

Fibre Optic Blade Monitoring for optimisation of offshore wind farm O&M

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Abstract

Since 2005 ECN is developing a system for low cost load monitoring of wind turbines. The system is based on optical fibres and provides a solution to wind farm operators determine the accumulated loads and consumed lifetime of their turbines. The system that is being developed by ECN is called Fibre Optic Blade Monitoring (FOBM) and consists among others of a newly and patented sensor with fibre Bragg gratings, an interrogator with a measurement computer, and software for data processing to provide key figures, statistics, and graphs to operators of wind farms for O&M optimisation. As part of the D OWES project (Dutch Offshore Wind Energy Services) ECN has been working on the development of the individual components and the system integration. This report describes the specifications of the entire system and its sub systems and the results of activities carried out in the D OWES project. The developments have shown that the FOBM prototype meets most of its specifications.

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Summary

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). The majority of the O&M costs and downtime are caused by corrective maintenance. If a substantial part of the O&M effort can be shifted from corrective to condition based maintenance, the O&M costs can be lowered, unexpected downtime can be minimised and more revenues can be obtained. To enable the shift from corrective to condition based maintenance, the diagnostics should be adequate to inform the operators about the health of the turbines and the components.

Since 2005 ECN is developing a system for low cost load monitoring based on optical fibres as one of the solutions to inform operators about loads and consumed lifetime. Most of the mechanical loads are introduced into the wind turbine components (blades, pitch systems, yaw system, drive train, tower) via the rotor. Several degradation mechanisms of these components are expected to have a direct or indirect relationship with the loading patterns (fatigue or ultimate load, torque levels, accelerations, etc.). With such information, operators should be able to determine which components are most heavily loaded and prioritise their maintenance schemes, or postpone maintenance actions for those turbines that have observed less loading than designed for.

The system that is being developed by ECN is called Fibre Optic Blade Monitoring (FOBM) and consists of:

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 strain and four temperature sensors 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.

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

As part of the D OWES project (Dutch Offshore Wind Energy Services) ECN has been working on the development of the individual components and the system integration. Among others the following activities were carried out:

- testing and optimising the already existing prototype version of the FOBM sensor to ensure that it will meet its specifications on accuracy, long term stability, reproducibility, easy installation and maintenance, and low costs;
- selecting and testing interrogators to verify that they can be used for wind turbine applications in combination with ECN's innovative FOBM sensor;
- development of data analysis software that analyses the measured data and assists operators to shift from corrective and preventive maintenance to condition based maintenance;
- carrying out field tests to assess its long term behaviour and identify spots for future improvement of the FOBM system.

This report describes the specifications of the entire system and its sub systems and the results of activities carried out in the D OWES project. The developments have shown that the FOBM prototype meets most of its specifications. The system is easy to install, and operated well during the test period at the Nordex N80 turbines for 4 months. The interrogator, the wireless LAN, and the measurement system showed no problems. The data analysis software was used to process more than one year of data that were measured with electrical strain gauges. The algorithms for filtering, data cleaning, data classification (single mode files), and reporting functioned in accordance with the original specifications.

The temperature and strain sensors showed good agreement with the trends measured with electrical sensors. A point of attention is the modification of the glued connection between the fibre and the metal assembly since it is likely that this connection may cause some drift over a longer period of time.

1

Introduction

1.1 Condition monitoring and condition based maintenance

Operation and maintenance (O&M) of offshore wind turbines is one of the main cost drivers of offshore wind energy today. First estimates in 2000 showed that approximately 25% to 30% of the energy generation costs would be caused by O&M. Recent figures as presented at the EWEA2011 offshore conference show that the real OPEX costs still contribute for 23% to the energy generation costs. Vestas presented almost similar figures at the EWEA 2011 conference [1]. Although it looks as if the OPEX costs are at present a bit lower than originally expected, the actual costs are the same or even higher. In the early days of offshore wind energy it was expected that the total investment costs would be around 2500 €/kW installed. The present figures are around 3000 to even 4000€/kW installed, meaning that the absolute O&M costs have also increased over time. The typical figures for offshore maintenance are around 2,6 €/ct/kWh, but with large variations possible.

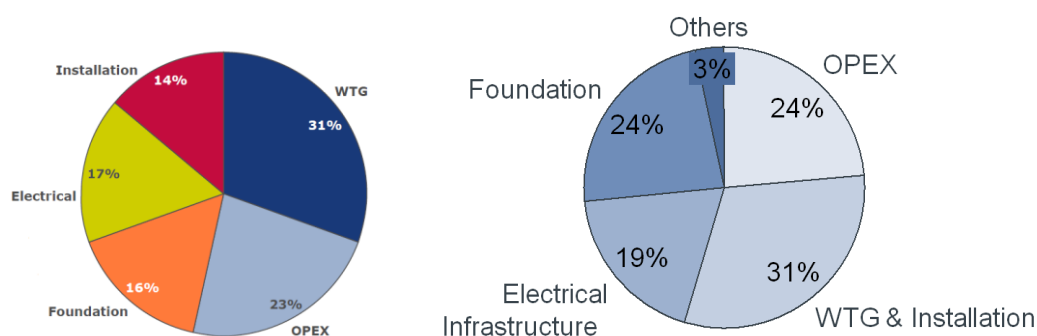


Figure 1.1: *Cost breakdown offshore wind energy as presented orally by several manufacturers at the EWEA 2011 offshore conference, e.g. [1]*

With the expected growth rates of offshore wind energy, and having more than 50.000 MW in the pipeline for Europe (BTM Consult) and average turbine sizes of say 5 MW, it is clear that some 10.000 turbines need to be accessed and maintained.

ECN has a wide experience with modelling the OPEX costs for offshore wind farms and determining cost effective O&M strategies. ECN uses among others the in-house developed tools like the ECN O&M Tool and the OMCE Calculator (= Operation and Maintenance Cost Estimator)¹. It is a general observation that the majority of the O&M costs and downtime are caused by corrective maintenance. If a substantial part of the O&M effort can be shifted from corrective to condition based maintenance, the O&M costs can be lowered and more revenues can be obtained. The shift to condition based maintenance will lead to less consequence damage, less downtime, better planning and use of resources, and repairs can be combined with already planned preventive maintenance. To enable the shift from corrective to condition based maintenance, the diagnostics should be adequate to inform the operators about the health of the turbines and the components.

Condition monitoring techniques have been used successfully for a long time in many branches of industry. Recently several different systems became commercially available for application to wind turbines, such as vibration monitoring systems for bearings and gearboxes and online oil monitoring systems. Next to the information provided by vibration monitoring systems, wind farm operators also receive information about the turbine's health from SCADA systems, and from inspection and maintenance reports. Between November 2002 and July 2007, ECN together with other research institutes, project developers and suppliers of condition monitoring systems has carried out a European project called CONMOW (Condition Monitoring for Offshore Wind Farms) among others to investigate whether cost effective condition monitoring techniques can be applied on a large scale for offshore wind energy applications and to quantify the added value [2][1]. It was concluded that most of the systems on the market are able to detect faults at an early stage and give an indication of the remaining life time and/or required operator interventions. To understand how the monitoring data should be interpreted, knowledge should be obtained from large populations of turbines, running under various conditions with identical fault situations.

Unique for wind energy are the attempts made to monitor the health of the rotor blades. They all have in common that they want to detect structural failures like cracks, loss of bonding, de-lamination, etc.. This can be done directly by putting sensors on the vulnerable spots, or indirectly by detecting changes in the structural properties like the natural frequency or noise propagation.

The above mentioned ways of monitoring all have in common that the failures need to occur (although small if the monitoring functions correctly) before they can be detected; the degradation of the component has already started. Secondly, the failure mechanism and the location where the fault will occur needs to be known in advance, otherwise no suitable detection method can be installed. For blades it is not always clear in advance which location is the most vulnerable one that needs to be monitored. Often it is known from laboratory tests, full scale tests, or design analysis. If so it is usually decided to reinforce the weak spots, rather than monitoring them. At present,

¹ To find out more about ECN's software and services for modelling OPEX costs of offshore wind farms, please check:
http://www.ewis.nl/fileadmin/ecn/units/wind/docs/EWIS/SP-310_OM_Tool_Brochure.pdf
http://www.ewis.nl/fileadmin/ecn/units/wind/SP-315_OMCE-Calculator_Brochure.pdf
http://www.ewis.nl/fileadmin/ecn/units/wind/docs/EWIS/IS-510_O_M_offshore_wind_farms.pdf

the authors are not aware of any blade monitoring system that has demonstrated in real life to be able to detect blade failures at an early stage and save money by adjusting the O&M strategy.

1.2 ECN's choice to develop low cost blade load monitoring

In 2005, ECN has decided to focus on low cost blade load monitoring, rather than on condition (health) monitoring. The rationale for this was as follows.

- Most of the mechanical loads are introduced into the wind turbine components (blades, pitch systems, yaw system, drive train, tower) via the rotor. Several degradation mechanisms of these components are expected to have a direct or indirect relationship with the loading patterns (fatigue or ultimate load, torque levels, accelerations, etc.).
- As long as the turbine (and thus the components) remain within the design envelope, all components should survive². By monitoring the blade loads it can be assessed if, how, how often, and for how long the turbine operates outside the design envelope. Such information may give reason to inspect the turbine more frequently or to postpone scheduled maintenance actions.
- If the design loads are not known by the operator, blade load monitoring can be used to compare the loads of the different turbines in a wind farm with each other. If the load patterns differ from each other substantially it might be wise to prioritise the maintenance actions; the most severely loaded turbines can be maintained first. Those turbines which are less loaded could be maintained some time later if resources are limited.
- The results of blade load monitoring could be combined with other results of diagnostics and condition monitoring. By doing so, it will be possible to determine relationships between the turbine loads and component degradation. If these relationships are well understood, monitoring the component condition could become superfluous. If not, load monitoring is complementary to the condition monitoring and will provide additional insight in the turbine behaviour.

The developments of ECN on low cost load monitoring are twofold:

1. Developing a low cost system that measures, acquires, and process the mechanical loads data of a single turbine. For this ECN has decided to use optical fibres as a starting point and the developments are called Fibre Optic Blade Monitoring (FOBM). The results of the developments are the subject of this report.
2. Developing a software model that extrapolates the loads measured on two or three turbines in an offshore wind farm to the loads on all turbines in the wind farm. This approach is called "Fleet Leader Concept for Wind Farm Load Counting". One of the pre-requisites for the application of the Fleet Leader concept is that the two Fleet Leaders in the wind farm are equipped with a reliable and low cost measurement system like the FOBM system. The Fleet Leader concept is beyond the scope of this report and will not be further discussed. For further reading, see [5].

² If components fail while the turbine operates within its design limit it is likely that either the actual loads on the components were underestimated in the design process, or the strength of the component is insufficient due to e.g. poor quality, design errors, etc.

