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FIBER OPTIC BLADE MONITORING

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Abstract

The development of blade monitoring was hindered by the unavailability of robust and cost effective measurement and data transmission techniques. The application of sensors based on optical fibers for measuring strains, temperatures and loads is increasing rapidly in many branches of industry. Load measurement systems with optical fibers are expected to offer a reliable measurement technique for monitoring blade loads, mainly because the sensors are not sensitive for electro magnetic fields and lightning. The costs of the sensors and required instrumentation are decreasing, but still too high. Wireless data communication techniques are already common practice and can be used for the data transmission between the rotor and the nacelle. Proper functioning in wind turbines has been demonstrated.

ECN is participating in several condition monitoring projects which all have the objective to reduce costs for operation and maintenance of (offshore) wind turbines and to detect component failures at an early stage. A new development especially for wind energy applications in which ECN is involved is the development of a condition monitoring system for rotor blades in close cooperation with FosWindpower and Knowledge center WMC.

The developments are focused on three aspects:

- The reliability, robustness and cost effectiveness of the sensors and instrumentation;
- The approach with respect to the sensor configuration and integration during the manufacturing process;
- The data analysis and presentation of the results

With respect to the cost, it will be difficult to meet the objectives. The costs of sensors can reduce sufficiently due to larger volumes and automation of the process. The optical components are a decisive factor.

Introduction

Condition monitoring in wind turbine applications is becoming more and more common practice. Especially for the drive train, a lot of experience is available from other applications and these offer a wide variety of experience. For other wind turbine parts or systems, similar applications are not always available. Especially with respect to rotor components, there are no of-the-shelf techniques and there are no similar applications. Apart from that, robust sensors, including instrumentation and data transmission techniques are often seen as not acceptable from the point of reliability and lightning. Conventional strain gauges, even installed in the root of the blades, are prone to failures on the longer term and the copper wiring makes them also sensitive for lightning. Also acceleration sensors, often placed on a larger radius are sensitive for lightning.

Optical sensors are not sensitive for EMC and lightning. They are also considered to be accurate, reliable and stable. Although these qualities are certainly not yet demonstrated in wind turbine applications, the availability of optical fiber sensors, especially Bragg sensors, offer good prospects. These sensors have demonstrated to work well in several applications. For wind energy, several options for coatings and integration are still open to make them more reliable, robust and cost effective.

Another point of attention is the blade manufacturing. With respect to the sensor installation/integration several options have been evaluated. Although the integration of the sensors in the blade material might result in a robust product, the installation during the blade production is difficult. Another possibility to mount the sensors near the surface, possibly covered by an additional layer should be considered. Currently the retrofit-option is applied, where the Bragg sensors are mounted in a housing, which can be glued on the surface. For the time being, this solution offers good prospects.

Apart from the sensors, the availability of improved techniques for data transmission between the hub and the nacelle or tower base is essential. The system should function apart from the wind turbine installation, because the existing interfaces between the hub and the nacelle are not standardized. Wireless bridges offers a cheap, robust and easy to implement possibility for data transmission.

An extensive Failure Modes and Effects Analysis (FMEA) of rotor blades has been carried out to determine what kind of failures can be detected with optical fibers. Based on the results of the FMEA, algorithms have been developed to process the data measured with the optical fibers and to inform operators, wind farm owners and turbine designers about the occurring loads and strains in such a way that they can:

- Prioritize their maintenance;
- Collect data and facts during rare events and damages;
- Limit the physical presence of technicians for inspections.

The algorithms focus on e.g. lifetime consumption, crack detection, and loss of bonding.

The paper will give an overview of the developments and improvements of the sensors, the measurement system and the algorithms over the period 2002 and 2004. The measurement system has been applied for more than one year in a large wind turbine and operational experiences will be mentioned in the paper.

Condition monitoring of wind turbine blades

Also from the point of view of condition monitoring, the rotor components, especially the blades, are very important. They are heavy fatigue loaded, have to withstand a large number of cycles, are difficult to access for maintenance and inspection and are exposed to erosion and lightning. However up to now there are not really systems available, suitable for continuous monitoring. Important reasons for this are lacking of similar applications, the poor possibilities for reliable measurements, the data communication with the rotor part and the large costs involved.

