ECN

Energy research Centre of the Netherlands

DOWES

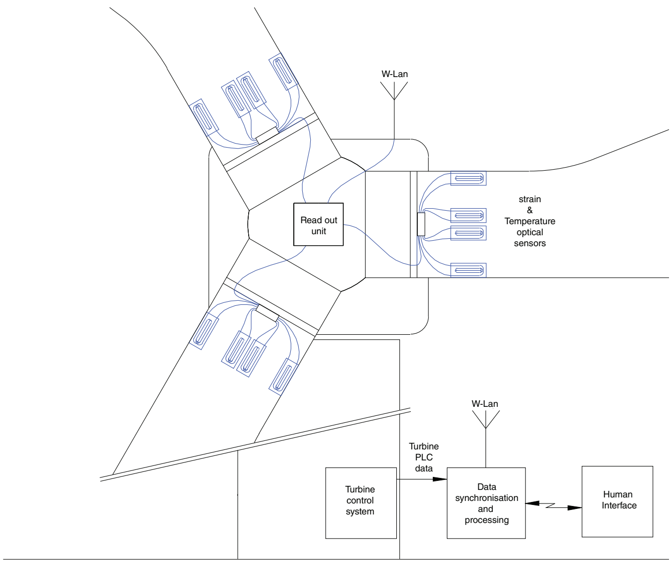
Dutch Offshore Wind Energy Services

Fibre Optic Blade Load Monitoring (FOBM)

Why Blade Load Monitoring?

Condition based maintenance is becoming more and more a means to better control the O&M costs of wind turbines, especially offshore where site visits are very expensive. Condition based maintenance as a replacement of corrective maintenance leads to less downtime, less consequence damage, better planning of activities, better use of resources and equipment, and thus lower costs. Many systems are already on the market to monitor the health of components. SCADA data, drive train monitoring, visual inspections, oil samples, etc. are all common practice in wind energy and have proven their added value. However, all these techniques have in common that they start providing useful information not before the degradation of the components really starts to occur. Since the degradation of the components is strongly related to the loads acting on the components, ECN has been seeking for a solution to monitor the mechanical loads. Since most of the loads are introduced via the rotor blades, ECN's development have been focusing on a low cost method to monitor the blade root bending moments and process the data in such a way that it is useful for turbine operators to decide e.g. if and which maintenance action is required to avoid failures from happening, to postpone or prioritise visits, or to decide on extension of the turbine life.

How does the FOBM system look like?



The system is based on optical fibres with Bragg gratings to measure the strain in the blade roots. As opposed to the commonly used copper strain gauges for measuring the blade root bending measurements, the optical fibres in theory should have less drift over time, longer lifetimes, and provide reproducible data. In the last decade, many attempts have been made to demonstrate the advantages of optical fibres for strain measurements in rotor blades but most of them failed. The technology was not mature enough, the influence of temperature was under estimated, installation of sensors and measurement equipment led to too long turbine standstill, and the final result looked far from professional. Finally, once the measured data was obtained, it was unclear what to do with it; it could only be added to the large amount of data that was already available to the operators.

ECN has now developed the FOBM system that makes use of the benefits of the optical fibre technology but overcomes its negative aspects. The system consists of:

1. a newly and patented sensor assembly that is easy to install and replace, that requires no calibration, and provides reliable, accurate and reproducible strain data over a very long period;
2. a commercially available interrogator to read out the fibre optic sensors;
3. a measurement computer that derives loads data from strain data and combines the blade loads data with turbine PLC data;
4. wireless-LAN to enable communication between the rotor and the turbine base;
5. software for data processing that filters and cleans up the time series, categorises the data per design load case, and provides key figures, statistics, and graphs to the operator for O&M optimisation.