1.3 Why optical fibres?

To apply blade load monitoring for a long period of time with little maintenance and re-calibration activities, the commonly used copper (electrical) strain gauges seem to have too many disadvantages. Their lifetime is typically 1 to 3 years, installation (and replacement in case of failure) takes too long for already operating turbines, the signals tend to drift over time which requires labour intensive recalibration, and due to the small size of the gauges material flaws may influence the strain measurements.

From the measurement systems based on optical fibres it was expected in 2005 that they would have less disadvantages. Since the sensor material (glass) is identical to that of the blade material the lifetime would be the same. The signals do not drift over time (if the light source remains constant), and re-calibration was expected to be superfluous; the systems would produce reproducible data over a long period of time.

At the early phase of the developments, ECN decided to test several optical measurement systems in wind turbines that were available on the market. Unfortunately, none of these systems met the high expectations for several reasons. It was concluded that especially the sensors (in most cases patches to be glued on the blade material) were not really suitable for FOBM applications in wind turbine blades.

- The time required for installation was too long (at least 3 days per rotor).
- Installation and repairs required skilled personnel and could not be done by regular wind turbine maintenance technicians.
- The relationship between actual and measured strain was not well defined and varied from sensor to sensor.
- The strain was measured over a small distance, while blade material is not always homogeneous. Due to this, insufficient information is obtained about the actual strains and loads.
- On site calibration for load monitoring was required, also after repair actions, meaning that the turbine had to be idled and pitched for several times.
- Installation of sensors for temperature compensation doubled the installation effort.
- Temperature sensors should be free of loads in longitudinal direction, which appeared to be difficult to realise.

The overall conclusion from the first experiments was that the technology was not mature enough. Moreover, once the measured data was available, the systems did not provide information to the analysts for optimising the O&M strategy or about vulnerable spots in the turbine.

But: the tests also showed that some of the benefits indeed were present and this was sufficient reason for ECN to start its own developments in order to overcome the shortcomings of the available optical measurement systems. Especially the obtained accuracy, the lack of drift, and long lifetime appeared to be attractive. The focus of ECN's developments has been on four main aspects:

1. Development of the innovative 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. Development of specifications for an interrogator (read out unit) to be used in wind turbines and testing of interrogators that are commercially available.

3. Development of software 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 optimisation³.
4. System integration and field testing.

The developments resulted in a Fibre Optic Blade Measurement (FOBM) system of which the system architecture is given in Figure 1.2.

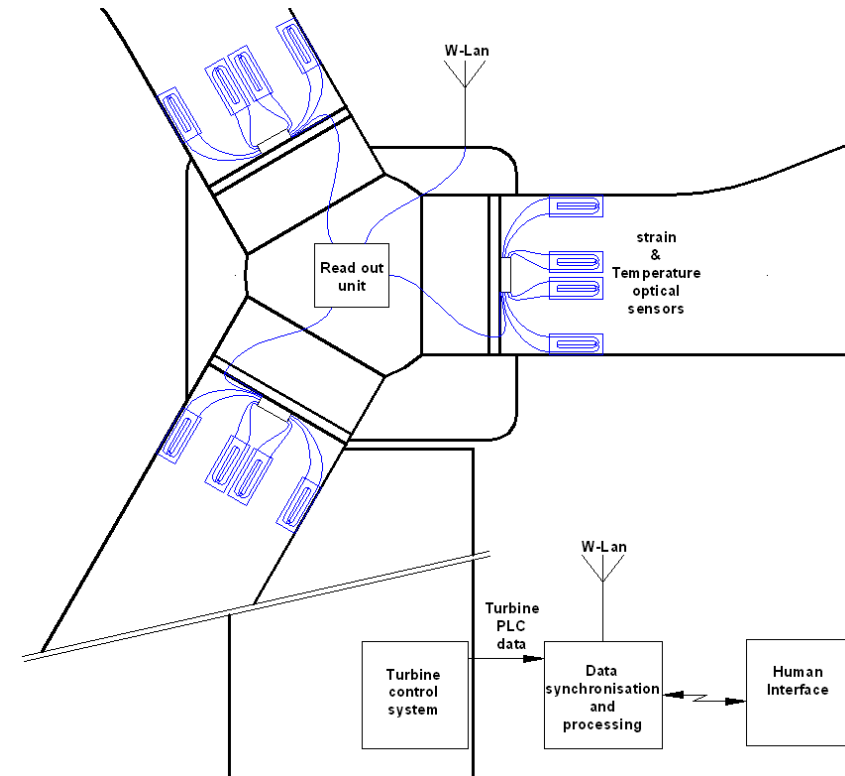


Figure 1.2: *FOBM system architecture*

The FOBM system consists of:

- four sensor assemblies in each blade root for measuring strains that can be converted into edgewise and flapwise bending moments;
- an interrogator placed in the rotating hub that reads out the fibre optic sensors;
- wireless-LAN to enable communication between the rotor and the turbine base;
- a measurement computer that derives loads data from strain data and combines the loads data with turbine PLC data; and
- software for data processing.

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

1.4 How to read the report?

In this report, the FOBM system and its different aspects will be discussed with a focus on the results achieved within the D OWES project (Dutch Offshore Wind Energy Services). In Chapter 2 the functional specifications of the FOBM system will be

³ The software is developed especially for the ECN FOBM system, but can also be used in combination with other measurement systems for blade load monitoring, e.g. with copper strain gauges.

discussed. The four aspects of the development (sensor, interrogator, software, and system integration) will be discussed in the Chapters 3 through 6.

In Chapter 7, an outlook is given of what future developments are needed to make the system suitable for large scale applications or make the system useful for other applications like load control with feedback from blade root bending moments, and measurements on sub-structures.

2

FOBM System and Functional Specifications

2.1 Functional specifications

In Section 1.3 four main areas have been mentioned on which the FOBM developments have been focussing. At an early stage of the developments functional specifications have been defined in consultation with the wind turbine industry for the FOBM system, with the aim to make it applicable for low cost and robust blade load monitoring in wind turbines.

1. To make the system useful for load monitoring, the user (wind farm operator or OEM) should be provided with a minimum amount of information only, rather than large amounts of raw measurement data. This means that the raw measurement data should be processed in an automated way before it is presented to the user.
2. The information should be as such that the user can make sound decisions on prioritising and optimising maintenance actions. This means that the user should be provided with information whether the extreme or fatigue loads are more benign than the design loads and/or easily compare the loadings between several turbines.
3. The information should provide the user with information on causes of (extreme) loads, e.g. unbalance, ice, brake actions, or too high cumulative fatigue loads. This means that not only key figures should be stored for further processing, but in some cases also events.
4. The system should be cheap, easy to install, and work reliable over a long period of time with minimal maintenance.
 - Easy to install means that 2 technicians need less than 2 working days in order to minimise installation costs and revenue losses.
 - High reliability with minimal maintenance means not more than one visit a year that can be combined with normal wind turbine maintenance. The accuracy and reproducibility should remain within pre-defined limits over a period of several years (preferably the turbine lifetime), meaning no drift of the offset and gain values.

- Minimal maintenance also means that if repair should be carried out (e.g. replacement of a damaged sensor) the repair can be carried out in less than 3 hours by regular wind turbine technicians and without re-calibration of the measurement chain. (After e.g. sensor replacement, the turbine should be allowed to continue running which means that re-calibration of the measurement chain by idling and pitching at low wind speeds needs to be avoided.)
5. On the longer term, the technology should become suitable (meaning robust and reliable enough) to be incorporated in the control loop of the wind turbine and enable for instance the implementation of innovative control models like individual pitch control.

The entire FOBM system with its architecture will be discussed in the following sections.

2.2 System architecture

Based on the specifications it was decided that strain and load measurements based on optical fibres are the best candidate for long term and reliable measurements. An architecture has been designed as presented in Figure 1.2. Four strain sensors placed in the blade root give sufficient information about the flapwise and edgewise bending moments. Combining these blade root signals with SCADA data enable the transfer of the blade loads into loads on other main components.

For ECN, it was a challenge to develop a Fibre Optic Blade Monitoring system that makes use of the benefits of the optical fibre technology but overcomes its negative aspects. The system that has been developed by ECN consists of (see also Figure 1.2):

6. 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 (four strain and four temperature sensors per blade);
7. a commercially available interrogator to read out the fibre optic sensors;
8. a measurement computer that derives loads data from strain data and combines the blade loads data with turbine PLC data;
9. wireless-LAN to enable communication between the rotor and the turbine base;
10. 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.

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

2.3 Specifications and basic choices

Retrofit vs. integrated solution

Since fibre optic blade monitoring is considered to be of relevance for optimising the O&M strategy at first instance, it is likely that the first systems will be installed in already operating wind turbines. ECN has decided to design the FOBM system as a retrofit solution that can be applied not only in new turbines but also in existing turbines. This decision is mainly of importance for the design of the strain sensors. They can be easily installed at the inner side of the blade root of a turbine in the field, but also during the production process of a blade. On the longer term, ECN believes that the FOBM system should become an integral part of the turbine controller and rotor blade.

Sensor locations and configuration

ECN has chosen not to measure the degradation of the blades (material and/or bonding) but to measure the blade root bending moments and to derive fatigue spectra and ultimate loads. To do so, the strain is measured at four positions in the blade root: two in flapwise direction and two in edgewise direction. Subtracting the two opposite signals gives a measure for the blade root bending moments in edgewise and flapwise direction. Each strain sensor is compensated for temperature influences by using optical temperature sensors. With this solution, also local temperature effects caused e.g. by sunlight heating up only the pressure side of the blades, are compensated for and only material strain due to external loading is obtained! This is a strong benefit compared to the Wheatstone bridges based on copper strain gauges.

Ranges vs. absolute load values

In order to generate sufficient details on the extreme and fatigue loading and make the system useful for long term load monitoring, ECN has decided that it is not sufficient to only measure the load cycles sufficiently accurate, but also the absolute values. This has led to very strict requirements for the strain measurements: an accuracy and stability better than 5 $\mu\epsilon$, and a resolution better than 5 $\mu\epsilon$ (preferably 1 $\mu\epsilon$). After assessing different means of strain measurements ECN concluded that optical fibres with Bragg gratings have the highest potential to meet the strict requirements.

Measurement principles

Next to the choice for optical vs. other means of strain measurements, ECN had to decide on the measurement principal: WDM (Wave length Divisions Multiplexing) technology vs. TDM (Time Division Multiplexing). After extensive reviews and testing, ECN has chosen for the WDM (Wave length Divisions Multiplexing) technology. As opposed to the TDM (Time Division Multiplexing) technology, WDM offers the opportunity to put high reflectivity sensors on one string with minimum loss of signal. Since it was foreseen already at an early stage of the developments that 4 strain and 4 temperature sensors had to be put on one string with intermediate connectors, the WDM technology provided better prospects for further developments. Moreover, the WDM technology in combination with a gas cell reference provides a very high accuracy. Possible disadvantages of the WDM system as opposed to the TDM system could be the higher price and the fact that each sensor in a string should have a different wavelength. However, for both technologies there has been a strong reduction of the prices of fibres, gratings, and interrogators in the last decade.