Strain, vibration and acoustic techniques have been researched widely over the past four years by a number of research institutes. The most promising methods are vibration monitoring based on accelerometers and systems based on strain measurements. For vibration monitoring based on accelerometers, a system is available, however no practical results are known. For systems based on strain measurements with fiber optic sensors, there are more developments going on. With the application of a wireless bridge for data communication an important obstacle has been removed. However the stage of "of-the-shelf" for the total system is certainly not yet reached.In figure 1, an example is given based on optical strain gauges with temperature compensation for measuring both bending moments in the blade root and strains in the middle section. This scheme has been applied in a measurement project, together with conventional strain gauges in the root section. ECN is also involved in the development of a condition monitoring system together with FosWindPower. The latter company is specialized in measurement systems based on fiber optics.

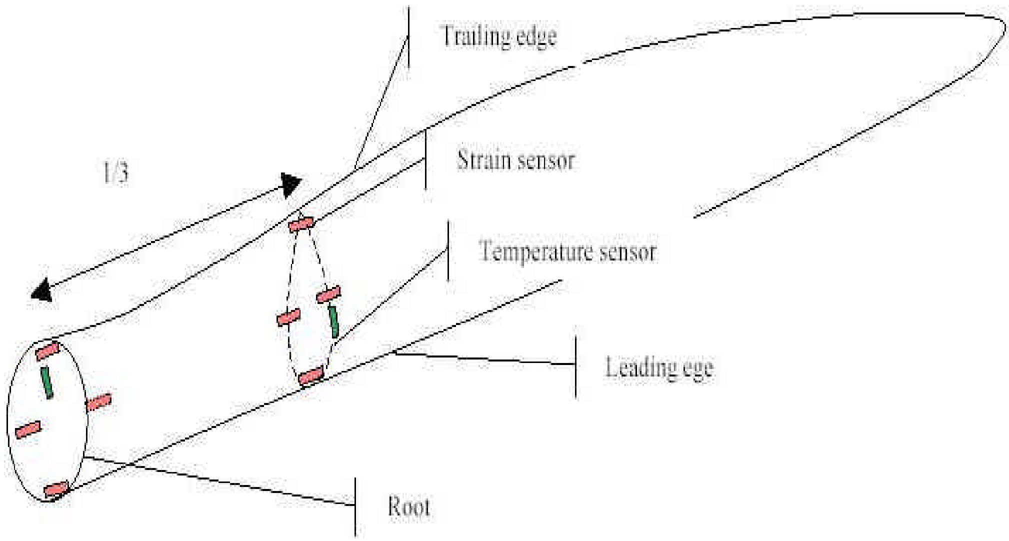

Figure 1: Strain sensor configuration in wind turbine blade

Measurement techniques

For measuring the characteristics of blades, more types of sensors can be used. Examples are, accelerometers, strain gauges, optical sensors and acoustic sensors. Normally for load measurements, conventional strain gauges are common practice. They measure the strain in two directions in the root of the blades, which is used as a measure for the loads. This is considered as an accurate measurement technique, which is commonly applied for load measurements. A major disadvantage of this measurement technique is that copper strain gauges are considered as unreliable over longer period and need to be calibrated periodically.

Optical strain gauges based on Bragg grating techniques, see figure 2, are expected to be more reliable. Another major advantage of optical fibers is that they are not sensitive for EMC, lightning, and so on. However, the sensors in combination with read out units are still much too expensive for condition monitoring applications on a large scale, while they are sensitive for temperature variations, which has a negative influence on the accuracy. A part of the research has been to obtain practical experience and to quantify the advantages and disadvantages.

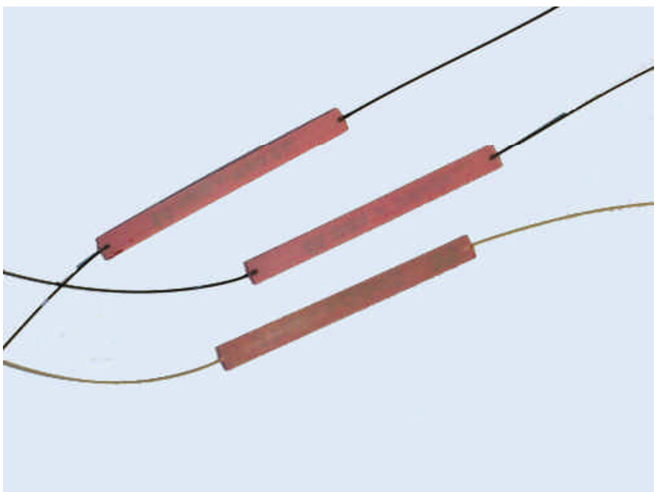

Figure 2: Optical strain sensors for retrofit application

There are several options for the installation of the sensors:

