ECN

Energy research Centre of the Netherlands

Load monitoring for wind turbines

Fibre optic sensing and data processing

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Acknowledgement/Preface

This report is written in the context of the project "*Measurement system Load Monitoring and O&M optimisation*" which is carried out within research line 5 (RL5) of the Dutch research program We@Sea. The aim of this project is to develop a blade load measurement system, which can be used for load monitoring of the blades during the life time of the turbine.
Support for the tests has been given by several parties. For the selection of the instrumentation, suppliers provided interrogators and sensors to perform laboratory tests. The test results are partly confidential. The dynamic tests for the sensor connection with the blade have been done by WMC.

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Summary

Condition monitoring of wind turbine components is of growing importance. For bearings, gearboxes and other rotating equipment, techniques are available from other applications. For condition monitoring of rotor blades, no suitable techniques are available up to now. However the interest for it is increasing in order to get more insight in the occurring loads and to reduce these loads by applying other control techniques. The developments with respect to application of more advanced control techniques and condition monitoring are hindered by the fact that no reliable and accurate measurement system for measuring the blade loads is available.

For the load measurements, optical techniques are often mentioned as the most promising because of the long life time of the fibers, the insensitivity for electrical interference and stability of the performance, which makes regular re-calibration superfluous. Optical measurement systems are in use for several years now, but the results are not always convincing and require further developments. The systems which have been used initially by ECN showed a lot of failures, so that measurements have been often interrupted. The installation of the sensors appeared to be very time consuming and had to be done by special skilled employees. The connection of the sensors itself also failed sometimes and the repair is laborious, because special skills and bonding techniques are required.

Another general disadvantage of condition monitoring systems is, that a lot of data is generated, which requires a lot of effort to analyze. Special knowledge is required for interpretation of the results. This implies additional work load and costs.

For the current project, the following objectives have been chosen in order to improve the applicability of load measurements and monitoring of the blades:

- Selection of an interrogator which meets the requirements for load monitoring.
- Selection or development of a sensor which is suitable for this application, including handling and installation.
- Development of a processing tool, which operates automatically and generates only the required information.

For the selection of interrogators, an inventory followed by a first selection was made in a desk study. This resulted in three candidates, which matched with the user requirements to a large extend. These interrogators have been tested at ECN and resulted in the choice of a device which meet the requirements to a large extend and which is also considered as suitable for further experiments and development tests for sensors. The accuracy and resolution are sufficient for the application, but also the selected interrogator showed strong sensitivity for polarization. The price level is still above target.

For the sensors, also a desk study has been performed. This showed that no sensor was compliant with the user requirements. The strain was often not measured directly, while installation and/or replacement were difficult. However, the desk study also resulted in a new idea with respect to a new approach. A sensor assembly was designed, built and tested. This sensor meets the following requirements:

- The sensor can be easily installed in the rotor blades. The installation of a sensor assembly takes 15 to 30 minutes, which implies that a turbine can be equipped with a load measurement system within a day. This minimizes the down time of the turbine.
- The sensor is designed for easy maintenance. A failure can easily be detected and the sensor can be replaced within five minutes. Calibration of the sensor can be done during production. On site calibration is not necessary, which implies “Plug-and Play”.
- Temperature compensation is included with respect to sensor properties.
- Installation and maintenance can be done by technicians that are trained for regular wind turbine maintenance. No special skills are required.

- The sensor is also compliant with respect to resolution and accuracy and does not show drift.

A request for patent is pending on this moment. Several parties have shown their interest for this sensor.

Load measurement systems produce large amount of data, which is difficult to handle by the operators. The project resulted in a concept for automatic data processing and providing key figures to the operator to make decisions for maintenance. This improves the cost effectiveness of the maintenance. The concept is described in a specification and the software is in development.
The software has the following features:

- The measurement system converts the strain measurements into bending moments. A well defined interface between measurement system and data processing enables the use of the software in combination with other measurement systems.
- The software automatically generates load spectra and equivalent loads in accordance with the relevant IEC-61400 standards and taking into account the operational conditions.
- The measurements are validated automatically.
- The measurements can be processed directly, which implies that storage of large amounts of measurement data is not necessary.
- The software allows comparison of loads between the individual turbines in order to prioritize maintenance and inspection schemes.
- Although an interface between the wind turbine and the measurement system is required with respect to the PLC-signals, the data processing is suitable for all types of turbines.
- The data processing also includes automatic warning and detailed event analysis.

The software development did not yet result in version ready for application. The requirements are available for a wide extend. The development is hindered by the complexity of large variations in loading in combination with unreliability of measurement data. Although the measurement system should generate reliable data, faults can have strong effects on analysis results. This implies that a lot of effort has been laid in this part of the data processing.

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1. Introduction

Condition monitoring of wind turbine components is more and more becoming daily practice with the ultimate goal to reduce maintenance costs by changing from preventive and corrective maintenance to condition based maintenance. Condition monitoring techniques for detecting failures of gearboxes, bearings and other rotating parts at an early stage are commonly used in various branches of industry. Sensors, hardware and software for data acquisition and diagnosis are widely available and can be applied to wind turbines.