For the read out unit, ECN has been looking for a robust interrogator that can be mounted in the hub and operate reliably over a temperature range of say -20 to +50 °C. During the developments it was concluded that although some commercially available interrogators (nearly) met the wind energy requirements w.r.t. accuracy, stability, etc., most of them were designed for quasi static use like in buildings, laboratories, or vehicles. Special tests were designed by ECN to verify if the systems can withstand rotations and accelerations.

Data transfer from hub to tower bottom

Data transfer to the turbine base is foreseen through wireless LAN to ensure that the FOBM system does not require slip rings and is thus independent from the turbine type.

Because the data transmission can be interrupted, it is required that data can be buffered in the hub unit.

Data cleaning, storage and processing

The measurement PC in the turbine base 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 (*To obtain single mode files, the 10 minute time series are cut into intervals with only one single mode of operation. This can be normal operation like production or idling, or a transient like start-up or shutdown*). Based on the PLC data, the software also approves or rejects measured time series and categorises them as one of the relevant load cases. Based on the single mode files, a database is filled with statistical data, load spectra frequency plots and capture matrices 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), and recent events are stored in the system.

For the entire monitoring setup which comprises the location of sensors, the length of time series, the categorisation of load cases, the derivation of pseudo signals, the required accuracy, etc., the recommendations for mechanical load measurements given in IEC61400-13 [3] have been used as a guideline throughout the FOBM developments. This should ensure that the results of the blade load monitoring programmes can be understood and interpret by operators, technicians and designers that have a basic background in wind engineering.

Remote access

The FOBM system can be accessed remotely by the operator to retrieve the required information and to modify relevant settings of the systems. The load monitoring setup is given in **Figure 2.1**.

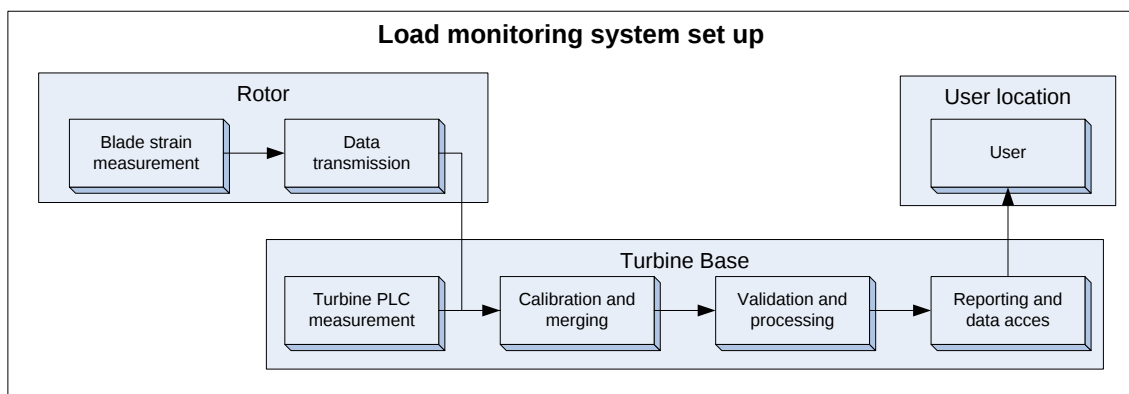


Figure 2.1: *FOBM system setup*

3

3.1 Sensor design

The design that has been used for the field tests is described in this chapter. 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 and patented sensor assembly for strain measurement in wind turbine blades as a "plug-and-play device", see Figure 3.1.

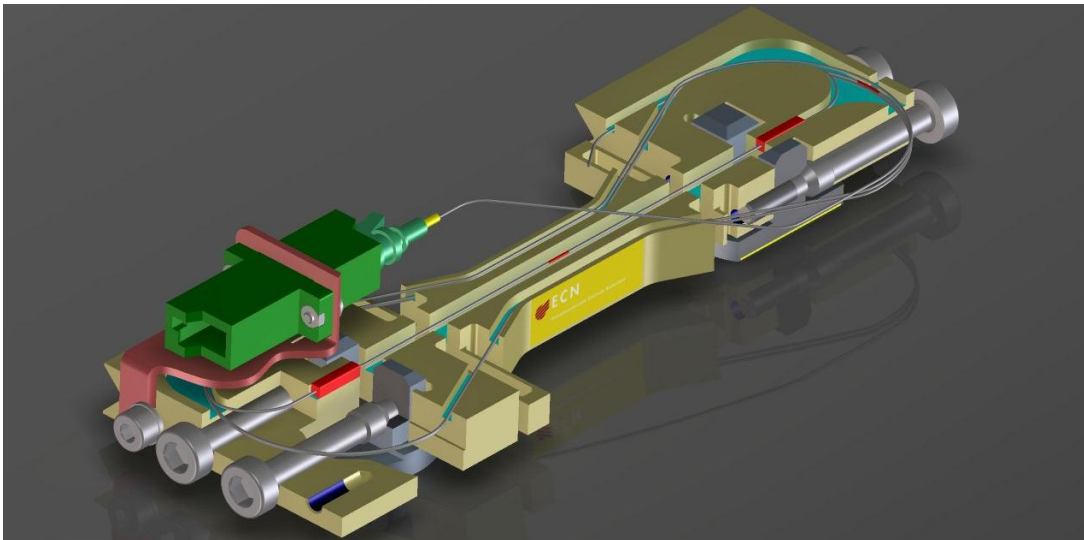


Figure 3.1: *FOBM sensor assembly design with two studs, a carrier, and a fibre with a Bragg grating for strain measurement and a Bragg grating for temperature measurement*

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. Since each strain sensor is compensated by a local temperature sensor, the effects of temperature differences over the blade (i.e. strain caused by temperature fluctuations and differences between sun and shadow sides) can be compensated for. This is not possible with Wheatstone bridges made from copper strain gauges.

Figure 3.2 shows the carrier and the studs. The strain sensor is mounted in between the studs whereas the temperature sensor is mounted opposite of the connectors.

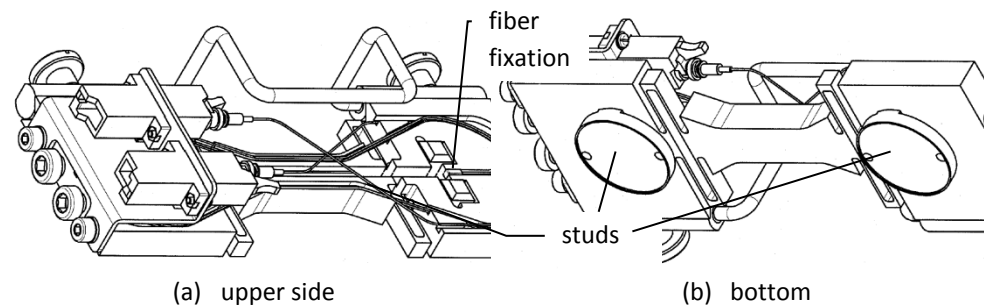


Figure 3.2: *Sensor assembly*

The studs are connected with the carrier via four bolts, which ensure a rigid connection on the interface surfaces. The studs are glued on the inner side of the blade root. A tool is available for easy mounting and accurate mutual positioning of two studs.

The present configuration has an E2000 connector at both ends. The E2000 connector is chosen to ensure easy handling with minimal chance on polluting the contact surfaces of the fibre. This type of connector ensures cleanliness of the contact surfaces of the fibre during mounting and replacement.

To install a sensor, the technicians need to glue the studs on the blade with the help of a dedicated mounting tool (see also Figure 6.1). After a short curing time, the technicians 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 ($5 \mu\epsilon$) over a long period of time. Re-calibration is not necessary, because the sensor itself is very stable. If, for whatever 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.

The fibre itself has a very high ultimate strain and can easily survive the life time of the turbine. A critical element that was extensively tested in the laboratory and during field tests is the glued connection between the blades and the studs. This connection is chosen for applications in existing turbines (retrofit). The design of the sensor however is also suitable for fastening methods other than gluing (e.g. screwing). This could match better with the manufacturing processes of the various blade manufacturers.

In Figure 3.3 the sensor is installed in the inside of a Nordex N80 rotor blade at the ECN test side EWTW. The picture also shows the connection to the patch cable and the protection box which was glued on the rotor blade. The protection box is meant as a mechanical protection only, e.g. in case technicians have to work in the blades and step on the sensor or if tools would fall on the sensor.

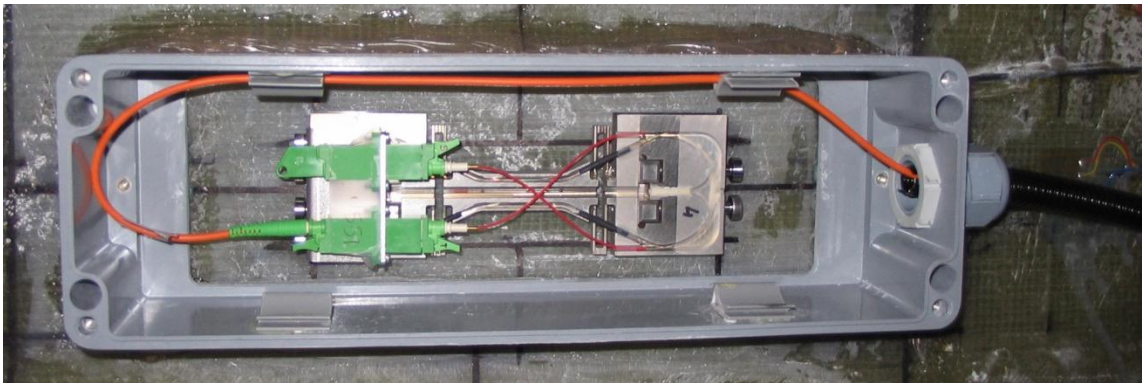


Figure 3.3: *FOBM sensor assembly installed in the Nordex N80 turbine with the grey protection box and connected to the patch cable*

3.2 Design choices and laboratory tests

This section briefly describes the background of the major design choices that have been made for the sensor assembly, and the main results of the laboratory tests that were carried out.