- The Bragg gratings can be put on a layer, which can be glued on the blade like classic strain gauges. This option is suitable for retrofit applications, when the system is installed in an existing wind turbine.
- Another option is to integrate the Bragg grating in the blade material. In this case installation should be done during the blade production process. This will require special provisions during the blade production. When this option is feasible, it might result in a more robust sensor configuration, which is less sensible for damage during maintenance actions. However, in case of damage, repair is not feasible.
- An option in between is, to mount the sensors on the blade surface at the manufacturer side and to cover the string of sensors with an extra layer. Mounting can be done in a controlled environment, while there is minor interference with the blade production process.

Integration of the sensors in the blade material is often seen as the most promising options. However there are a lot of uncertainties to be solved. We identified the following problems, which has not yet been solved:

- Integration of the strain sensors in the blade material demands special properties with respect to the coating. This must ensure good contact with the blade material and give good protection during blade production. Before integration in the blades, the sensors can be tested and replaced if necessary. However after blade production, repair is not possible. So the installation of the sensors in the blades during production should be well under control and uncertainties should be minimised.
- For the temperature sensors free motion of the Bragg sensor should be ensured, while there should be a good thermal contact. In order to realise this, the Bragg sensor should be integrated in a layer or housing.
- Integration of the sensors in the blade material is mainly of interest when the strain is measured in a large number of locations. Good insight in the blade behaviour and design is necessary to identify the hot spots, which are of interest for strain monitoring. When the condition monitoring is only focussed on blade load monitoring, only strain measurements in the blade root are of interest which only requires a small number of locations which is good accessible after production.
- Not only blade manufacturers are interested in blade condition monitoring, but also the operators and maintenance companies. This means that the possibility to install these kind of provisions afterwards is certainly an advantage.

During the development we have chosen for the retrofit option, where the sensors are glued in the blade root. For the short term, this option is seen as the most realistic in order to have a system suitable as a first generation blade monitoring systems. However, on the longer term, when blade condition monitoring is applied on a larger scale, and the sensor technology is sufficiently developed, the integration of sensors might push aside the retrofit option.

Instrumentation

The sensors are mounted in optical lines. Each line can accommodate 4 to 8 sensors (strain as well as temperature), depending on the maximum range. Nine optical lines can be connected on the rotor module, which is installed in the rotor. This rotor module converts the measured frequency shift due to the Bragg grating deformation into strain signals. Due to the temperature sensitivity of the strain sensors, temperature sensors are also installed for temperature compensation.

Figure 3: Fiber optic rotor module for eight lines

Basically, the rotor module (figure 3) is a measurement system, which sends data via a wireless bridge tot the nacelle or turbine module. However it might also incorporate some diagnostic functions. In this case it might send messages directly via e.g. GSM in case of serious alarms, such as extreme overloading. The diagnostics for early fault detection will be performed in the nacelle or turbine module, which also incorporates the storage facilities and user interface. Users can communicate with the nacelle module via Internet.

For the diagnostics, the system should also get wind turbine data, such as rotor speed, wind speed, blade angles and electrical power. This requires an interface with the wind turbine control system. The nacelle module as well as the rotor module can be controlled remotely. After installation, no local activities are foreseen. Replacement of the rotor module for periodic calibration is considered as an option for the prototypes. Normally the system will be accessed by the wind farm operator. In case of recognition of faulty situation, specialists or manufacturers can also access the system for more detailed signal analysis.

