Fibre Optic Load Monitoring
of Wind Turbines

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Load Monitoring for Condition Based Maintenance

Operation and maintenance (O&M) of offshore wind turbines is one of the main cost drivers of offshore wind energy today. At present, the OPEX costs contribute for approximately 25% to the Levelised Cost Of Energy (LCOE). 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 common practice in wind energy and have proven their added value. However, all these techniques have in common that they start providing useful information after the components really start to degrade or fail. Since the degradation of the components is strongly related to the loads acting on the components, ECN has been developing a solution to monitor the mechanical loads. Since most of the loads are introduced via the rotor blades, ECN's developments 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.
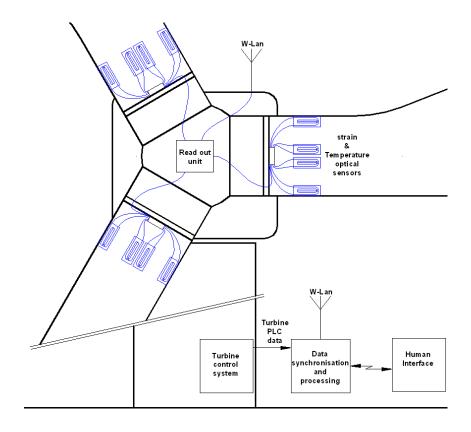
Fibre Optic Load Monitoring System

The specifications for the fibre optic load monitoring system are based on ECN's broad experiences with measurement campaigns in wind turbines and understanding the shortcomings of electrical strain measurements. The procedures for data processing, analysis and reporting are in line with the IEC standards for wind turbines.

The measurement system to measure the loads in the rotor blades of the individual turbines consists of[1]:

1. a newly and patented sensor assembly with fibre Bragg gratings that is easy to install and replace, that requires no calibration, and provides reliable, accurate and reproducible strain data over a very long period (four assemblies per blade);
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;
6. software that combines measured blade root bending moments with SCADA data and generates also loads for other main components like drive train and tower top.

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[1] *The fibre optic load monitoring system can be purchased as a complete package, but it is also possible to purchase only the sensors or only the software from ECN. The sensors can also be applied in other parts of the turbine (e.g. tower) and can even be used for other applications than wind energy. The software can also be used in combination with other measurement systems.*

Sensor Assembly

ECN defined the following specifications for the sensor assembly.

- The sensor assembly is easy to install and replace by regular wind turbine maintenance technicians who need no special skills on fibre optics (Plug-and-Play).
- The entire system can be installed by the technicians in less than two days.
- To prevent the effects of non-homogeneities the sensor should measure the average strain accurately over a well-known distance.
- On-site (chain) calibration is superfluous after replacement of the sensor.
- The sensor has the same lifetime as the rotor blade.
- Technical data:
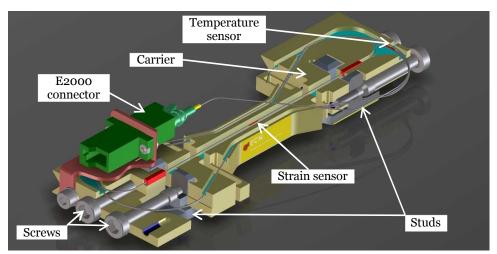 - Strain resolution   : $1\ \mu\varepsilon$
  - Strain accuracy / stability   :   better than $5\ \mu\varepsilon$
  - Maximum strain level   : $-1000 \ldots +1000\ \mu\varepsilon$
  - Long term drift   :   less than $5\ \mu\varepsilon$ in one year
  - Temperature range   : $-20\ldots+40\ ^{o}C$
  - Long life time   : $> 10^{7}$ cycles @ $\pm 1000\ \mu\varepsilon$

To meet the above specifications, the sensor consists of a fibre with a Bragg grating mounted between two studs via a carrier. The studs are mounted at a mutual distance of 100 mm to the inner side of the blade root. 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. Since each strain sensor is compensated by a local temperature sensor, the effects of temperature differences over the blade can be detected. The fibre is manufactured with draw tower technology (*www.fbgs.com*) and

has proven to have a very high ultimate strain (up to 6%). The assembly with Draw Tower Gratings can easily survive the life time of the turbine.

