service life (RSL), find weak points and defines necessary actions. However, the individual WT's configuration and parameterisation have a strong impact on the endured loads and the resulting lifetime consumption. Therefore, it is recommendable to perform operational data analysis and field measurements at the individual WT to determine its parameterisation and/or validate simulation. For WT types with missing design data, RSL determination based on reconstruction of the endured load spectrum by statistically extrapolating the measured load spectra using operational and/or wind data has been investigated.

Statistics from independent measurements at more than 1500 WT reveal a high share of WT affected by fatigue relevant intolerable mass imbalance and blade angle deviation, or changed structural properties (natural frequencies, damping). Measurements reveal the negative impact of increased loads due to imbalance, turbine fault shut down or wake effects. These fatigue loads are under-estimated by simulation with "ideal" design parameters. Suitable measurement methods are available and cost-effective since they increase the accuracy of the RSL assessment since they allow validation of simulations and quality control of measures taken for load reduction. Both, under-estimating or over-estimating the RSL of a WT in a good or bad condition has a negative financial impact.

### **Key words**

Wind turbine, service life extension, measurements, simulation validation, imbalance, blade angle deviation, load reduction control parameterisation structural properties

### **1 Introduction**

At present in Germany, there are more than 1000 wind turbines (WT) per year reaching the year 20 of their service life, which is equal to the typical WT design lifetime. Then for safety reasons, the German civil building authority requires, according to the DIBt guideline [1], an assessment of the endured loads and the remaining service life (RSL) to allow WT service life extension. To determine the remaining service life (RSL), it is mandatory to combine an in-depth fatigue load simulation of the WT for the individual site conditions with a detailed inspection, Fig. 1 right. This procedure does not take explicitly into account the fact that loads and related lifetime consumption depend as well on the WT's individual configuration and parameterisation. Therefore, it is highly recommendable to perform not only an operational data analysis but as well additional field measurements at the individual WT to reveal its parameterisation, rotor condition and/or validate simulation, Fig. 1 left. For WT types with design data no more available, especially structural data, simulation is only possible with a generic model more or less representing the total system behaviour. Again, measurements are required to calibrate this model with the real WT dynamic behaviour. The determination of the endured load spectrum and the RSL based on a longer individual load measurement campaign combined with a statistic approach using operational and/or wind data has been investigated in a research project [2].

Statistics from independent measurements at more than 1500 WT, reveal the need for individual field measurements [30a] as a share of more than 70% of WTs are affected by intolerable deviations of fatigue-relevant parameters, e.g. mass imbalance, Fig. 2, or structural properties like tower's natural frequency or defective dampers. By a simulation with "ideal"

design parameters, the real increased fatigue loads may be significantly under-estimated. Since defining limit values for rotor mass imbalance and blade angle deviation are mandatory in the design fatigue load analysis according to standards and guidelines [1, 6, 7] it is reasonable to use the measured values of the individual turbine for RSL assessment. Furthermore, simultaneous measurements at neighbouring, similar WT in one wind farm may reveal strongly different power curves and/ or load spectra, Fig. 3 and 5. This complicates the transfer of measured loads from one WT to another, validations measurements are necessary to prevent that loads.

Reliable and cost efficient measurement methods are already available. The benefit of field measurements for a more accurate determination of the individual WT's RSL is obvious. The new standard of DNV GL on WT lifetime extension [4] as well as the soon published revision of the publication on principles for the WT's service life extension assessment by the German Windenergy Association BWE [5] now mention the possibility and benefit of field measurements. The latter document assembles on one hand extensive experience from the last years in the area of RSL assessment of many parties involved, OEM, operators, independent experts, institutions and certification bodies. On the other, recommendations are given for the minimum requirements to assure a trustable analytic and practical assessment. Even, an extensive "round robin" RSL assessment of a real 16 year old WT in a small German wind farm was carried out to compare and discuss differences in the determined RSL and derive best practices [5].