At the start of the development of the sensor assembly, ECN has determined the following specifications in addition to the specifications of the entire FOBM system given in Section 2.1 :

- The sensors should measure the average strain accurately over a well-known distance in order to prevent the effects of non-homogeneities.
- The sensors should be easily replaceable, without any damage to the blade and should be done by regular maintenance staff without special skills for fibre optics (Plug-and-Play).
- On site calibration should become superfluous after replacement of the sensor.
- The fixation of the sensor should be rigid and stable over the lifetime of the blade.
- The sensor assembly should be insensitive for fatigue and survive the life time of the blade.
- The installation should not require special skills other than required for normal turbine maintenance.
- The following accuracies and resolutions should be obtained:
 - Strain resolution : 1 $\mu\epsilon$
 - Strain accuracy / stability : better than 5 $\mu\epsilon$
 - Maximum strain level : -1000+1000 $\mu\epsilon$

The most important items for the development have been:

1. Choice of the Bragg gratings and optical fibres
2. Connection of the strain and temperature sensors (fibres) to the carrier
3. The sensor assembly (carrier with studs)
4. Installation aspects of the sensors in the blade

ECN has chosen for the Wave length Divisions Multiplexing (WDM) technique. The major advantages of the WDM technique are the high accuracy and the flexibility in choosing the sensor locations on a string. Unlike for Time Division Multiplexing (TDM), the interrogator range is split up in sub ranges for the sensors in one string. So all sensors in a string should have different wavelengths and overlaps are not allowed.

Next, ECN had to choose for a technique to write a Fibre Bragg Grating. Two options are available for this:

1. Starting with a conventional telecom-grade optical fibre
2. Using specialised processes focused on sensor applications

Following the first method, a standard single mode telecom fibre is used. For this process the UV-acrylate coating is removed. After writing the grating, the surface is recoated. During this process the risk of damaging the fibre is significant, which results in a reduced strength of the fibre and hence a reduced reliability. Because the writing process is not time critical and well controlled, sensors can be produced with high reflectivity and low sensitivity for polarisation. The technique is suitable for small series and costs are relatively high.

The second method, called Draw Tower Grating (DTG) from the company FBGS, is a sophisticated process specially focussed on sensors. During the production process of the fibre, the gratings are written and a very tough coating is applied all in one go. The result is a fibre which can withstand extremely high strains. The costs of the gratings are low. Apart from individual gratings, also complete strings of gratings can be produced, with the gratings at a specified mutual distance and with different wave lengths. This implies that the number of splices to build a string can be minimised. Disadvantages of these fibres are the lower reflection of the grating, the sensitivity for polarization and the small core diameter.

After extensive testing and assessment, ECN has chosen for the DTG's for the following reasons.

- The allowable strain is large enough to cover the required measurement range in combination with the pretension.
- The costs of the gratings are low.
- Strings can be produced without splicing, which increases the reliability.

However the choice also implied that some disadvantages need to be dealt with.

- The present DTG-fibres with Bragg gratings have a small core diameter which causes damping and unwanted polarization effects if used incorrectly and with wrong components.
- The small core diameter of the DTG-fibre requires special handling for mounting connectors and splicing in order to realise an acceptably low damping in the string.

Field tests have shown that the present configuration works satisfactory and is easy to handle and install. The entire string with connectors for instance showed an acceptable damping. The supplier of the DT-fibre has announced that soon fibres with a larger diameter will become available and that the disadvantages mentioned above will no longer apply.

The final sensor assembly is discussed in Section 3.1. Numerous tests have been carried out (in the laboratory and in the field) during most of the development steps to monitor if the sensor assembly indeed meets the strict requirements for applications in wind turbine blades. These tests comprised among others the accuracy and reproducibility of

the fibre Bragg gratings, fatigue and ultimate tests for the stud bonding and the bonding between the fibre and carrier, the installation procedure, and testing of the entire measurement chain.

The accuracy and reproducibility have been tested at the Knowledge Centre WMC and have been compared with copper strain gauges. A test block was instrumented on both sides with on each side a sensor assembly and copper strain gauges, see Figure 3.4. This test block was then clamped in a test rig for fatigue testing, see Figure 3.5 and various tests were performed with the objective to verify among others:

- the strength of the glued studs;
- the strength of the bonding of the fibres on the carrier;
- the agreement between the signals from the copper strain gauges and from the optical measurements;
- the agreement between the signals from both optical strain sensors;
- the agreement between the temperature sensors and a PT-100 temperature sensor;
- making a general assessment of the sensor assembly during fatigue testing.

Various fatigue tests were performed during which the strain was varied between ± 250 and $\pm 900 \mu\epsilon$, and the frequency was varied between 0,1 and 0,3 Hz. The overall conclusions from these tests are as follows.

Bonding and gluing

The strength of the bonding between studs and test block and the bonding of the fibres on the carrier showed no problems.

Temperature measurements

The temperature measurements of the optical sensors matched quite well with the PT100's. The sensitivity of the optical sensor was in line with a PT100, although the range of the temperature difference was rather small during the tests (less than 5 °C) .

Strain measurement

The strain measurements of the optical sensors followed the strain gauge signals quite well. The ranges of both sensors were identical. However, the differences in offset ($15\mu\epsilon$) were larger than specified ($5\mu\epsilon$ at maximum). This difference was most likely caused by creep in the glued connection (fibre-carrier). Similar observations were done in the field tests in 2011, but not for all assemblies.

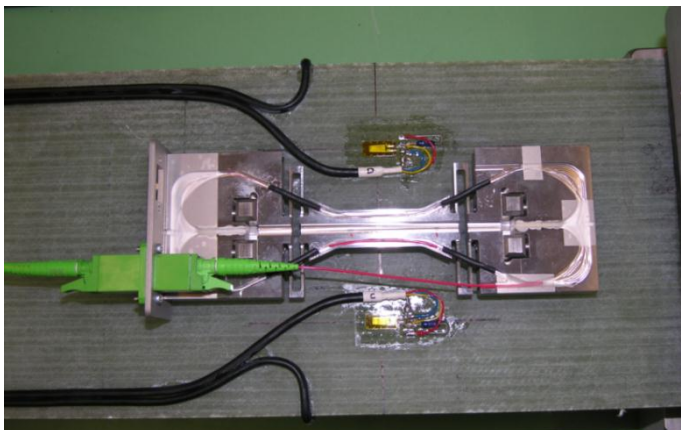


Figure 3.4: *Test block with sensor assembly and copper strain gauges for verification and comparison*

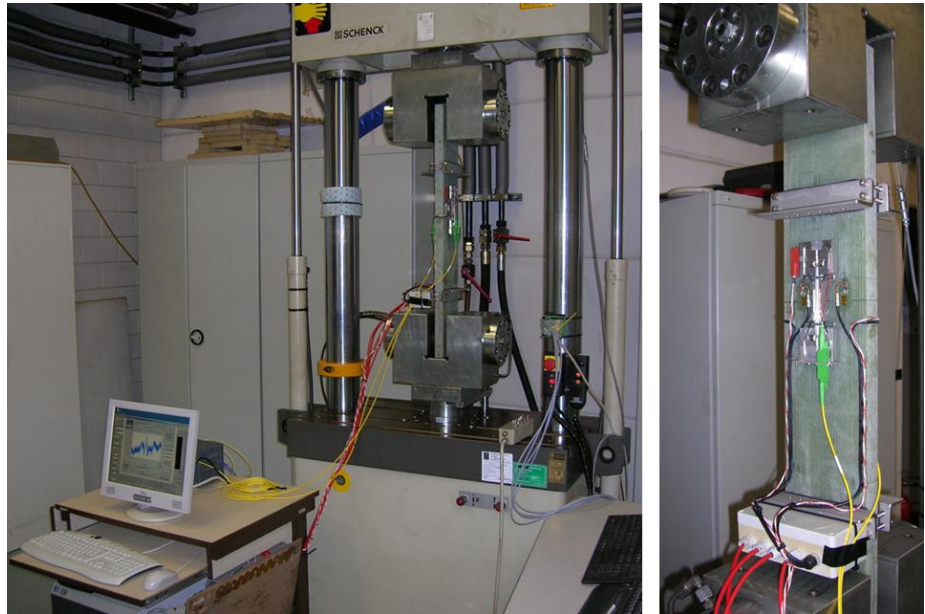


Figure 3.5: *Test block clamped in test rig of WMC for fatigue testing Installation and maintenance*

The above mentioned tests and experiments demonstrate that the chosen sensor assembly in general meets the requirements for wind turbine applications. End of 2010, the configuration could be used for accuracies in a range of $15\mu\epsilon$ and for applications where peak-through (ranges) are more important than absolute values.

4

Selection of Interrogator

The development of an interrogator for FOBM applications is beyond the ECN developments. Industrial parties with a strong background on fibre optics do provide such interrogators. ECN has reviewed the specifications and documentation of 14 systems commercially available and compared them with the specifications required for wind turbine applications:

Strain resolution	: 1 $\mu\epsilon$
Strain accuracy / stability	: better than 5 $\mu\epsilon$
Maximum strain level	: -1000+1000 $\mu\epsilon$
Frequency	: >16 Hz
Sensors per blade	: 4 stain sensors / 4 temperature sensors

Based on the findings of the desk study it was decided to test four systems extensively at the ECN laboratories in 2009 through 2012.

1. HBM DI410

This model is a relabelled version of the Micron Optics SM-130. It is a dynamic interrogator with 4 channels and a maximum measurement frequency of 1000 Hz. It is a WDM system. The interrogator is not designed for installation in an industrial environment, so for installation in a turbine modifications are necessary.

2. Smart Fibres T4

This model is developed for wind turbine applications and is installed in several applications. Technobis offered also an interrogator based on this model for an attractive price level. The performance of the T4 is considered as representative for the Technobis interrogator. The interrogator is a TDM system, but the wavelengths of the individual sensors within a string should not overlap. This implies that the same restriction as for the WDM-system also applies. Because of the TDM, the measurement frequency varies with the number of sensors in a string. Maximum frequency is 50 Hz.

3. Insensys OEM 1030-422
This model is developed for wind turbine applications. It has three channels. Because of the TDM, the measurement frequency depends on the number of sensors. Maximum frequency is 500 Hz.
4. FibreSensing WindMeter
Similar to the Insensys interrogator, this one is designed especially for wind turbine applications. It has three lines, is based on the WDM technology, is available in a robust housing and has a minimum power consumption. The maximum frequency is 100 Hz.

The interrogators from HBM and FibreSensing are shown in Figure 4.1.



Figure 4.1: *Interrogators as used in the field tests: HBM (left) and FibreSensing (right)*

A general test plan was prepared for all 4 devices, in which the types of tests are described. The test plan has also been discussed with the suppliers. The performance requirements can be affected by several conditions as indicated in Figure 4.2.