The sensor is suitable for applications in both existing turbines (retrofit) and new blades. Since all assemblies are calibrated after production under well-defined conditions, on-site calibration after repair is not necessary which keeps the downtime to a minimum.

Installation Aspects

To glue the studs on the inner side of the blade root, the technicians are provided with a dedicated battery operated tool for quick mounting and accurate mutual positioning. Prior to bonding of the studs, the specific areas of the blade are grinded using the stud mounting tool. For the mounting of the studs an adhesive was selected with a low curing time (15 minutes at 20 ^{o}C) and which can survive the dynamic loads. Completion of the mounting of the studs takes only 20 minutes, including the curing time!

The dedicated housing (see picture at cover) enables simple mounting, inspection, and replacement due to the base plate and removable cover. The housing should be mounted during the curing of the stud connection.

Finally, the technicians mount the carriers on the studs, using only four bolts for rigid connection, and plug-in the patch cables into the two E2000 connectors. The protective covers are attached to the base plates to shield the sensors from moisture and impacts.

After the sensors are installed, the interrogator can be mounted in the hub, the PC can be installed elsewhere in the turbine, and all devices can be connected with electrical cables and optical fibres. First runs have shown that the tight installation schedule can indeed be met. The entire measurement system is designed to limit the amount of onsite work; most of the preparatory work can be done in the workshop.

Read-out Unit (Interrogator)

ECN defined the following specifications for the read-out unit for wind turbine applications:

Minimum Wavelength range:	1520-1580 nm
Strain resolution:	1 $\mu\varepsilon$
Strain accuracy / stability:	better than 5 $\mu\varepsilon$
Sensor readout frequency:	>16 Hz
# Fibre Bragg Gratings per blade:	8 (4 strain + 4 temp.)

Various suppliers provide interrogators that meet the general specifications. At present ECN uses the WindMeter from FibreSensing (*www.fibersensing.com*). This device is based on WDM technology for readout of the sensors and is especially designed for wind turbine applications, It has three channels, is available in a robust housing and has a minimum power consumption. The maximum frequency readout frequency for the sensors is 100 Hz.
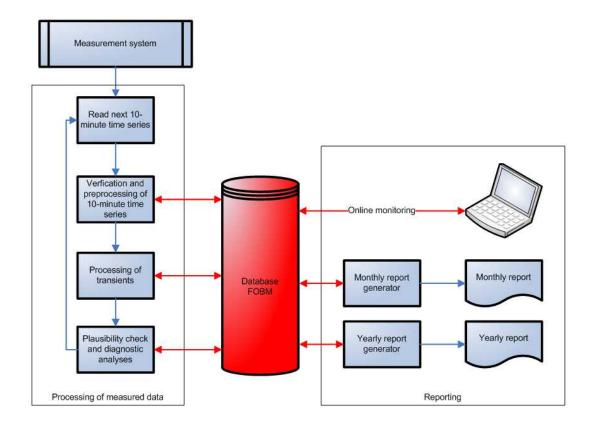
Software for Data Analysis and Reporting

ECN has developed software that automatically analyses the large amounts of raw data and provides information to operators of wind farms about accumulated loads, extreme loads, dynamic behaviour and vulnerable spots. The software contains an algorithm that first cleans and filters the data and removes spikes. The software detects the load cases (operational modes) present in the time series, possibly splits the 10 minute time series into single mode files, and stores the data with statistics of the single mode files into the relevant database field. The identification of the load cases is being done based on the turbine PLC signals like power, nacelle wind speed, rotational speed, etc. Next, ECN has developed software that reads out the database contents and generates reports, plots, and key figures with which the operator can take sound decisions for wind farm operation and maintenance. The data processing software contains two main processes.

1. An on-line module which continuously collects and processes the relevant data from the measurement system and subsequently stores the results in a database.
2. Reporting module, which provides online access to the database and which generates periodic reports.