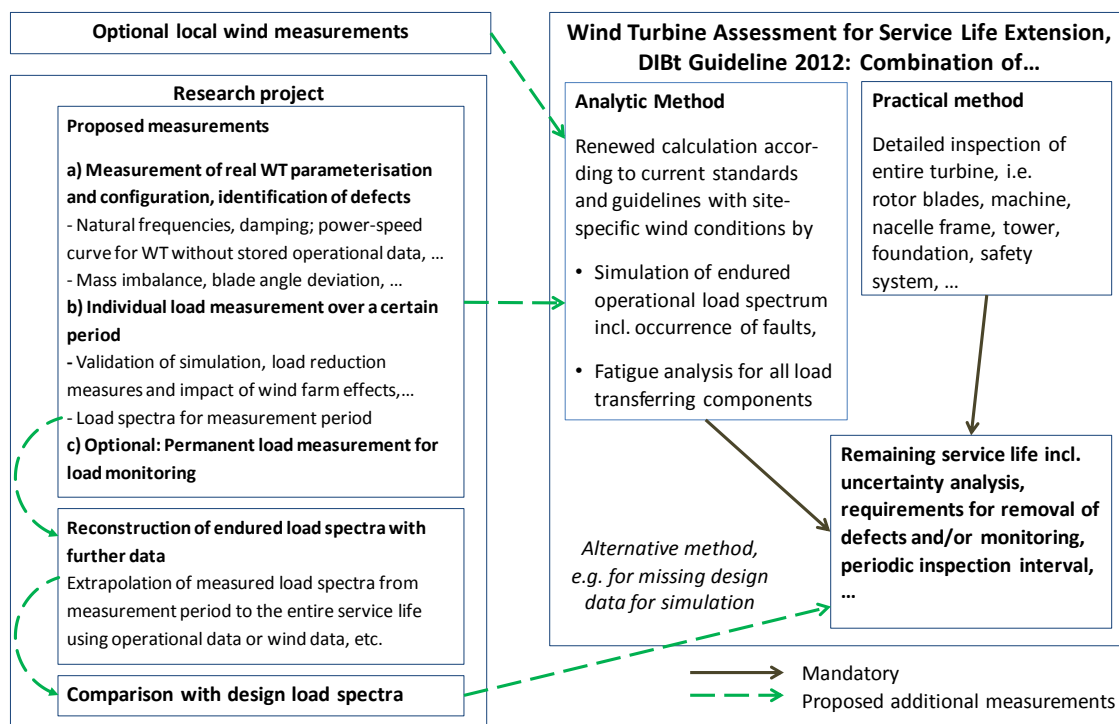


Figure 1: Scheme of RSL determination according to German building authority guideline (right) and measurement methods recommendable for increasing the RSL result's accuracy (left)

## 2 Reasons for individual wind turbine loads exceeding design loads

Already since the 1990s, standards and guidelines for safe WT design exist [1, 6, 7]. However, in many aspects, wind energy stepped beyond the existing knowledge of engineering and physics in the areas of meteorology, material and engineering science, aero- and structural dynamics, etc. Furthermore, the fast growth of the market demand for new and larger rotors and tower heights led to shortened design and testing phases despite the extensive certification requirements. Therefore, many aspects may lead to the fact that for a WT type or the individual series WT the operational loads may exceed the design loads. Several aspects are listed below.

They are illustrated by example in the schematic figure 2 and the measurement results shown in the following figures.

a) **Design simplifications:**

\* For some older WT types, it turned out that design load spectra for type approvals/certification did not consider some load components. These were thought, as state of art, to be negligible but later turned out to be relevant, e.g. torsional vibration effects

\* For operational fatigue load analysis, it was assumed for some time that it is sufficient to perform simulation for wind speed steps of 2 m/s. Hence, for some variable-speed WT, harmful loads from tower or blade natural frequency excitation by the rotor speed or blade passage were not included in the design load spectrum. However, later in the field damages and measurements revealed their existence. Unexpected resonance issues are still today an issue at quite new WT types, due to the long and slender blades and towers.

\* For some WT types, it turned out that the physics are more complex than assumed during design so that structural components are affected, e.g. series issues at blades, nacelle bearings, frames, foundations and transition pieces, etc.

\* For some WT types it was assumed that fatigue loads from stop events are not as relevant as the operational loads from normal production. However, especially emergency stops due to faults may cause very high loads due to the fast pitching and breakdown of the thrust, etc. For countries with very frequent, even daily, grid failures it is known that power electronics which are trouble free in Germany for 10 to 20 years have to be exchanged within a year or even shorter periods, and that the mechanical components as well endure high stress in these countries.

b) **Deviation of site-related conditions:**

\* Even for Germany it turns out more and more, that there is still a lot to learn about the real wind at site. Deviations of the mean wind speed, turbulence, deformed or reversing vertical wind speed profile, or atmospheric stability issues are observed by .

\* In addition, changes in the terrain surface through forest growing, complex sites with large flow separation behind hills and forest, atmospheric layers and jets with different wind speeds and directions (for large WT) are impacting on loads and energy production.

\* Finally, later installation of neighbouring WTs impacts through wake effects, especially if minimum inter-turbine distances from certification are not considered. Fig. 2 and need to be investigated according to [5] to assure structural integrity.

c) **Deviation of dynamic properties and parameterisation:**

\* Every year, there are WT found where e.g. the tower's natural frequency lies outside the range stated in design and certification. Hence the control parameterisation, e.g. to prevent resonance, has no longer the desired effect.