In figure 4 a typical configuration is given. This has been installed in a NORDEX turbine on the

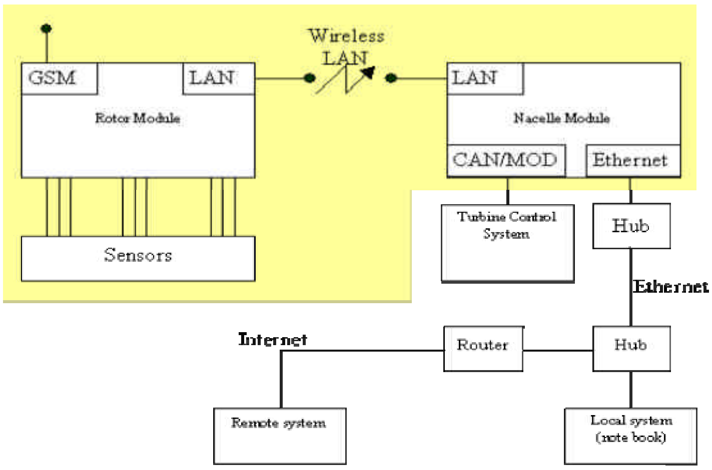

Figure 4: Blade condition monitoring configuration

test field of ECN (EWTW). The measurement data is combined and stored in the Nacelle Module. Apart from that, we also have a back-up facility at ECN, because the system is still under development and software modification might imply the need of historical data in order to initialize the diagnostics software.

Operational experience

The sensor configuration as well as the instrumentation has been installed in a turbine and was applied for measurements during a one year period. Apart from the optical sensors, conventional strain gauges have also been installed in the root section of the blade.

From figure 5 we see that signals from the optical strain gauges and the convential strain gauges show a very good similarity. The weight of the blades is of course dominant in these signals.

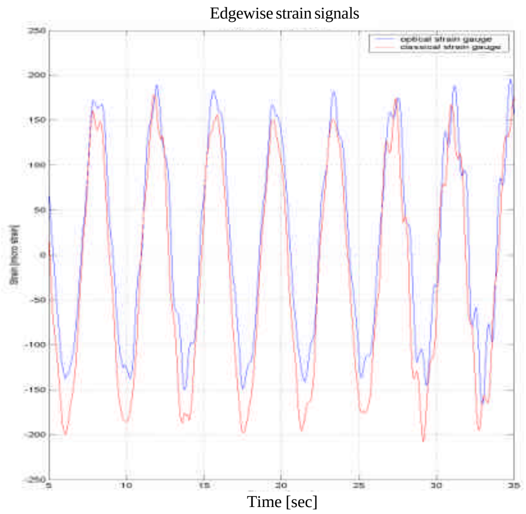

Figure 5: Time series of edge-

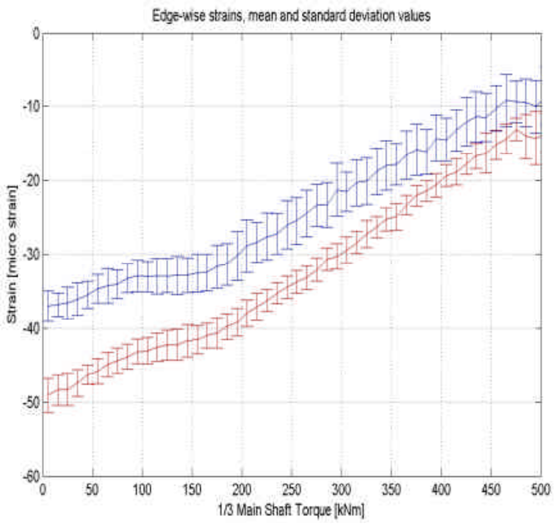

Figure 6: 10-minute mean

Looking to the 10-minute mean values however, gives a somewhat different view (see figure 6). The scatter of the optical strain gauges is larger than for the conventional strain gauges. This scatter is caused by the lower resolution of the optical sensors while they are also sensitive to temperature changes. This makes that the current sensor design is less suitable for absolute strain measurements at low load levels. For measuring fatigue loads the measurements are considered to be adequate.

From this evaluation we learned that the application of Bragg sensors does not automatically ensure reliable and accurate measurements, which does not require any calibration. The resolution of the used system was sufficient for measuring fatigue loads. However for absolute load measurements at low levels, modifications for the temperature compensation, together with an improved resolution was recommended and has been implemented in the current design.