Both processes function independently with a database as interface between the two parts. The database is primarily meant for: (1) storage of results of the diagnostic analyses, and (2) storage of control parameters and reference data required for verification and processing the measured data. The data stored in the database is in principle is limited to:
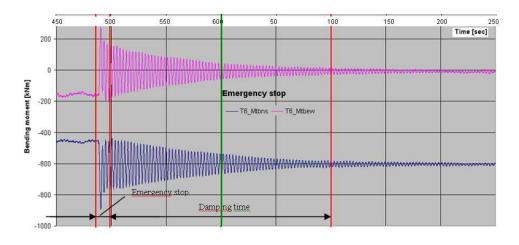
- Data processing information
- Logging information
- Operator warnings
- Rejected measurement data
- Capture matrix and related time series
- Statistical values of single mode files
- Cumulative data
- Frequency analysis results

Once the measurement campaign is running, the software determines every 10 minutes which load cases have occurred (normal operation, start-up, shutdown, emergency shutdown, etc.) and filters out erroneous data. For this, ECN has developed innovative algorithms to carry out quality checks automatically. Next the software determines statistical data (a.o. min, max, mean, stdv, and equivalent loads), updates the load spectra plots, and analyses the frequencies. Finally, the software is able to generate monthly reports with a.o. statistics, capture matrices, and load spectra. The results are available as cumulative results (from the start of the measurement campaign) or as results over the last month.

ECN has paid special attention to the processing of transients (start-up, shutdowns, emergency shutdowns, etc.) and the determination of statistical values. Default, the measurement system acquires 600 seconds time series and the majority of the time series will contain only one mode of operation like energy production, parked, or idling.