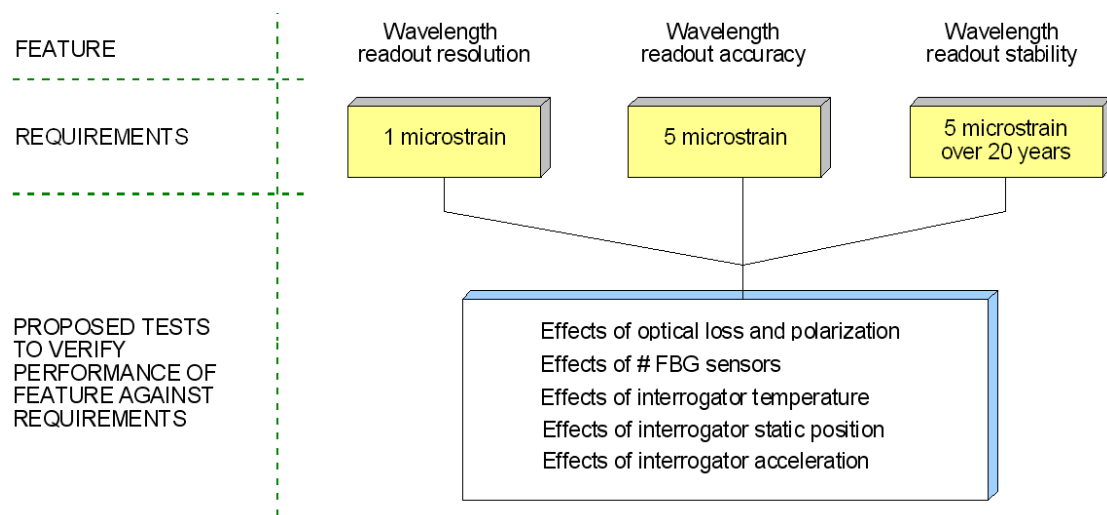


Figure 4.2: *Performance requirements and tests*

The effects of polarization and attenuation are of importance for the accuracy, because of the sensitivity of the peak detection for these phenomena. Polarization can easily occur due to bending of fibres during installation and operation. Attenuation (optical loss) can also occur due to splices in the fibres and connectors in the string. The effects

of one connector might be rather low, but several gratings are used in series with intermediate connectors. The light is transmitted and reflected, so attenuation occurs during each passage and can become an important factor.

The tests done in the laboratory were designed to better understand uncertain issues. In a string, several gratings were put in a series. Depending on the technology (TDM or WDM), using more gratings (8 for wind turbine applications) will have effects due to attenuation and polarization. This also depends on the types of grating (reflection) and the type of the fibres used (core diameter). Apart from this, the interrogator might also be sensitive for the environmental conditions in the hub (temperature, vibrations and position).

In order to quantify the effects, the following tests have been carried out:

- the accuracy under static and dynamic conditions;
- the effects of attenuation and polarization;
- the effects of temperature and temperature variations of the interrogator;
- the influence of the position and position changes of the interrogator (acceleration tests).

Finally, ECN has chosen to execute further developments like testing of the sensor assemblies with the HBM DI410 interrogator which is a re-labelled version of the SM130 interrogator of Micron Optics. The interrogator has 4 channels. Using one channel per blade implies that identical strings can be composed for each of the blades. The fourth channel was used as a spare in case of fracture of one of the fibres.

The HBM interrogator was available already in 2009. It was therefore also used for field tests in 2010. For this, the interrogator had to be made more ruggedized since it is not really designed to be used in a rotating hub. In 2011, ECN had available the interrogator from FibreSensing and after successful laboratory tests were carried out, this interrogator is ECN's first choice for applications in the hub of wind turbines.

ECN will continue to discuss the specifications for interrogators with suppliers and from time to time new products are being tested and assessed.

5

Data Processing Software

5.1 Structure of FOBM data analysis software

All measurement and condition monitoring systems generate large amounts of raw data. However, no operator or technician is interested in the raw data only; he is mostly interested in information that supports him in taking sound decisions.

The load measurements are used for load monitoring of the turbines, mainly rotor blades and tower. ECN has developed various algorithms that combine the blade root bending moments with turbine geometry data and SCADA data (e.g. pitch angle, azimuth angle) to determine the loads also for other main components. The remaining part of this chapter focusses on the analysis of blade root bending moments, but similar analysis methods are also available for other main components

The load monitoring system should generate information for the operator about the encountered loads of the blades during operation in relation to the design. An important condition is that the load monitoring system should simplify and not increase the tasks needed for operations. This implies that the system should operate fully automatically and the amount of data provided to the operator should be kept minimal.

ECN has developed 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 overall structure for the blade load monitoring system with the two main processes is depicted in Figure 5.1.

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.

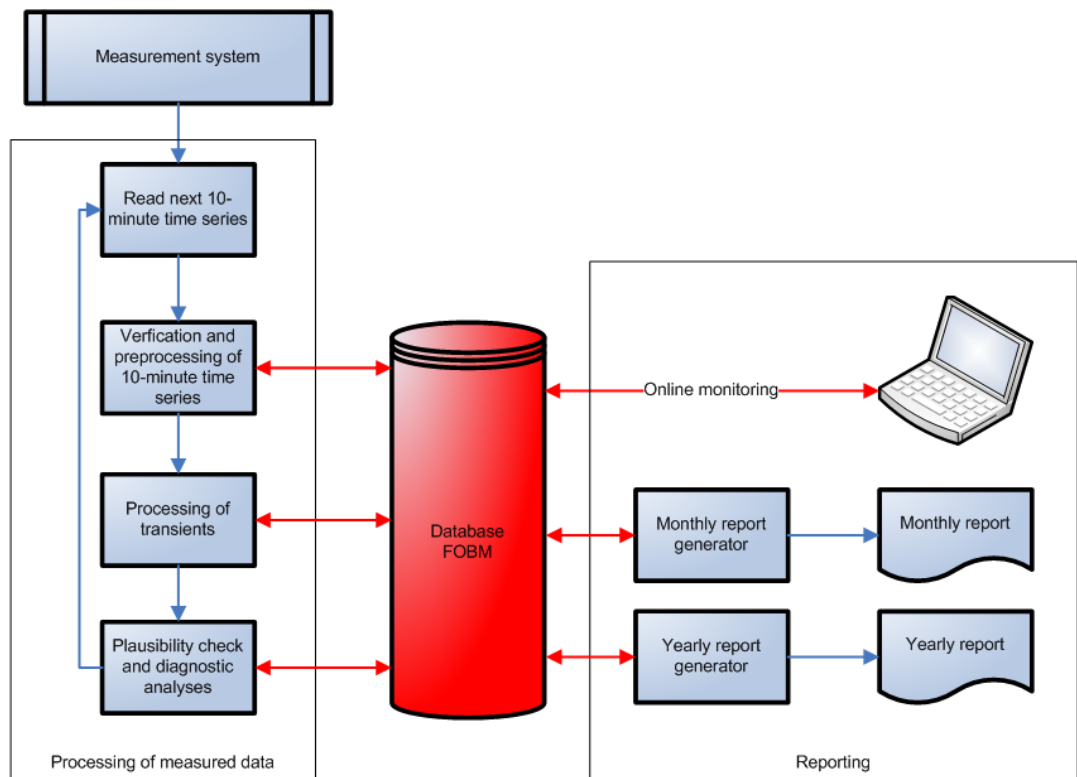


Figure 5.1: *Overall structure data processing and information retrieval*

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

The rejected measurement data that could not be processed automatically can be extracted from the database by the analyst at a later stage. The analyst can then analyse the data further manually and determine the reasons for rejection (e.g. errors in the measurement system or too strict criteria for acceptance/rejection).

From the beginning on, the software starts building up a capture matrix with sufficient data to represent the operational conditions of the turbine, meaning that the time series in each bin of the capture matrix should cover data in between the minimum and maximum load values that are expected for the turbine under consideration. The operator can use these reference data to check if extreme and/or unusual events have

occurred during the reporting period. The data can also be used to derive finger prints (in case of frequency analyses), envelopes, and criteria for rejection. The decisions on how many time series should be kept in each bin of the capture matrix and which time series are considered as representative are to some extent arbitrary. During the first measuring months the analyst should assess and update the capture matrix manually as part of the software configuration process.

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. The process is explained schematically in Figure 5.2. More examples of the content of the reports is given in Section 5.4.

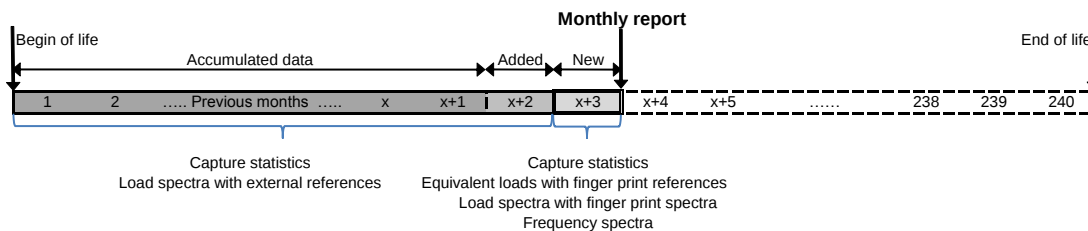


Figure 5.2: *Schematic presentation of the process which data are stored and for how long*

5.2 Processing transients

During the development of the processing algorithms, special attention has been paid to the processing of transients (start-up, shutdowns, emergency shutdowns, etc.) and the determination of statistical values. Default, the measurement system acquires 10 minute 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. This means that the time series are all single mode files (only one operational mode present). An example is given in Figure 5.3.

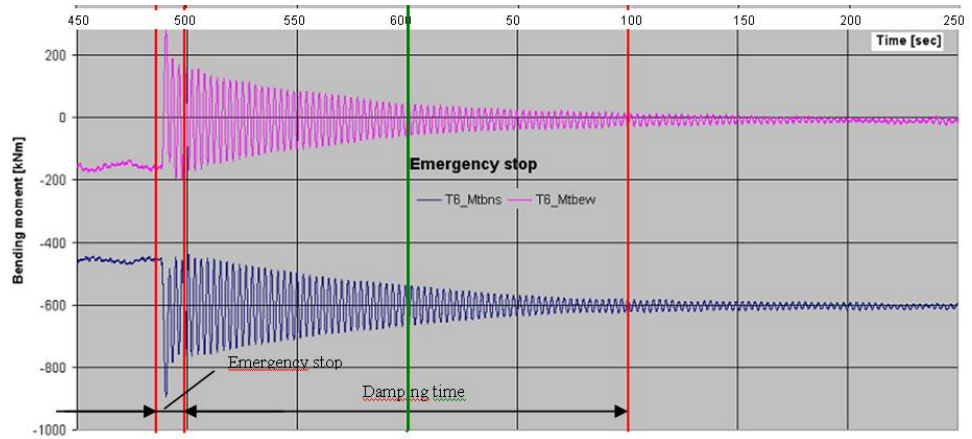


Figure 5.3: *Emergency stop that started at $t=480s$ in the first time series and lasted until $t=100s$ in the subsequent time series. The data processing software combines the two time series and generates 3 single mode files (normal operation, emergency stop, parked)*

5.3 Filtering and cleaning

The raw measurement data may be contaminated with certain kind of measurement errors that will bias the resulting load spectra. For example, large spikes in the data often result in high peaks in the load spectra and equivalent loads. Such spikes may result in erroneous cumulative load spectra. Because of the strongly varying operating conditions it is not sufficient to let analysts perform a simple validation, e.g. checking the cumulative loads spectra on a daily basis. The measurement data need be carefully validated, taking into account the operational conditions, before it is processed and added to cumulative loads spectra. The software is designed to validate the measured time series automatically. When data appear to be unreliable, possibilities for recovery are examined. Only when the processing software rejects data, it will be stored in the database and manual intervention can be considered. For practical reasons the amount of rejected data should be very limited, which implies that the measurement system should be very reliable. During the first weeks of operation the measurement system should be configured for automatic data validation and minimising the amount of rejected data.