\* Malfunction of leaking dampers, e.g. in blades of stall turbines, cause increased vibration and as well significant rotor imbalance from the lost oil.

\* Furthermore, different pitch and power curves are found at WT of the same type even at the same site, meaning that for one and the same wind speed the endured loads differ, e.g. due to operation at different rotor speeds, fig. 5.

\* Yaw misalignment is as well a topic relevant for loads, however the design fatigue load analysis includes already a permanent yaw misalignment of 8°.

\* If wind vanes and nacelle northing are not correctly, an implemented wind sector management to reduce wake loads cannot do its job as the turbine is not shut down in the disturbed sectors. Wrong turbine northing of up to 30° of a whole wind farm may even occur in Europe for new WT.

d) **Deviation of rotor condition:**

\* The negative impact of blade erosion or icing on aerodynamics and mass imbalance is obvious for everybody.

\* Additionally, statistics from independent measurements of rotor mass imbalance and blade angle deviation reveal that nearly three quarters of the WT are affected by an intolerable exceedance of the related limit values. These are mandatory to be stated in the course of WT design fatigue load analysis, see design standards and guidelines [6, 7].

\* Harmful stall vibration from blade angle deviation is found every year at Pitch WT and for some WT types a serial issue reducing blade lifetime to approx. 6 years.

\* The aerodynamic asymmetries from production tolerances of the twist change from maximum chord to blade tip increase loads as well. Frequent automatic emergency shut

downs, e.g. due to torque fluctuation or tower vibration from blade angle deviation additionally stress all components.

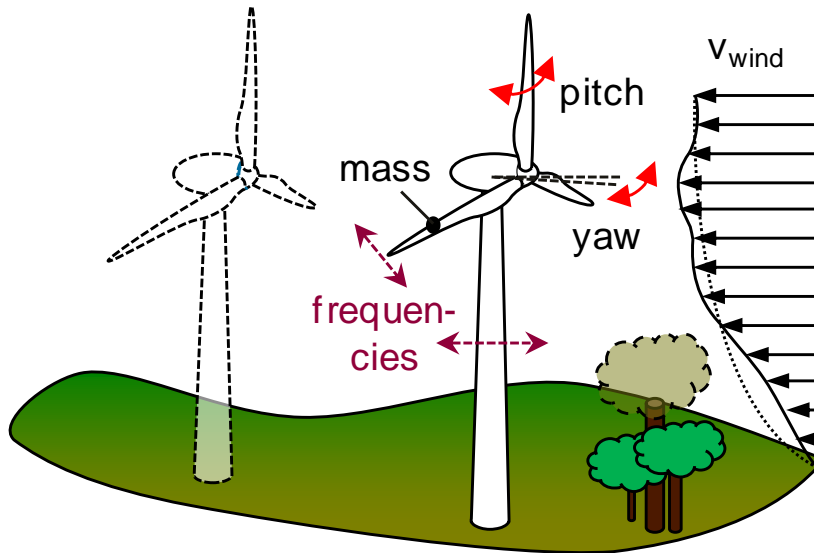


Figure 2: Schematic illustration of some aspects for increased loads: Terrain changes, siting, wind profile, turbine condition and parameterisation,

- e) **Missing root cause analysis of repeating damage patterns:**
  - \* If the same issue occurs again and again, it is wise to attack the cause, e.g. search for origin for excess loads (e.g. blade angle deviation) instead of caring only about the symptom, e.g. replacing yaw brakes, gear box or main bearing. The probability of structural pre-damage increases the longer a root cause is not eliminated.
- f) **Pre-damaged structure:**
  - If the structure is pre-damaged, e.g. by cracks after extreme events, the ageing mechanisms change and the same loads cause more harm, fatigue is accelerated.
- g) **Delayed O&M and repair:**
  - If due to difficulties in WT access, availability of spare parts or financial reasons, O&M and repair are delayed, loads may be increased as well, e.g. worn yaw brakes producing additional nacelle vibration and consequent damages
- h) **Spare parts:**
  - If a component is not available or the supplier does even no longer exist, used spare parts with unknown history and lifetime consumption are installed – or even not specified alternative spare parts. This may change significantly the overall system behaviour with a negative impact on the loads
- i) **Human errors and quality control:**
  - \* The tight working schemes during production, erection and O&M in combination with the impact of fast changing weather conditions may cause that tasks stay unfinished and will not be finished by others if documentation and quality control is poor, e.g. for the blade angle adjustment, etc.
  - \* It is observed from time to time, especially for staff not familiar with system dynamics, that changing vibrational limit values in the control or resetting from remote a WT with frequent shut downs is considered as an appropriate workaround.