Diagnostics for condition monitoring

The diagnostics are based on the general load measurements. At present, no distributed strain measurements are foreseen. Based on the blade root measurements, several analysis methods can be of interest, which gives the operator information about the loads encountered, which can also be extrapolated over the life time. To the extend possible, the analysis of loads corresponds with the requirements in the IEC standards [3]. The following analysis are "under construction" at this moment.

Damage calculation at strain level

Each strain cycle will contribute to the fatigue damage of a blade. Please note that this procedure is valid for both blade root measurements and distributed measurements. The number of occurrences of strain cycles can be counted with a rainflow count procedure and stored in a Markov matrix. Generic or better specific, data can be used to assess the observed strains. The material data for fatigue are usually presented as S-N curves showing the maximum allowable strain range S to survive a certain number of cycles. The total damage of GFRP during a certain period at different ranges equals the sum of all partial damages at a certain range. The results can be presented in a graph similar to figure 7.

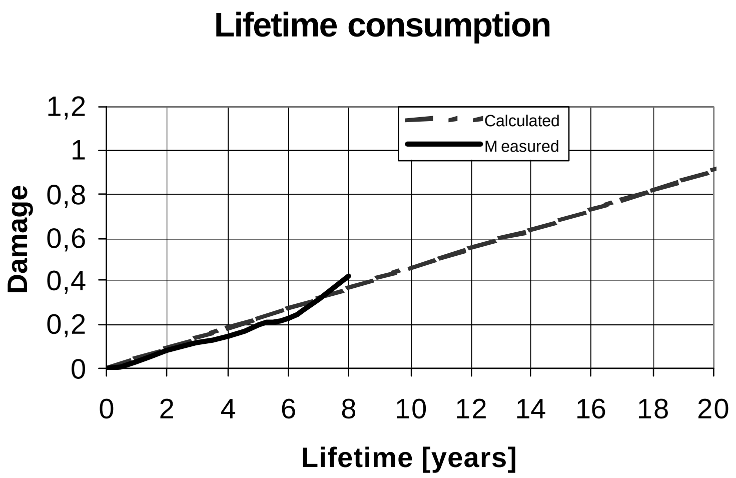

Figure 7: Damage estima-

Load spectrum

The alternating edgewise and flap wise bending moments are first counted and stored in rain flow count matrices in which the occurrence frequencies of the alternating loads with a certain

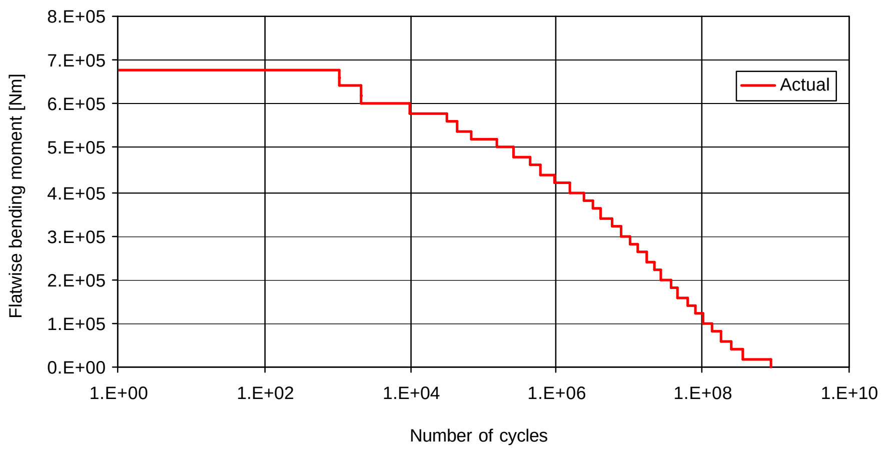

Figure 8: Example of load spectrum of flap wise bending moment

mean and a certain range are given. Without any design data available it is recommended to present the counted fatigue loads as load spectra. Load spectra in fact show the number of times that certain ranges are exceeded. Load spectra do not provide information on the mean levels anymore. An example of a load spectrum of a flap wise bending moment is given in figure 8. Such a spectrum can be constructed by continuously counting the fatigue loads during steady state operation and combining them with the loads during transient events and extrapolating them to 1 year or over 20 years lifetime. Such spectrum provides information of one blade of one turbine only. The spectrum becomes even more relevant if it can be compared with other spectra.