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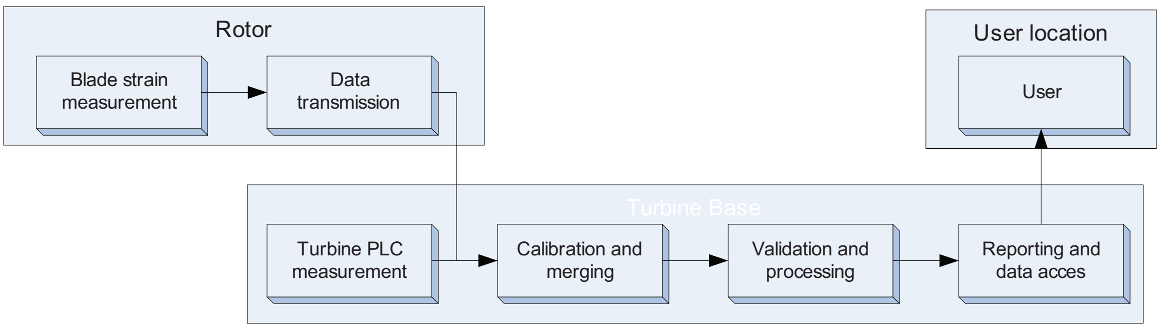
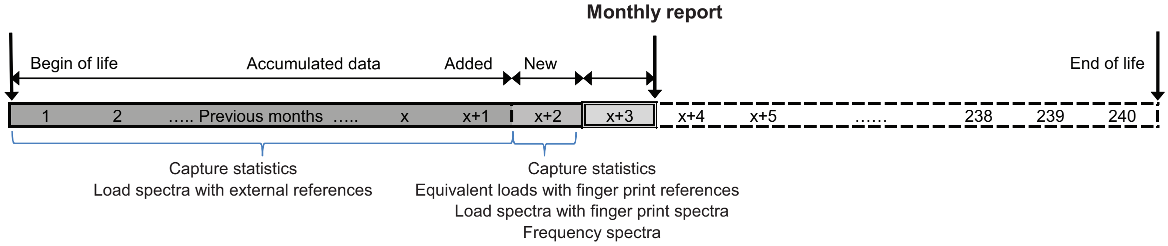
The entire system can be installed by regular maintenance technicians in less than one day and requires no further skills on fibre optics.

Load monitoring system set up



To measure the blade bending moments in flapwise and edgewise direction, four sensors need to be installed in each blade root. All four sensors are connected to one string and one string per blade is connected to the interrogator. The measured data can be obtained remotely.

Innovative algorithms for data cleaning and filtering
In general, operators want to understand if the turbine operates within its design envelope or not. If not, adequate measures should be taken. Next, operators want to understand if certain turbines are more heavily loaded than others. If so, O&M activities can be prioritised, as well as the analyses of condition monitoring data and inspection results; if not, maintenance could be postponed for some time.



Time scheduling for monthly reporting and data approval

ECN has implemented the data analysis as follows. From the beginning on, the software starts building up a capture matrix with statistically sufficient data that can be used as a reference data set further on. All time series relevant for the capture matrix are being stored (a.o. for traceability purposes). The time series are also being used to derive finger prints, envelopes, and criteria for rejection. Once the measurement campaign is running, the software determines every 10 minutes which load case has occurred (normal operation, start-up, shutdown, emergency shutdown, etc.) and filters out erroneous data (extensive and automated quality checks!). Next the software determines statistical data (a.o. min, max, mean, standard deviation and equivalent loads), updates the load spectra plots, and analyses the frequencies. Time series themselves are only stored if they are used for finger print information or when the processing is not finished successfully.

The software provides reports every month and with information about the captured data, the deviations with respect to the long term statistics, and a comparison with the finger print data. Furthermore, the monthly reports contain information about extreme loading conditions and possible errors of the measurement system. On the longer term, the operator can ask for reports with information about the cumulative loading of the blades and rotor (equivalent loads, fatigue spectra) to monitor the consumed lifetime. The information can be used for comparison with design data or for comparison with data of other turbines.