### 3 Examples for measurements at the individual WT

As example for aspect b) and c), fig. 3 shows the tower top load spectra from a several hours' simultaneous measurement during normal operation at two new neighbouring Multi MW WT of the similar WT type. The measurements were done for root cause analysis for frequent vibration-related WT shut down at certain wind directions and significant production differences.

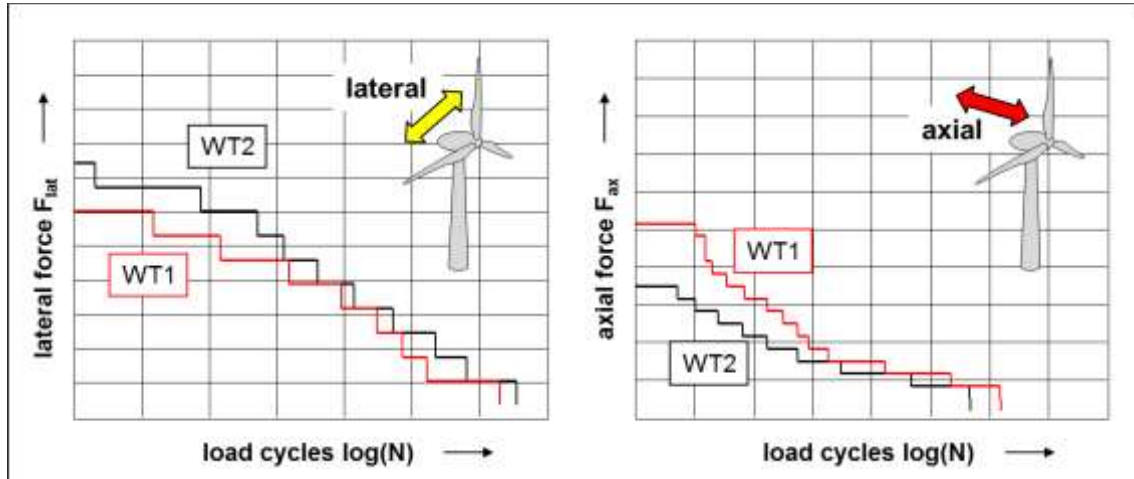


Figure 3: Detection of strongly differing tower top load spectra by simultaneous measurement at two similar, neighbouring Multi-MW Pitch WTs; different control parameterisation and strong wake effect (WT2) from too short WT distances

The load spectra obviously differ strongly for several reasons:

- \* WT1 was affected by a strong wake effect from a too close other turbine causing increased axial vibration. These increased loads can be prevented only by wind sector management
- \* SCADA data analysis revealed that wrong parameterisation of WT2 did not prevent excitation of the tower's natural frequency by the rotor speed, causing the increased lateral vibration.
- \* Differences of the pitch and power curve were as well detected.

It is obvious that the load spectrum of one WT cannot be used to estimate the endured loads of the neighbouring turbine despite that they are of the similar type. These measured real load spectra would not be obtained by a simulation with the "ideal" parameters from design.

To illustrate the impact of intolerable mass imbalance and blade angle deviation on the operational loads, Fig. 4 shows measurement results for two turbines before and after balancing resp blade angle correction. The imbalance-related amplitudes were obtained by sliding window order analysis of a longer measurement during production. Before balancing, the resonance effect of the tower's natural frequency is clearly seen: the amplitude changes significantly with the rotor speed. After taking the corrective measures for load reduction, the amplitudes are nearly independent from the rotor speed. This shows that the measured real blade angle setting and mass imbalance of the individual WT are important input parameters for a correct fatigue simulation for RSL assessment.