1. The wind conditions at the site will differ from the design wind conditions as specified in relevant standards. With the capture matrix and the available rainflow count matrices and the annual wind speed distributions, the load spectrum can be constructed for the three IEC wind speed classes [4]. If the actual loads are more benign than the loads for the design wind speed class, the operators may expect a slower degradation of the blade and thus a longer fatigue life. An example of such a comparison is given in figure 9.

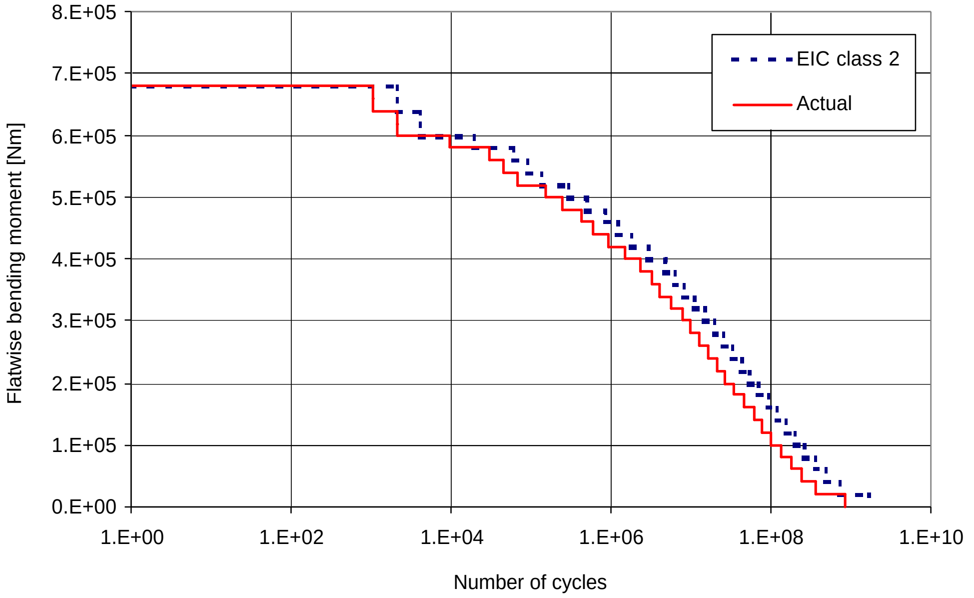

Figure 9: Example of comparison between actual load spectrum and load spectrum in accordance with the design wind conditions (in this case IEC class 2)

2. A second comparison can be made between the loads of different turbines within a wind farm. The turbines with the highest loads will suffer the earliest from fatigue damage and should be inspected most frequently. An example is given in figure 10.

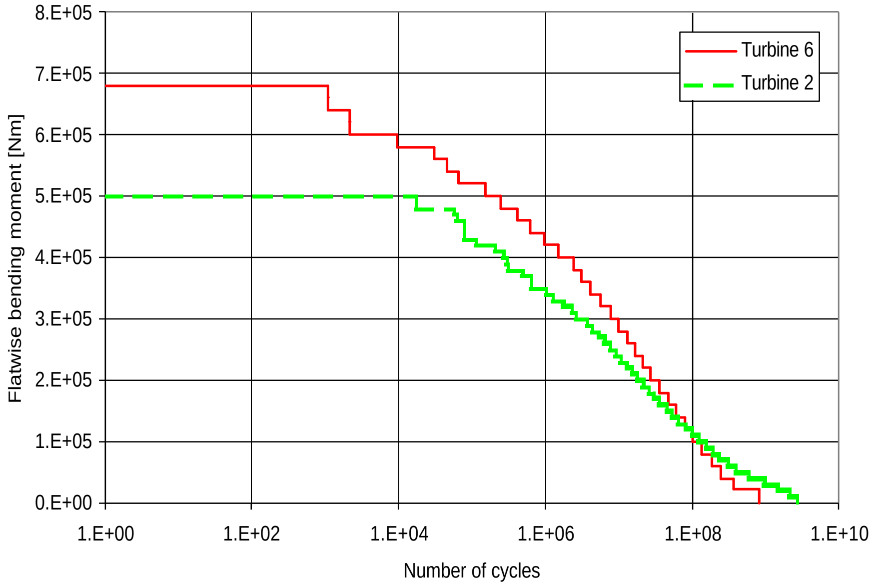

Figure 10: Example of comparison between the fatigue loads of two wind turbines within one wind farm