The processing software is suitable for all turbines that each have different sets of SCADA data and different properties and geometries. The turbines are all operated differently with respect to starting, stopping and power production. The data processing software requires a.o. SCADA data and status information of the turbine. An interface module has been developed to easily connect the turbine information and data to the data analysis software.

5.4 Monthly reports

The software provides reports every month 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.

The data analysis software in fact is independent from the way the loads are measured, since it processes time series with a limited set of SCADA data and loads as [kNm] or [kN]. The software can be applied to all time series, as long as the file formats with the headers are correct. In this section, some examples are shown where data measured with copper strain gauges have been processed with the FOBM data analysis software. At the time the data analysis software was tested (early 2010), insufficient data from the FOBM measurement system were available.

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 software 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 quarantine. 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.

An example of a table with the number of measured files per operational mode is given in Figure 5.4. It contains data from the measurements carried out during 396 days with copper strain gauges at a Nordex N80 turbine at the ECN Wind turbine Test site Wieringermeer (EWTW). As can be seen, many files (48,84 %) were put into quarantine because some signals were disconnected for a longer period of time and therefore rejected by the FOBM software. In January 2009, more than 82 % of the measured data could be processed automatically by the FOBM software.

It was concluded that the software functioned very well w.r.t. automatic validation and processing. As long as the measurement system operates without errors, only a very limited number of measured time series will be put into quarantine. Based on the field tests there was no reason to modify the software. Care should be taken when configuring the software and limits for acceptance and rejection.

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	

Figure 5.4: *Tables with number of measured files per operational mode for the total measurement period (left) and one month only (right, January 2009)*

Equivalent loads:

The equivalent loads (one of the statistical values derived from the time series) 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. An example for the edgewise and flapwise bending moments is given in Figure 5.5. The individual dots are the equivalent loads of all data points in the database. The red lines are the equivalent loads derived from the limited number of time series in the capture matrix.

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

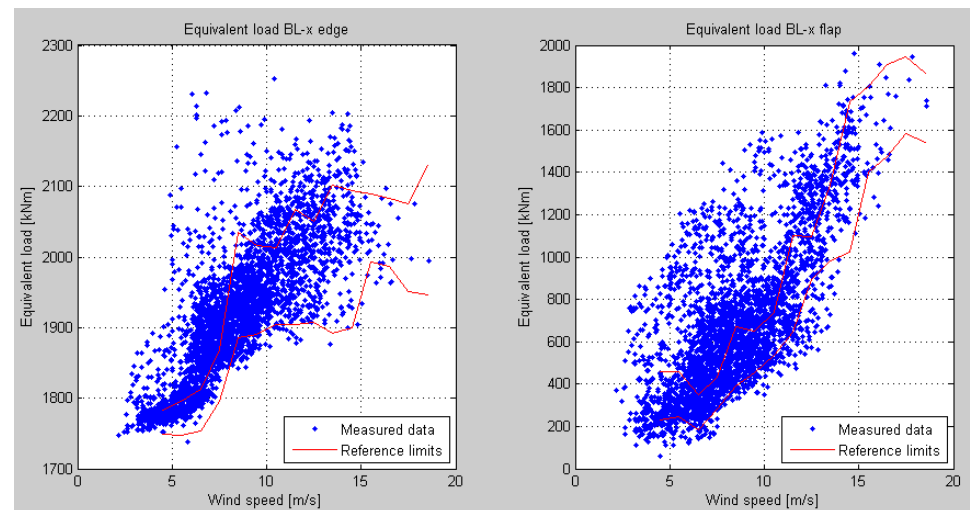


Figure 5.5: *Plot with the equivalent load as a function of the wind speed (10 min. average) during normal operational modes*

Mean, min, max, stdv:

Similar to the equivalent loads, the software can report plots with mean loads, minimum and maximum values and the standard deviation as a function of wind speed, see Figure 5.6. It can be done for one month or for the entire measurement period.

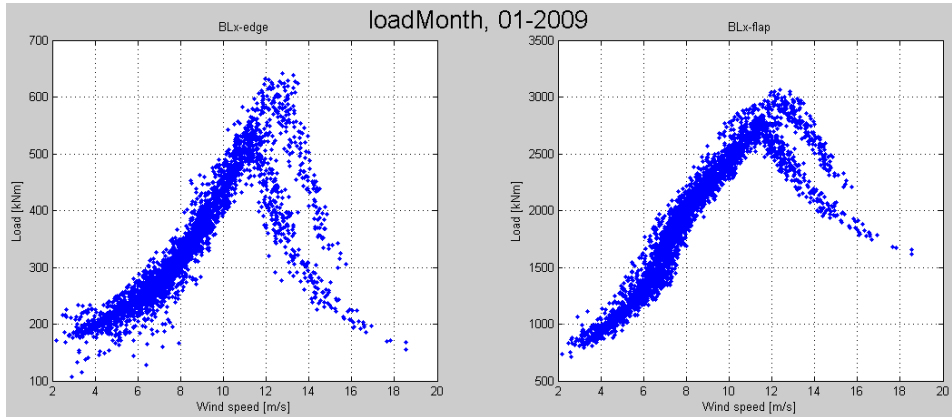


Figure 5.6: *Plots with the mean values of the bending moments as a function of wind speed*

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, see Figure 5.7. For the life time an external reference should be used, see Figure 5.8. This external reference can be chosen depending on the application. For prioritising maintenance, other turbines of the same farm could be used for this reference. When the user is interested in the consumed life time, a design spectrum is the most obvious choice.

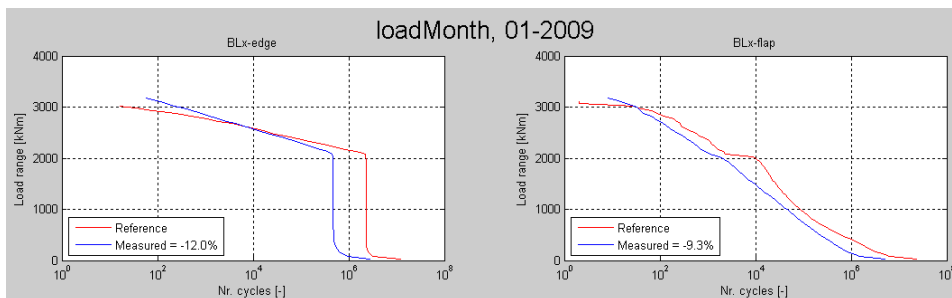


Figure 5.7: *Plots with the load spectra (edwise and flapwise) during one month of operation (January 2009)*

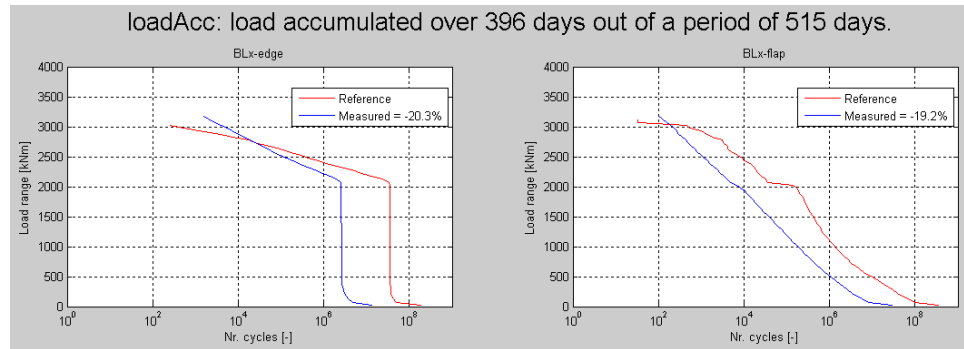


Figure 5.8: *Plots with the load spectra (edwise and flapwise) during the entire measurement period, compared with a reference spectrum.*

Frequency plots (Average Power Spectral Density):

Under certain conditions, frequency spectra of the blade loads are made. Changes in the structural properties of the blade may affect the spectrum. Shifts in frequency or changes of the amplitudes can be detected. In Figure 5.9, the frequency plot for two directions are given. As a function of time, these plots can also be presented by a rain fall plot to quickly assess the changes in structural behaviour.

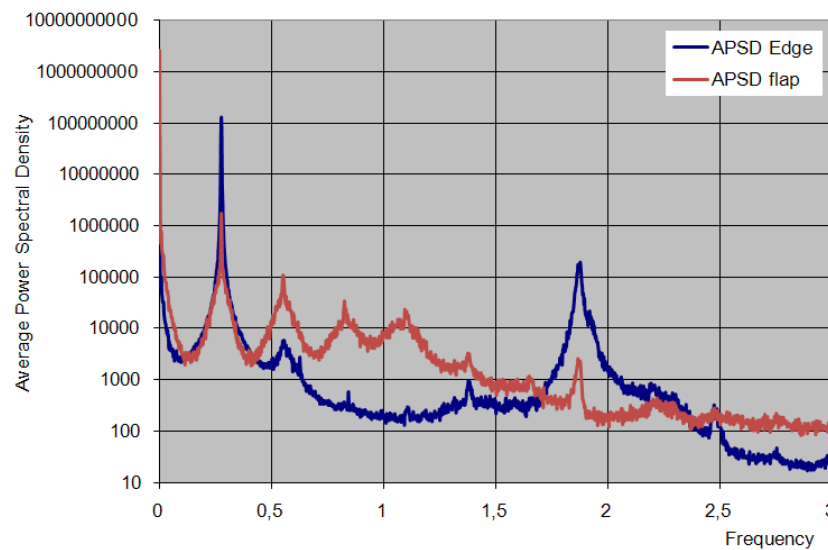


Figure 5.9: *Auto Power Spectral Density plots of both the edgewise and flapwise bending moments*

6

Field Experiences

6.1 Purpose of the field tests

In May 2011, the FOBM system was installed in one of the Nordex N80 turbines at the EWTW according to the architecture presented in Figure 1.2 and Figure 2.1. Instead of using 12 sensor assemblies, 2 assemblies have been used: one in the leading edge and one in trailing edge of a single blade only. This Nordex turbine was chosen for the FOBM experiments because it was already instrumented with a.o. electrical strain gauges in the blades and tower. A measurement campaign was ongoing for several years, so a lot of high quality measurement data was already available for comparisons with the optical experiments. The purpose of the field tests was a.o. to:

1. Verify the adequacy of the developed instrumentation procedure and the mounting tools;
2. Verify the agreement between the electrical strain, load, and temperature measurements with the optical ones;
3. Verify the robustness of the system, the long term behaviour and identify areas for improvement.