**Mass imbalance related lateral acceleration amplitude**

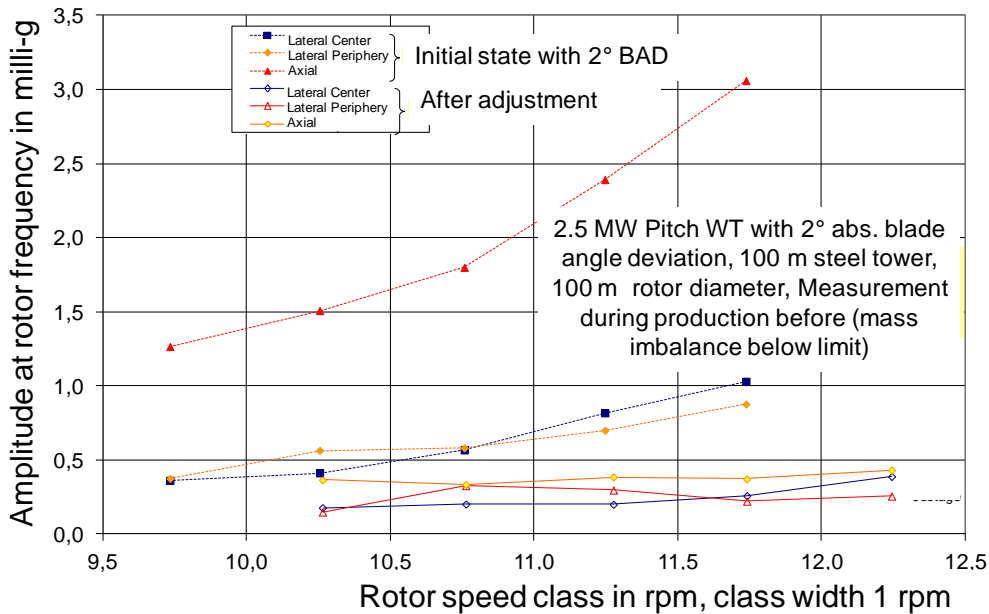
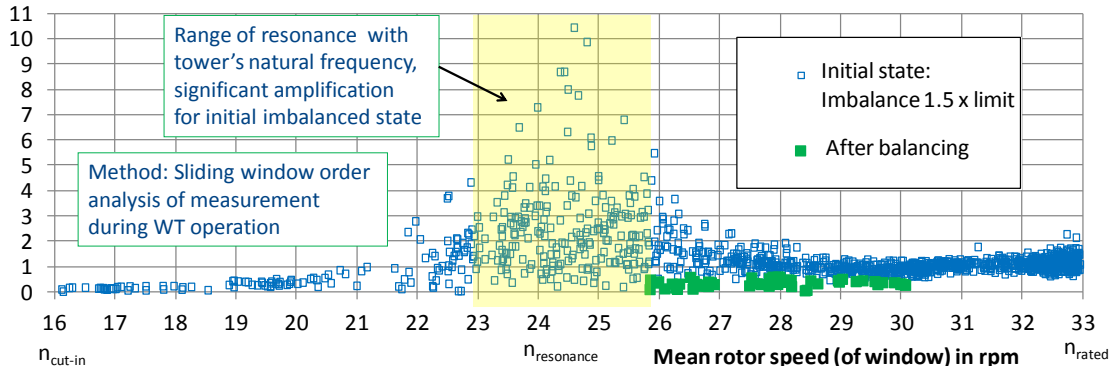


Figure 4: Top: Significant operational load reduction by balancing a 600 kW variable-speed turbine, where the tower's natural frequency is excited by the rotor speed through an initially intolerable mass imbalance Bottom: Significant operational load reduction by blade angle correction at a variable-speed 2.5 MW WT

Fig 5 shows the significantly differing rotor speed and power curves from 10 min SCADA data of two similar neighbouring variable-speed WT. In addition, the blade types differ slightly. Concerning the siting, the investigated WT is for the main wind direction in the wake of the neighbouring WT, so it can be assumed that the lower rotor speed curve has implemented by purpose for load reduction. For the same wind speed, a lower rotor speed means lower load cycle numbers from the rotor's revolution.