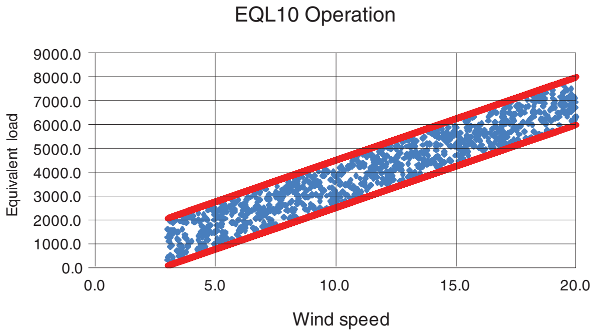
Statistics:

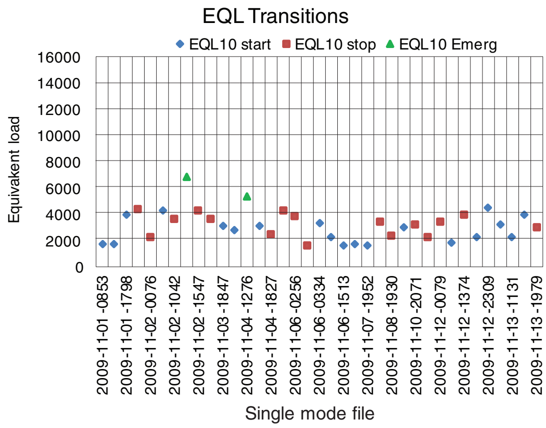
After every month an overview is generated about the performance of the measurement system. This report provides details about the measurements as processed during the last month and about the measurements during the life time.
The data processing performs checks on the data quality, which implies that data might be rejected due to measurement faults or unidentified operational modes. These time series are put in quarantiaine. These files are stored for further analysis as required. The results with respect to the encountered loads can be adjusted with respect to the loss of data.

Turbine ID:	Month		Lifetime	
Start:	Files	Time [hour]	Files	Time [hour]
Elapsed time		744		39850
1 Start	20	3	1071	134
2 Power production	4400	700	230672	36660
3 Emergency shut down	2	2	107	98
4 Normal shut down	18	2	964	80
5 Idling at high wind	10	0	536	11
6 Parked at high wind	5	1	268	27
7 Idling at low wind	50	10	2678	536
8 Parked at low wind	1	2	54	107
9 Waiting for wind	50	1	2678	27
Valid single mode files	4556	719	239028	37679
Quarantaine	80	25	4285	2171
Time covering	96.6%		94.6%	

Equivalent loads:

The equivalent loads are calculated for all single mode files. For the stationary operational modes (e.g. power production), the equivalent loads are plotted as a function of the wind speed.





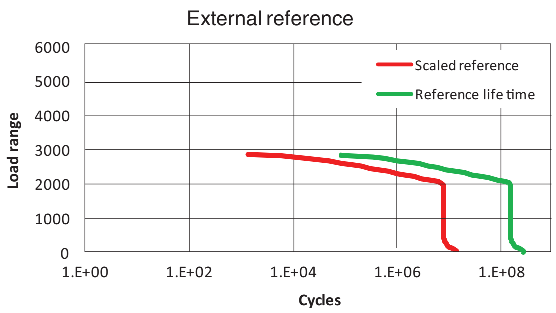
Equivalent loads during turbine operation

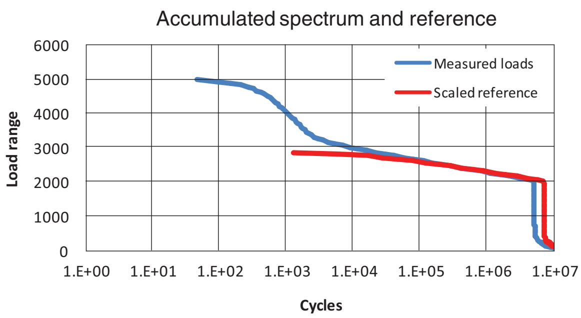
Equivalent loads during starts and stops

For the transient, the values are plotted for all individual single mode files. The values should be within the limits as determined based on the capture matrix. Based on these plots, extreme values can easily be identified.

Load spectra:

In order to give the user information about the encountered loads efficiently, the load spectra are plotted for the reporting month as well as for the life time. For the monthly spectra, a reference is used based upon the capture matrix. For the life time an external reference should be used.