Equivalent loads

A simple method to compare fatigue loads can be achieved by the calculation of equivalent loads. The equivalent load is conceptually the single load amplitude that, when applied with the total number of cycles in a given time history appearing at a given frequency (e.g. 1 Hz), results in the same fatigue damage as the sum of all the different rain flow-counted load amplitudes in the measured load spectrum. The great advantage of the equivalent load is that it provides a single descriptor of the fatigue damaging potential of a particular loading during a given time period.

If the design load spectrum is available, the equivalent design load can be determined and compared directly with that of the measured loads. If detailed material data is available, the equivalent loads can be determined more accurately and will become even more meaningful.

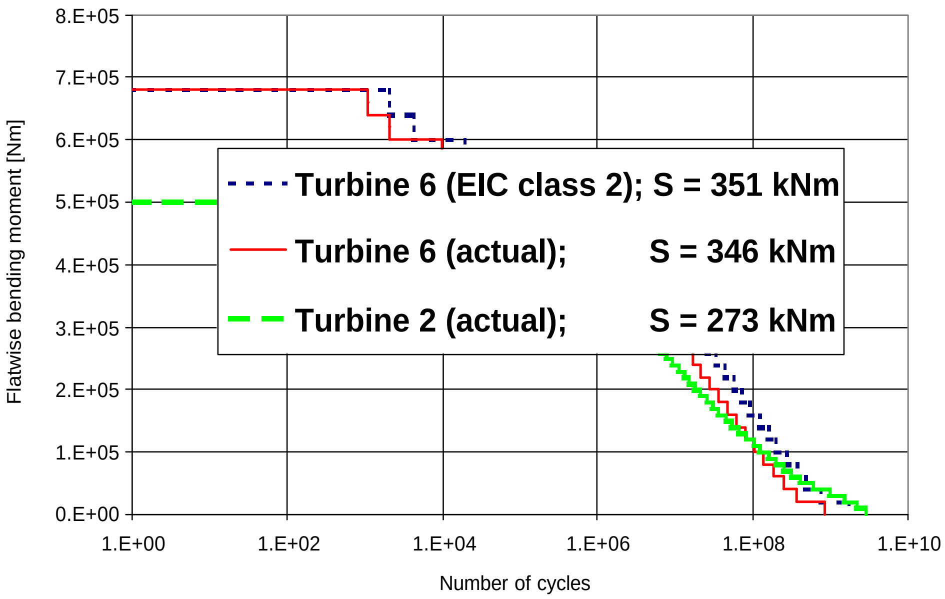

Figure 11: Three load spectra reduced to three equivalent loads

Future work and conclusions

With the system as presented here, we have a powerful start for condition monitoring of one of the most vulnerable components of wind turbines. With respect to the hardware and software further development work will be necessary. Because this also requires experience, this will be done together with field applications.

The system as presented here will be installed on a NORDEX turbine before the end of 2004. It will be in operation for about one year in order to get operational experience with it and to optimise and extend the algorithms. During this period, all the measurements will be stored on the turbine module, with a backup at ECN. Based on this historical database, algorithms can be tested off-line before they are implemented in the turbine system. Apart from that, the algorithms also use historical information in rain flow matrices and recursive relations. This means that in case of modifications, initialisation will be necessary in order to be able to compare the results and to keep to development time short.

Apart from the software development, development work will be necessary with respect to sensor technology and instrumentation. For the sensor technology, a first step might be to integrate the strain- and temperature sensors on one layer. However in order to achieve sufficient cost reduction and sensor configuration simplification, we should strive for strain sensors which are less sensitive for temperature. Finally partial or complete integration of the sensors in the blade material should be considered as the ultimate solution.

For the instrumentation, also further cost reduction will be necessary. This refers to the investment cost as well as with respect to the calibration. At this moment we assume that the rotor module should be exchanged yearly for inspection and calibration. This solution is of course not acceptable for installation in remote areas. Hardware exchange is not acceptable during the lifetime of the blades and all maintenance of the system should be possible by remote access.

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