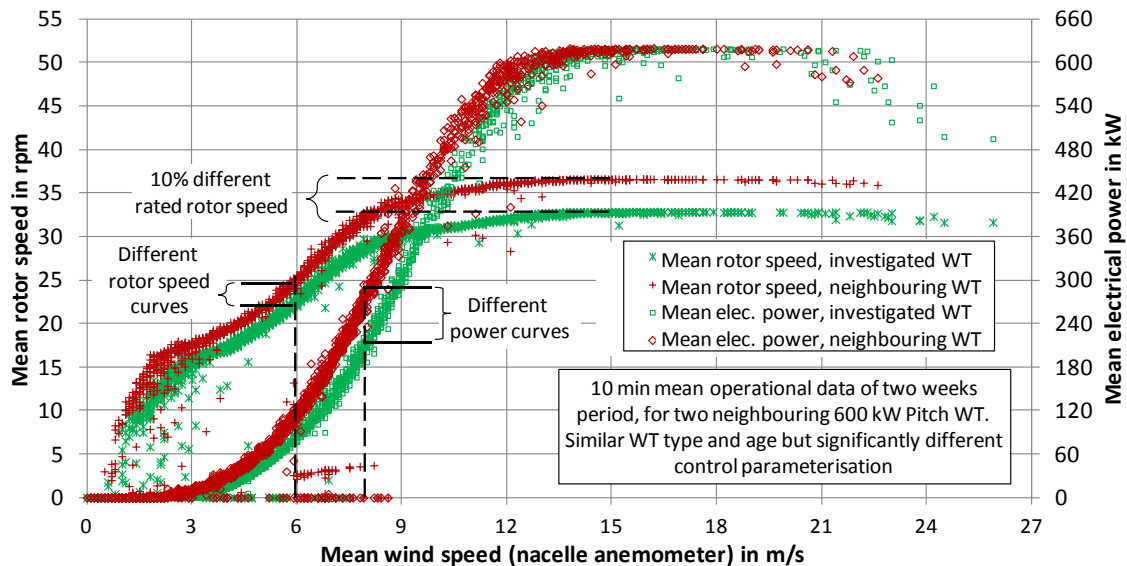


Figure 5: Detection of strongly differing power and rotor speed curves of two similar, neighbouring 600 kW Pitch WTs (different control parameterisation for load reduction)

#### 4 Necessity of analysis of WT start and stop and failure events during fatigue analysis

For most WT and sites, the majority of start and stop events occur around cut-in wind speed where low loads can be expected. However, standards and guidelines require to include the case with production an occurrence of fault in the fatigue load analysis. Hence, this should be done carefully during RSL assessment as not only the measurement but as well the evaluation has a strong impact on the obtained load spectrum. When the WT stops due to excess tower vibration, fig.5, it is obvious that such a case needs to be investigated. The lateral tower top acceleration measurement shown that the blade and tower natural frequency vibration superimpose unfavourably leading to high amplitudes. After a certain time of nearly 1 min the evaluation algorithm in the control detects a certain limit value exceedance and stops the WT. Two questions arise:

- whether and how does design simulation model these vibration superimpositions,
- what is the correct start time and time section to grasp the stop-related loads correctly .

Some stops cause a several minutes remaining tower vibration because of the low structural damping. However, for some WT types it is known that the time series length for design simulation of faults is less than 1 min. In fig. 6 the load spectra from the signal of fig. 5 (lateral, i.e. horizontally parallel to the rotor axis and additionally axial, i.e. parallel to the rotor axis) are shown for three start times of the section. Only the start time -40s relative to the time stamp of the stop in the SCADA data includes the maximum amplitudes which are by a factor 3 larger than for the time sections starting later.

Fig. 7 shows exemplarily the load spectrum of the tower strain gauge (DMS) for a 10 min time series with, after 5 min, an emergency stop due to pitch system failure, causing strong tower and blade vibration with the related natural frequencies. The load spectrum for the preceding 10 min time series of normal production is shown for comparison. The signal was filtered with a 3 Hz low pass. It is visible that the time series with stop produces significantly higher amplitudes with low load cycle numbers, while for normal operation the load cycle numbers for lower amplitudes are higher. Since for high amplitudes only very small load cycle numbers are admissible due to the non-linearity of the Woehler curve, this type of stop should be searched in the SCADA and status data and be included in the endured load spectrum.

Finally, the impact of signal filtering is illustrated by fig. 8. Filtering is applied during measurement evaluation to remove over-estimation of load amplitudes caused by superimposed noise. To illustrate that the choice of filter parameter strongly influences the obtained load spectra, Fig. 8 shows exemplarily load spectra for the same 2 min time section of the emergency stop after pitch system failure, causing strong tower and blade vibration with the

related natural frequencies. The cut off frequency of the low pass is varied between 1.5 and 10 Hz. For a low cut-off frequency the blade vibrations are removed from the signal and the very large amplitudes from the tower vibration are counted. However, nacelle and rotor components will experience the total, superimposed signal. Since the investigation of hot spots may for several WT types identify the blade root as critical component, the filtering that has to be chosen differently as for investigating the tower. This shows that using load measurements for fatigue analysis needs experience with the required careful sensor installation, pre- and post-processing as it has a high impact on the result and uncertainty of the following load reconstruction using operational and/or wind data or simulation validation.