In the following sections the main results of the field tests will be discussed.

6.2 Verification of instrumentation procedures

During the development of the FOBM system and especially of the sensor assembly, limiting the time needed for instrumentation of the system has been an important design requirement. Since the system has been developed as a retrofit solution at first instance, it is important to minimise the time for standstill and associated revenue losses, and to limit the number of working hours on site. For this, ECN has developed a kind of recipe book and several mounting tools. Furthermore, a lot of the preparation work can be done in the workshop prior to visiting the turbine (e.g. preparing optical

fibres at the correct lengths, mounting connectors, preparing junction boxes, etc.). On site, the interrogator needs to be mounted in the hub, the sensors need to be mounted, and the cables and optical fibres need to be connected. In the Figure 6.1 the installation of the sensor assembly is presented step by step. In the upper two pictures, the mounting tool to assist in mounting the studs is given, together with the glued studs and the glued prototype version of the protection box (of which the final version is shown in Figure 6.2).

In the middle of Figure 6.1, the sensor assembly mounted in the blade root is shown with all fibres connected. On the left hand side of the FOBM sensor assembly, the copper strain gauges can be seen (two configurations as a Wheatstone bridge, one with parallel gauges and one with a T-configuration) and a PT-100 (red) for temperature measurements.

At the bottom of Figure 6.1, an overview of the sensor assembly, some fibres, and a junction box is presented. The picture is made from the inside of the blade, looking to the hub.



Figure 6.1: *Instrumentation of the FOBM sensor assembly and the location of the electrical strain gauges*

The field tests with the FOBM system in the Nordex N80 turbines at the ECN's test station EWTW have proven that the sensor assemblies indeed can be installed by regular maintenance technicians within a short time. The (mounting) tools and procedures designed for installation have proven to be adequate. Some minor improvements have been proposed. If the technicians become more experienced, installation of the entire FOBM system with 4 sensor assemblies per blade can easily be done in less than two days with two technicians.

The pre-assembled and calibrated sensor assemblies could be connected to the FOBM system as "plug-and-play" and no additional on-site sensor calibration was necessary. The measurement system could be accessed remotely as planned. The wireless LAN system has worked well and all data were transferred in time from the hub to the measurement PC. During the field tests, the data was stored at the measurement PC first and transferred to ECN's database for further processing later on.

Field tests have also led to a redesign of the protection box in order to make it easier to install and make the sensor better accessible, see Figure 6.2.



Figure 6.2: *New protection box design to allow easier access to the assembly with its screws and connectors. The re-design was based on the field tests carried out in the Nordex N80 turbine;*

Although the entire system has proven to work well, both the sensor assembly and the software are continuously being improved. The prototype of the assembly is subject to redesign to reduce manufacturing and assembling costs. The software is being expanded with more reporting functionalities.

6.3 Verification of optical measurements

The FOBM system as explained in the previous section ran from April 2011 up to and including July 2011. Many comparisons were made between the two optical sensors

and between the optical and electrical sensors, and many plausibility checks were carried out. The main conclusions are reported in this section.

6.3.1 Temperature measurements

The temperatures were measured with a PT-100 element and with the optical sensors mounted at the sensor assembly. In Figure 6.3 the electrical measurements are compared with the optical ones (10 minutes averages, leading edge) and it can be seen that both measurements are close to each other and follow the same trend. The average difference between the two sensors is $0,46^{\circ}\text{C}$ and remains constant over the measurement period. Maximum differences found were plus and minus $1,6^{\circ}\text{C}$. These differences are most likely caused by the fact that the PT-100's are glued on the blade material whereas the optical sensors are glued on the sensor assembly and have some delay when the temperature of the blade is changing. Since the optical sensor is being used to correct the optical strain gauge which is also mounted at the assembly, the temperature measurements are considered as reliable and adequate for the purpose for which they are designed. Similar results were found for the measurements done at the trailing edge.

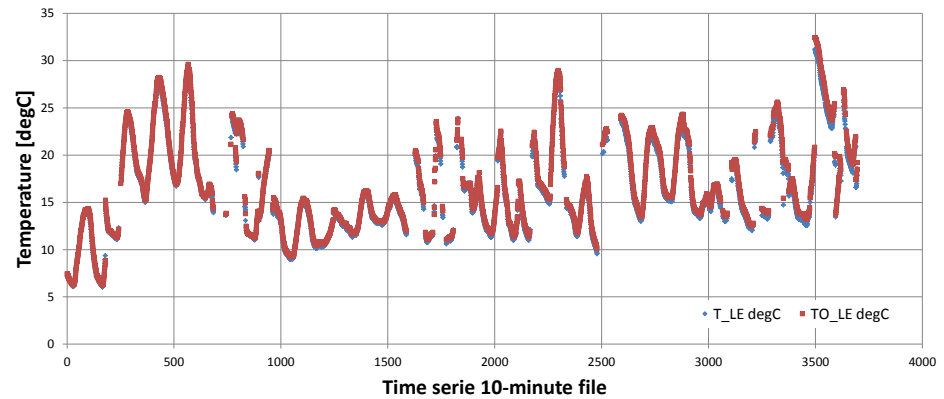


Figure 6.3: Comparison between temperatures measured with the PT-100 sensor (blue) and the optical sensor (red), 10 minutes average values, leading edge

6.4 Strain measurements

The strains are measured with the FOBM strain sensor in [nano meter], transferred into micro strain and corrected for temperature influences by the results of the optical temperature sensors. The measurements are compared with the results of the electrical strain gauges and only the gauges glued parallel are considered further on. (*The T-configuration takes into account the influence of the Poisson ratio which is too uncertain for these verifications.*) The conversion from raw optical output in [nm] into [$\mu\epsilon$] is shown in Figure 6.4 for the 10 minute averages of the trailing edge signal.

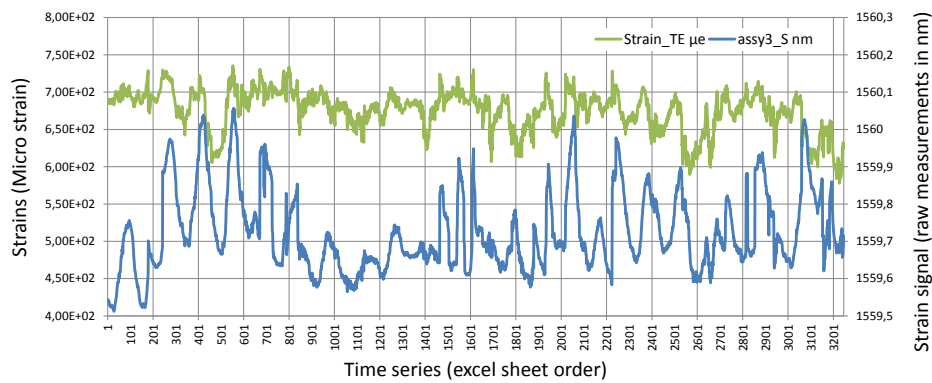


Figure 6.4: Mean values of optical strain sensor (blue) and mean value from optical sensor converted into strain with temperature corrections (green)

As a plausibility check, both strain signals derived from the optical strain sensors were plotted. The leading and trailing edge signals are expected to have opposite values, but more or less the same trend and amplitudes. In Figure 6.5 the output from the leading edge sensor (blue) has been corrected for the opposite value and for the offset and should show good agreement with the signal from the trailing edge (green). As can be seen, the overall trend and the amplitudes show good agreement. However only one thing is remarkable. At the start of the measurements, the trailing edge values are higher than the leading edge values whereas at the end of the measurements the values are lower. This indicates some drift in one of the sensors that needed to be investigated further. The tests showed that the sensors had an accuracy of around 20 $\mu\epsilon$ instead of the specified 5 $\mu\epsilon$.

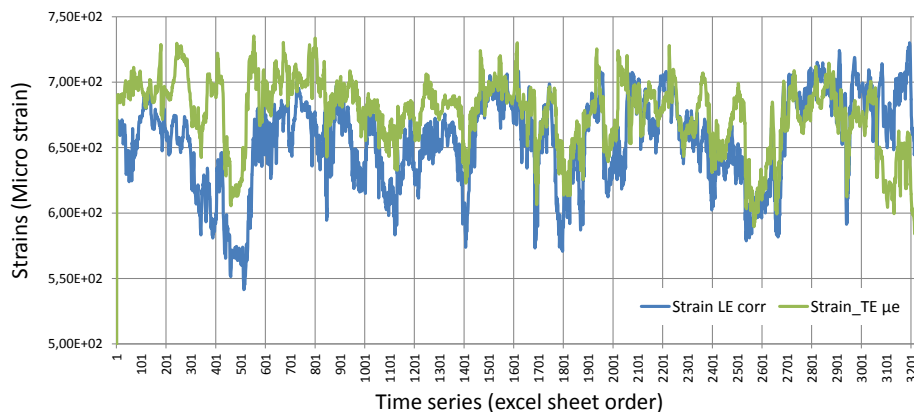


Figure 6.5: Comparison between leading edge and trailing edge signals

The output from the optical sensors was processed further on and combined to one strain signal in [$\mu\epsilon$] that could be directly compared with the electrical strain measurements. It was concluded that the strains measured optically were on average a factor 1,43 lower than the strains measured electrically. The optical signal was corrected and compared with the electrical signal as can be seen in Figure 6.6. Both signals show good agreement and the differences are close to zero.