Such time series can be processed straight forwardly. However, transients may also occur and if they occur the start and end will be randomly within the time series. ECN's processing algorithms isolate such transients if they occur in the middle of a time series, or combine the start and finish of a transient if it is present in two time series as indicated in the above picture. This means that the time series are all single mode files (only one operational mode present).
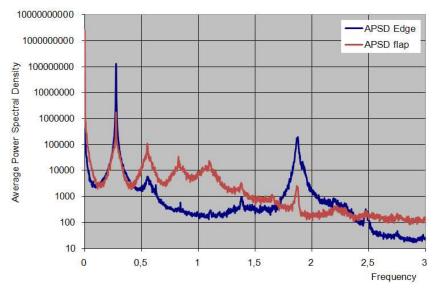
The (monthly) reports provide information about the captured data, the deviations with respect to the long term statistics, and a comparison with finger print data. Furthermore, the monthly reports contain information about extreme loading conditions and possible errors of the measurement system. On 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: *Example of tables with number of measured files per operational mode for total measurement period (left) and one month only (right, January 2009)*
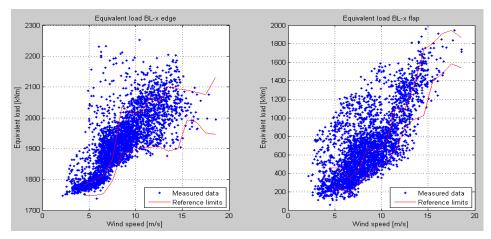
```
Number of days accumulated: 396
-------------------------------------------------
|   mode                    |number |   hours  |
|---------------------------|-------|----------|
| 01 Start up               |    27 |     2.01 |
|---------------------------|-------|----------|
| 02 Power production       | 17610 |  2916.41 |
|---------------------------|-------|----------|
| 03 Emerg. shut down       |     6 |     0.22 |
|---------------------------|-------|----------|
| 04 Normal shut down       |    27 |     1.00 |
|---------------------------|-------|----------|
| 05 Idling low wind speed  |   538 |    74.11 |
|---------------------------|-------|----------|
| 06 Idling high wind speed |    57 |     7.26 |
|---------------------------|-------|----------|
| 07 Parked low wind speed  |  1318 |   191.82 |
|---------------------------|-------|----------|
| 08 Parked high wind speed |   749 |   112.46 |
|---------------------------|-------|----------|
| 09 Waiting for wind       |   307 |    45.44 |
|---------------------------|-------|----------|
| 10 Not identified         |     0 |     0.00 |
|---------------------------|-------|----------|
| Quarantaine files         | 19591 |  3201.27 |
|---------------------------|-------|----------|
| Capture index             | 51.14 |          |
-------------------------------------------------
```

```
Month currently displayed is: 01-2009
-------------------------------------------------
|   mode                    |number |   hours  |
|---------------------------|-------|----------|
| 01 Start up               |     6 |     0.37 |
|---------------------------|-------|----------|
| 02 Power production       |  3124 |   518.16 |
|---------------------------|-------|----------|
| 03 Emerg. shut down       |     0 |     0.00 |
|---------------------------|-------|----------|
| 04 Normal shut down       |     4 |     0.14 |
|---------------------------|-------|----------|
| 05 Idling low wind speed  |   161 |    26.20 |
|---------------------------|-------|----------|
| 06 Idling high wind speed |     0 |     0.00 |
|---------------------------|-------|----------|
| 07 Parked low wind speed  |   302 |    47.54 |
|---------------------------|-------|----------|
| 08 Parked high wind speed |    65 |    10.08 |
|---------------------------|-------|----------|
| 09 Waiting for wind       |    56 |     8.21 |
|---------------------------|-------|----------|
| 10 Not identified         |     0 |     0.00 |
|---------------------------|-------|----------|
| Quarantaine files         |   873 |   133.30 |
|---------------------------|-------|----------|
| Capture index             | 82.08 |          |
-------------------------------------------------
```
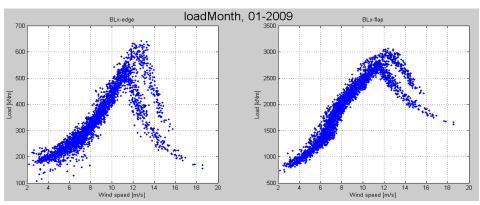
Frequency plots (Average Power Spectral Density): Example of APSD of both the edgewise and flapwise bending moments
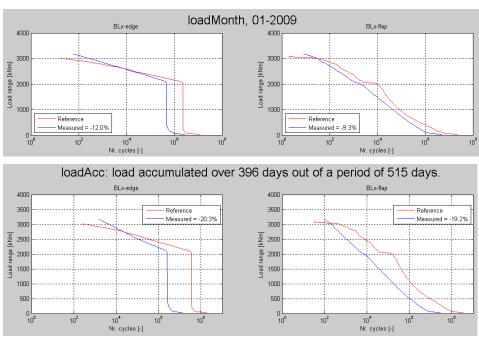
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Equivalent loads: *Example of plots with the equivalent load as a function of the wind speed (10 min. average) during normal operational modes*

Mean, min, max, stdv: *Example of plots with the mean values of the bending moments as a function of wind speed*
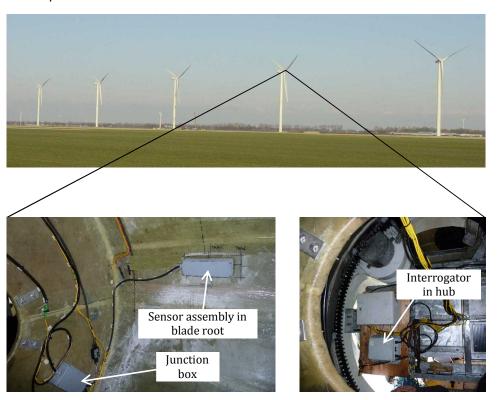

Load spectra: *Example of plots with the load spectra (edwise and flapwise) during one month of operation (January 2009) and the entire measurement period*
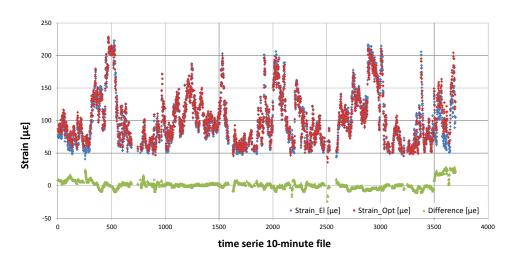
Experiences

The fibre optic load monitoring system is initially developed as a device to measure blade root bending moments in operating wind turbines over a long period of time with high accuracy and long term stability. The system has been operating successfully for several years now in one of ECN's test turbines.