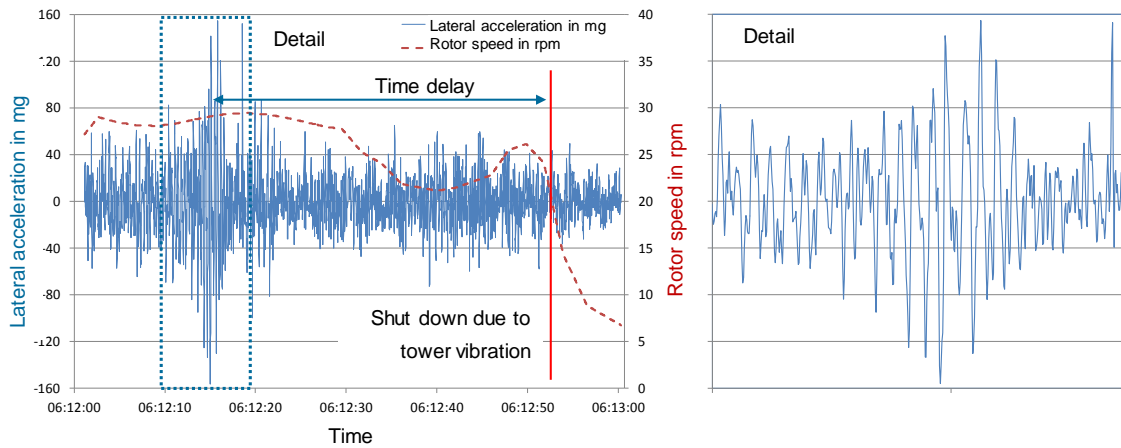


Figure 5: Measurement of lateral tower top acceleration during normal operation with occurrence of fault: stop due to excess tower vibration from superimposition of blade and tower natural frequency vibration, time delay between event and shut down due to algorithm in WT control

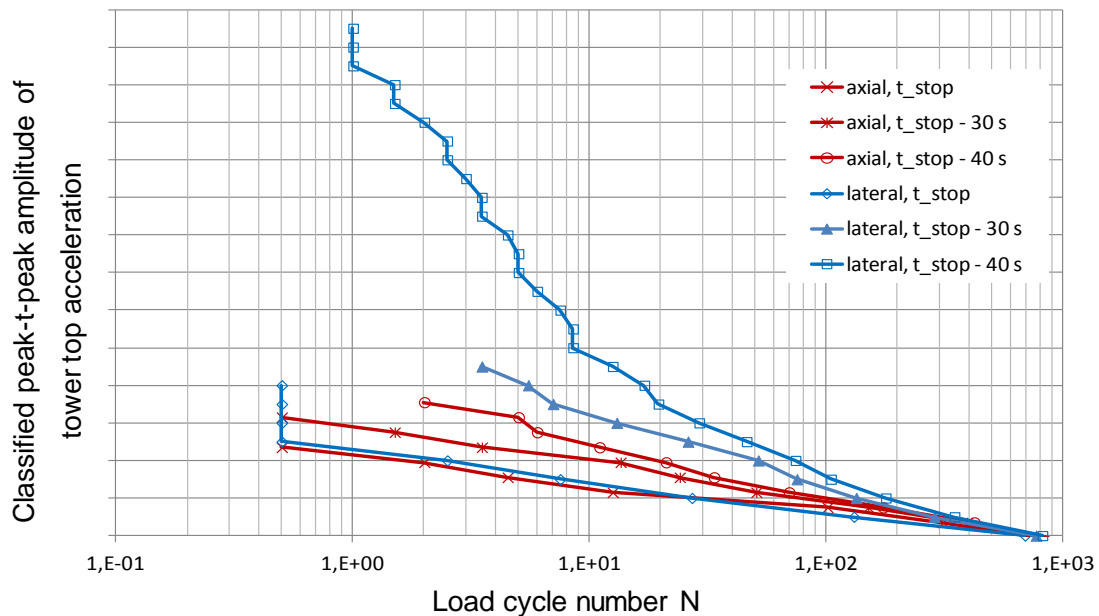


Figure 6: Load spectra for 2 min sections with different start times for measurement of shut down due to excess tower vibration of fig.5