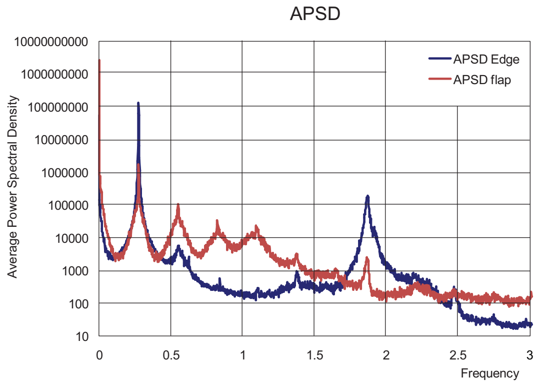




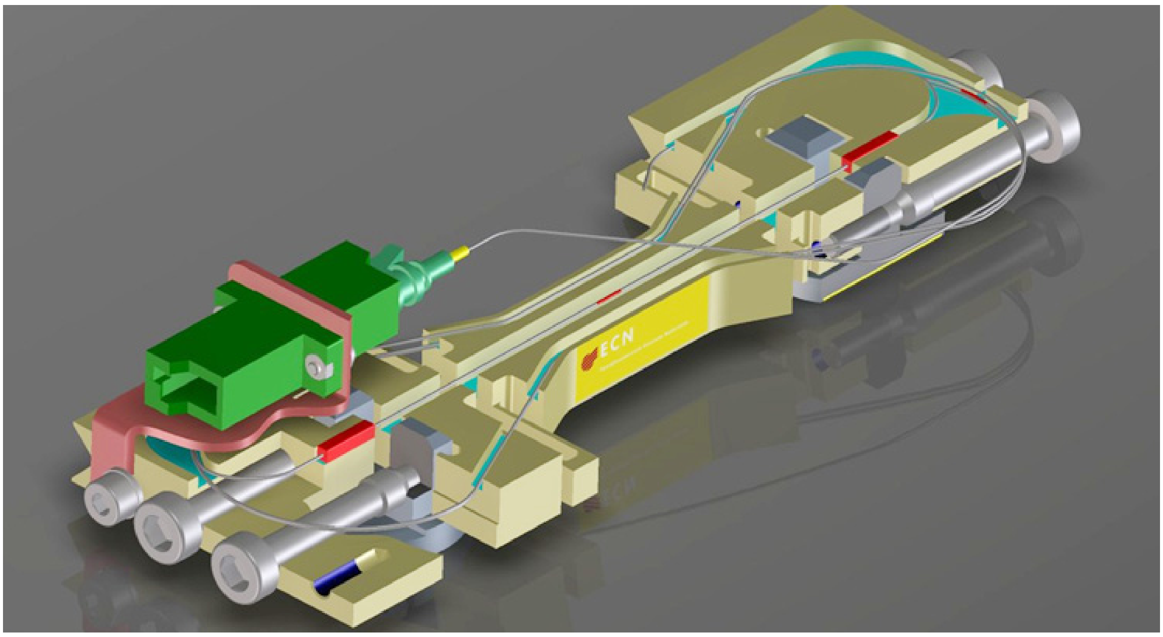
Example of measured load spectrum and reference values over measuring period

In the example a design spectrum is used, which is scaled with respect to the measuring period. Comparison with the measured spectrum gives an impression about the encountered loads compared with the design spectrum. When the user is interested in the consumed life time, a design spectrum is the most obvious choice. For prioritising maintenance, other references can be more useful. E.g. a measured load spectrum of a turbine of the same farm could be used so that the encountered loads on the turbines can be compared. This information can be used for maintenance planning.

Frequency plots (Average Power Spectral Density):
Under certain conditions, spectra of the blade loads are made. Changes in the structural properties of the blade affects the spectrum. Shifts in frequency or changes of the amplitudes can be detected.
In the first period of operation, finger prints are made and stored in a capture matrix. For these finger prints, time series are selected within wind speeds bins of 1 m/s and with small rotor speed variations.
In the figure, the frequency plots for two directions are given. As a function of time, these plots can also be presented by a rain fall plot.