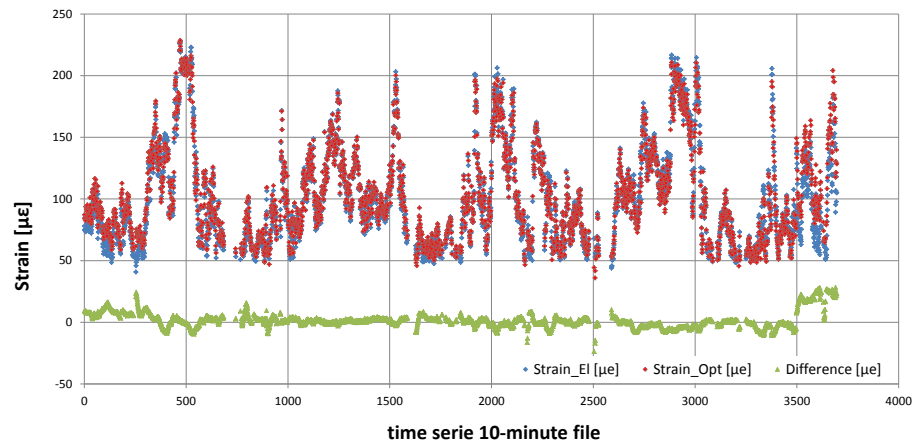


Figure 6.6: *Comparison between 10 minute average values of the optical (red) and electrical (blue) strain measurements, and the differences between the two (green)*

End of July 2011 it was concluded that the large differences between the electrical and optical signals had to be investigated in more detail. The already present strain gauges were mounted 20 cm from the optical sensors. To minimise the influence of any local effects in the blade root material and of the protection box it was decided to apply additional electrical strain gauges directly under the FOBM sensor (in between the studs) and next to it, see Figure 6.7.

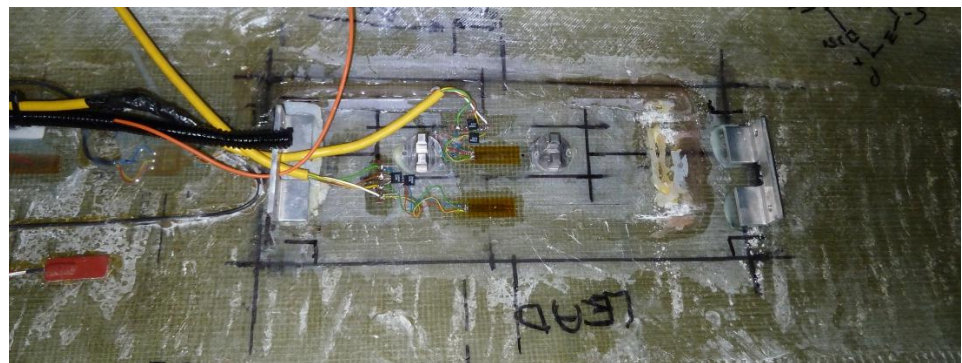


Figure 6.7: *Additional strain gauges glued in the blade root under and close to the FOBM sensor*

Measurements showed that the signals from the new sensors were approximately 1,2 lower than of the original electrical strain gauges, but still a factor of 1,2 higher than the signals from the optical measurements.

Early August it was decided to dismount the optical strain sensors from the Nordex turbine and to build up a laboratory test rig to better understand the differences between the various blade root strain measurements, see Figure 6.8. Electrical strain gauges were glued under the FOBM sensors and in between the sensors. Moreover, electrical strain gauges were glued at the other side of the beam. A force was applied in the middle of the beam in between the FOBM sensors to simulate bending.

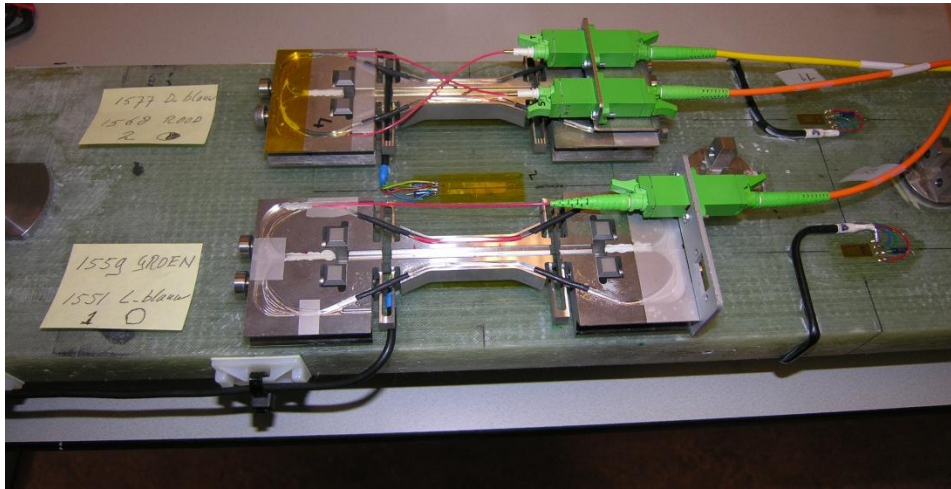


Figure 6.8: *Laboratory tests to compare the electrical strain measurements with the optical measurements*

The results of the laboratory tests are plotted in Figure 6.9 and as can be seen, good agreement was found between the optical and electrical strain measurements. The fit between the optical sensor and the electrical strain gauge glued between the studs is very good. The maximum difference between the optical and electrical one glued under the FOBM sensor is less than 4%. It should be noted that the same difference is also existing between the two electrical measurements!

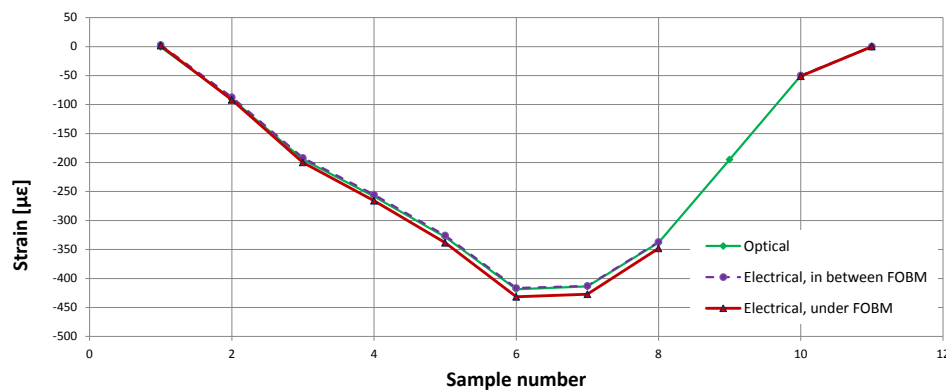


Figure 6.9: *Results of laboratory tests showing good agreement between optical and electrical sensors, but also differences between the two electrical sensors*

The level of agreement between the optical and electrical strain gauges was already found during the numerous laboratory tests that were carried out during the development of the FOBM sensor. The large differences between the blade root measurements were in fact a surprise. The exact reasons for the differences could not be determined completely. Several aspects were discussed, e.g. the quality of how the electrical strain gauges are glued, the local effects of the blade material on the strain gauges, temperature effects, conversion from raw data to strains, taking into account geometry of the materials, or the effect of the protection box. Some of the effects were investigated in more detail, but final answers were not found.

Apart from drawing conclusions on the accuracy of the optical measurements, ECN has also drawn conclusions on using electrical strain gauges as a reference. After the tests in

the Nordex N80 turbine and from the laboratory tests it was found that differences occurred not only between optical and electrical measurements, but also between the different electrical measurements. ECN has the idea that using electrical strain gauges as a reference for verifying the optical measurements is no longer valid. Reproducing electrical strain gauge measurements with high accuracy appears to be difficult. Perhaps the reproducibility of the optical measurements is better than that of the electrical measurements.

6.5 Long term behaviour of the system

The system has been used for approximately 4 months. In that period, no problem has occurred. The HBM interrogator has been installed for more than one year in the rotating hub and is still functioning. Later on it has been replaced by an interrogator from FibreSensing and this device also works without any problem.

The measurement software has also proven to work well. It checked the raw optical data and converted it into 10-minute time series with blade root bending moments and other turbine data. These files can be processed further on with the data analysis software described in Chapter 5.

The wireless LAN and the measurement infrastructure has worked without any problem or loss of data. Every day 144 10-minute time series were produced.

The only point of concern is the drift over time as shown in Figure 6.5 and also determined during the laboratory tests. The current developments focus among others on solving this issue.

7

Conclusions and Future Developments

7.1 Conclusions

As part of its developments to lower the O&M costs of offshore wind farm ECN has decided to focus part of its effort on low cost load monitoring and the development of the Fibre Optic Blade Monitoring System (FOBM). The FOBM developments are ongoing at ECN since 2005. Within the D OWES project ECN has been working on:

- testing and optimising the prototype version of the FOBM sensor to ensure that it will meet its specifications on accuracy, long term stability, reproducibility, easy installation and maintenance, and low costs;
- selecting and testing interrogators to verify that they can be used for wind turbine applications in combination with ECN's innovative FOBM sensor;
- development of data analysis software that analyses the measured data and assists operators to shift from corrective and preventive maintenance to condition based maintenance;
- carrying out field tests to assess its long term behaviour and identify spots for future improvement of the FOBM system.

The developments have shown that the FOBM prototype meets most of its specifications. The system is easy to install, and operated well during the test period at the Nordex N80 turbines for 4 months. The interrogator, the wireless LAN, and the measurement system showed no problems. The data analysis software was used to process more than one year of data that were measured with electrical strain gauges. The algorithms for filtering, data cleaning, data classification (single mode files), and reporting functioned in accordance with the original specifications.

The temperature and strain sensors showed good agreement with the trends measured with electrical sensors. However, the absolute strains measured with the optical strain sensors did differ from the strains measured electrically. It should be noted here that

after the tests were completed, the assumption that the electrical strain measurements should be accepted as the reference is no longer valid. Adding additional electrical strain gauges gave results that differed substantially from the strains measured with the electrical strain gauges that were already in place. A point of attention is the drift that was measured during the field tests for one sensor. Possible solution is the modification of the glued connection between the fibre and the metal assembly.

7.2 Future developments

After the finalisation of the D OWES project, the FOBM system was substantially improved. The sensor assembly has proven to work well in both laboratory and field conditions and the installation procedures have proven to work well. Two interrogators were selected and tested and do meet the requirements for operating in wind turbines under harsh conditions. The future developments that ECN has foreseen are the following.

- ECN will gradually improve the current configuration. Among others, the issue with the drift will be solved, the assembly will be re-designed to make it cheaper for series production, more field test will be carried out to demonstrate the benefits of the system, the specifications for the interrogators will be sharpened, the data analysis software will be further tested and improved, and the reporting software will obtain more functionalities.
- Sensors for monitoring blade root bending moments are a necessity if turbine manufacturers want to implement control algorithms based on blade loads, e.g. individual pitch. At present, hardly any sensor is available that has proven to be reliable enough to become part of the control loop. ECN will improve the current design in a way that the FOBM sensor meets the strict requirements for control purposes.
- ECN believes that measuring turbine loads in the end will inform operators and OEM's about the degradation of components and the need for maintenance and repair. In the near future ECN is going to combine the FOBM developments with the Fleet Leader developments. Two or three turbines (the Fleet Leaders) can be instrumented with the FOBM systems and with the Fleet Leader software [5] the loads on all turbines can be determined at very low costs. For this, the FOBM software will be integrated with the Fleet Leader software



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