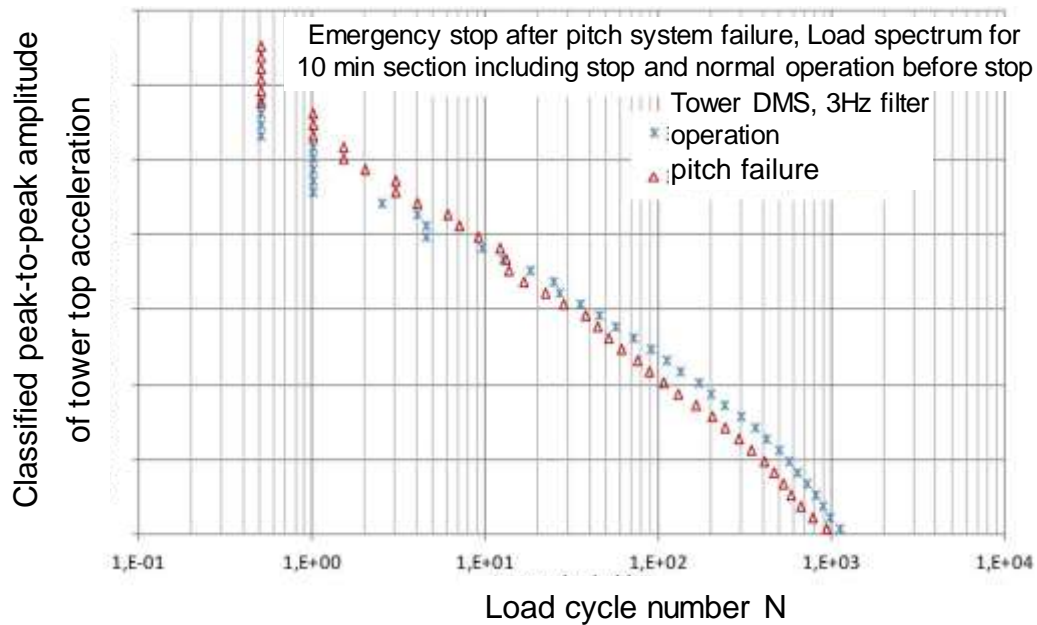


Figure 7: Load spectrum of tower strain gauge signal for 10 min section of operation before and 10 min with pitch system failure emergency stop with significantly higher maximum values for load cycle numbers below  $N = 10$

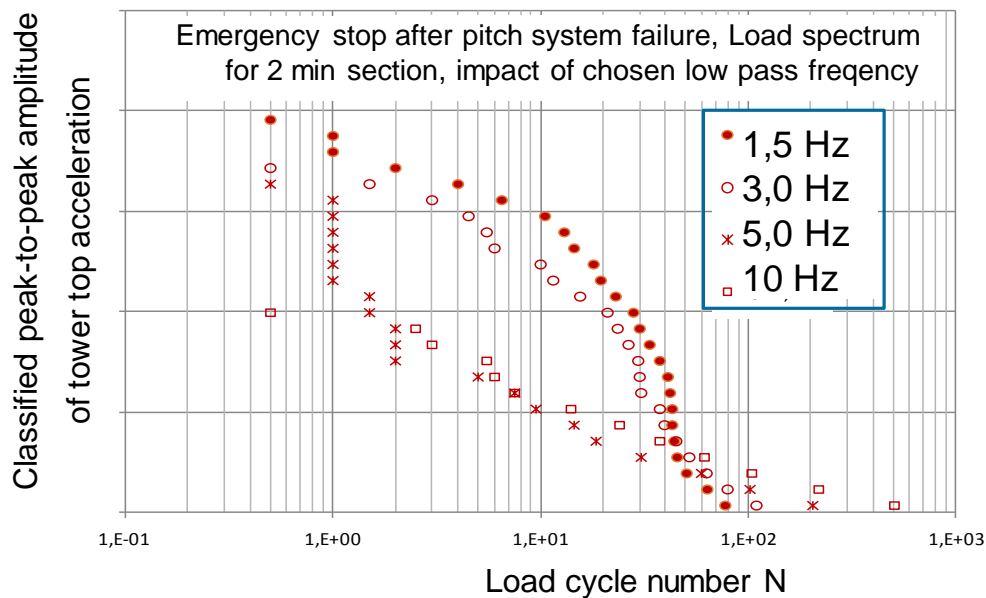


Figure 8: Load spectrum of tower top acceleration for 2 min section, impact of low pass filter frequency on obtained load spectrum, including or excluding blade natural frequency

### Conclusions

In the course of RSL assessment for service life extension, field measurements are a very suitable additional tool to determine the individual WT's configuration, parameterisation and structural properties. Intolerable rotor conditions such as blade angle deviation and mass imbalance increasing fatigue loads, can be identified too. Increased loads can be measured long before a crack as consequence occurs, so the measurements are important for prevention of accelerated lifetime consumption. Furthermore, if any measures for load reduction are implemented, it is advisable for quality control to perform measurements before and after the action to validate the load reduction. Finally, a longer load measuring campaign may serve as

validation for simulations or even as input for the RSL assessment by a reconstruction of the endured load spectra using wind or operational data. However, this should be carried out very carefully and by experienced staff since measurement system installation, data pre- and post-processing as well as the amount and quality of operational and/or wind data has a high impact on the result uncertainty. Since the investigation of all load transferring components and their hot spots is required, additional modelling and work is needed to derive the loads in locations where no sensor was installed.

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