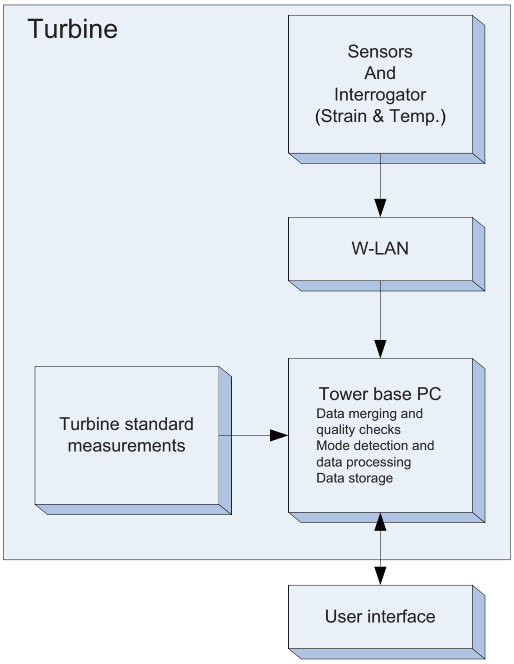
Optical Sensor Assembly
The FOBM system requires four sensors per blade to determine the blade load bending moments in edgewise and flapwise direction. ECN has developed a special sensor assembly for strain measurement in wind turbine blades as a “plug-and-play device”. The sensor consists of a fibre with a Bragg grating mounted between two studs via a carrier. The studs are mounted on the inner side of the blade root at a distance of 10 cm. The carrier ensures that the fibre follows the displacements of the studs and with this approach the strain in the blade root is measured over a sufficient length to avoid local effects of the blade material. The carrier protects the fibre for sharp bending and also accommodates a second Bragg grating for temperature compensation. Each strain sensor can be compensated by a local temperature sensor which avoids the effects of temperature differences over the blade.
To install a sensor, the technicians need to glue the studs on the blade with the help of a dedicated mounting tool. After a short curing time, they can mount the carrier on the studs, tighten the screws, and plug-in the patch cables to the two connectors. The carrier with the fibre and connectors is assembled in the factory under well defined conditions and is already calibrated.
During operation, the sensor provides strain data under both tension and compression with high accuracy (5 με) over a long period of time. Re-calibration is not necessary, because the sensor itself it very stable. If, for what so ever reason, the sensor should fail it can be replaced by taking off the failed sensor assembly from the studs and put on a new one. Since all assemblies are calibrated in the factory, on-site calibration is not necessary.
This innovative and patented sensor assembly has proven to work reliable, to provide strain data with high accuracy, and to offer easy installation and replacement.



The fibre itself has a very high ultimate strain and can easily survive the life time of the turbine. The most critical element is the connection between the blades and the studs. This connection is chosen for application in existing turbines. The design of the sensor is suitable for application of other fastening methods which match in the manufacturing process of the blades.

System Architecture
Apart from the sensor and the software for data analysis, the system consists of a commercially available interrogator to read out the fibre optic sensors, a measurement computer that derives loads data from strain data and combines the blade loads data with turbine PLC data and wireless-LAN to enable communication between the rotor and the turbine base.

Interrogator:
The interrogator, which meets the requirements for wind turbine applications are available at the market, although robustness, price level and performance still requires additional development. Although several types of gratings can be used in our sensor, we prefer to use Draw Tower Grating with Ormocer coating in combination with an WDM interrogator with three channels. This approach ensures a robust and stable measurement system, while the disadvantages of wavelength gratings is minor due a the well controlled production process of complete measurement strings. In this case four different sensor assemblies are sufficient to cover the whole measurement range for one blade, while the configuration for each blade can be kept identical.



Measurement PC:
The measurement PC is a standard device with windows operating system. Data is imported from the turbine PLC as well as from the blade load measurement system. The measurement software combines these data, and processes the data which results in single mode files. Based on these files, a data base is filled with statistical data, load spectra frequency plots and a capture matrix with finger print information. The amount of data to be stored is limited, because the original time series are thrown away after successful processing. Only time series which are used as finger print information (capture matrix) are stored in the system.

User interface and remote access:
The user can get access to the system in order to retrieve the information required. This can be realised via standard communication provisions. During the development phase, the reporting module is running on the remote computer. For commercial implementation other configurations will be more consistent with the application.

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