Many field and loboratory tests have been carried out and comparisons have been made with strain gauge measurements. The system has shown to be stable over a long period of time and operate within the required accuracies. Fatigue and ultimate tests have shown that the sensor and system meet the design specifications. The software for data analysis has proven to work well. The system is about to be installed in a commercially available turbine.

Comparison between 10 minute average values of the optical (red) and electrical (blue) strain measurements, and the differences between the two (green)

Benefits and Future Applications

Apart from applications in wind turbine rotor blades, the sensor can also be applied in other parts of the wind turbine, e.g. for measuring and monitoring loads and strains in the tower (bottom) and substructures.

Compared to electrical strain gauges the optical solutions are insensitive to EMC and can be used in highly flammable and explosive conditions. Compared to electrical strain guages and patches with optical sensors that are glued directly onto the material (or are integrated with the material), the sensor design of ECN' has three strong benefits.

1. Overall strain: The sensor assembly is mounted on 2 studs which are positioned 10 cm from each other. This configuration provides excellent opportunities to measure overall material strains and avoid the local influences of in-homogeneities, small gaps, and/or stress concentrations. Especially for materials like reinforced concrete and plastics, the local strains are not always a measure for the average material strains.

2. Periodic measurements: Since the sensor can be easily put in place once the studs are mounted, the sensor provides a perfect solution for dedicated offline measurement campaigns. In wind turbines, but also in civil engineering or transportation it is possible to mount the studs first, determine a finger print, and repeat the measurement periodically. In between, the sensor and measurement system can be taken away and used for other purposes.

3. Production and manufacturing process: The studs can be mounted at the end of the manufacturing process of e.g. a rotor blade, tower, or a civil structure. It can be decided to also install the sensors and cabling at that stage. However, it is also possible to postpone the installation of the sensors until the entire turbine is commissioned. This could be a preferred option if it is expected that the sensor assemblies are subject to high (impact) loads during assembly and installation. Since the sensor assembly is an add-on that does not influence the actual manufacturing process of a rotor blade, blade manufacturers can easily offer the sensor as an option to their clients with minimal interference of the normal processes.
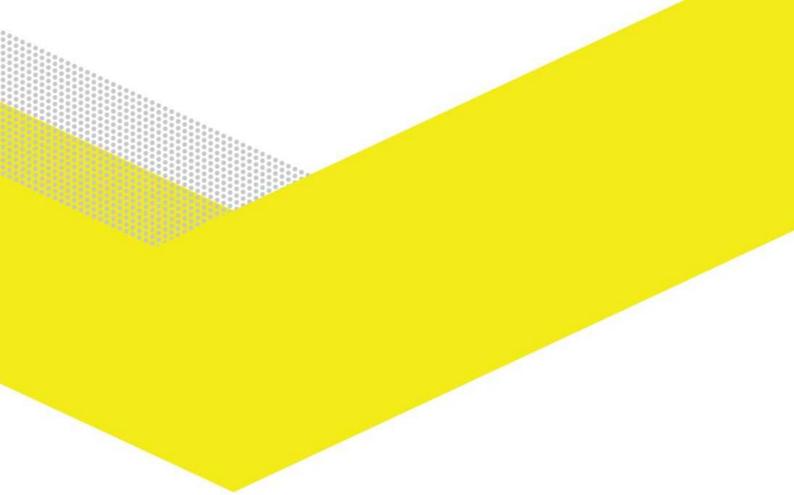
Interested?

If you are interested in learning more about the entire system, the sensors, or the software please contact us. We can explain in more detail the functioning of the system and discuss the benefits that the system may have for you. We are willing to set up a collaborative project with you to install a demo system in a turbine.

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