For monitoring rotor blades, suitable techniques are in development now. Various techniques to assess the health of blades are investigated. A promising method is to measure and to analyse the blade loads continuously. The classical copper strain gauges are economically feasible. A major disadvantage of this measurement technique is that copper strain gauges are unreliable over a long period and need to be calibrated periodically. Another option, optical strain gauges based on Bragg grating techniques pretend not to have these disadvantages.

However, the sensors in combination with read out units are too expensive for condition monitoring applications and are insufficiently tested on their suitability. Since a few years, the Bragg grating sensors show a significant decrease in price and also the read out units have the potential to become much cheaper.

Optical sensors also show some disadvantages which have to be handled. A practical one is that people working in this area are not familiar with optical components, which imply that handling should not require additional skills. Also installation and replacement of components should be simple and risk-free without necessity of elaborate calibration procedures. This requires a different approach for the sensor installation. Furthermore, aspects like accuracy, reliability and temperature sensitivity should be addressed.

The data processing, which has to result in information for the user with respect to the behaviour of the blades and the remaining life time should be fully automatic. However, the loads can vary dramatically because of varying operational and external conditions. An emergency stop will cause very high loads on the blades, which are acceptable because of the limited number of occurrences. However, during normal operation these loads are unacceptable and might lead to an alarm for the operator. Apart from this, measurement faults might result in wrong conclusions about the encountered loads. The data processing should handle these situations automatically, without major interventions of the operator.

Blade monitoring is basically a problem of realisation of reliable load measurements followed by robust data processing. Optical load measurements have the potential to realise such a measurement technique, but requires the availability of a reliable optical interface (interrogator), reliable and easy to handle sensors and suitable installation tools and provisions. The development of the software is also essential for the application, but not directly relate to the measurement technique. With a well defined interface between the measurement system(s) and the data processing tool, various configurations can be handled. This makes the application of the data processing tool much more general than the optical measurement techniques only.

1.1 Objectives

The objectives of the project are:

1. Selection of an interrogator which meets the requirements for load monitoring. The system should be suitable for operation within a wind turbine and withstand the severe environmental conditions during the life time of the turbine. It should also be suitable for using it as a measurement device during sensor development.
2. Development of a sensor which can be installed and replaced by personnel without specific skills with respect to fibre optics. No field calibration should be necessary after

replacement. The sensor should be temperature compensated. The life time should be in line with the life time of the turbine.

3. Development of a data processing tool, which processes the measurements automatically, including quality checks. The software should basically be suitable for operation with different measurement systems and for different turbines.

For the realisation of the objectives, the project started with the selection of an optical interrogator. The interrogator is considered as an item which is available on the market. Suppliers are often specialised firms with specific knowledge which is not available at ECN. However, experience in previous projects learned that the existing models are not yet fully developed which implied that better performance was promised than could be realised. Because of this it was decided to select three out of thirteen systems in a desk study and to test these systems in the laboratory. The laboratory tests resulted in one system, which met the requirements sufficiently but not completely to support the sensor development and field tests.

Optical sensors are also available on the market in different configurations. For installation in wind turbines, simple patches are available which can be installed on the surface of the blades. The installation of this type of sensors appears to be very time consuming while the signal quality often raises as many questions as answers. The relation between the measured signal and the actual strain/temperature is not always clear. Sensors on opposite locations in the root of the blade often show very different ranges of measured signals which cannot be explained. The installation and repair also requires specialised skills, and cannot be done by regular maintenance staff. Conditions for a successful application of fibre optic measurement systems on a larger scale are simple installation of robust sensors, measuring the strain.

1.2 How to read the report

This report gives an overview of the developments as executed with respect to fibre optics and load measurements. The applications for these measurements techniques are summarized in chapter 2. The technology of the fibre optic measurement technique is explained in chapter 3. Although the total field of fibre optic sensing is much wider, only the sensors and instrumentation based on Bragg gratings are explained. For strain measurements, in particular for wind turbines, this technique is commonly used.

The selection process for the interrogators is described in chapter 4. The process started with a desk study [Ref. 1] with respect to used technologies and available instrumentation. The desk study did not result in an unambiguous choice. Three candidates appeared to be of interest and it was decided to set up a test for these interrogators.

The sensor technology and developments are described in chapter 5. These developments include the design of the sensor itself as well as the installation of the sensors. Especially the principle of the sensor is of interest, because it combines the advantages of easy installation, direct measurement method, replaceability and less calibration.

The developments with respect to the diagnostic software are treated in chapter 6. The software development was focussed on giving information to the operator in a condensed form without requiring additional actions from his side. Consequence is that the system should process the measurement data fully automatically and prepare and store the information in a very condensed form.

2. Application

Load measurements for wind turbines are of importance from several points of view. The following applications are the most promising:

1. *Control*: The objective of the controller is to optimise the production of the wind turbine with minimal loads. Especially the blade loads are of importance. However the loads are not measurable directly, which limits the performance of the controller. A more direct method to measure the blade loads real time opens the possibilities to improve the controller performance, which implies higher production in combination with lower loads.
2. *Blade monitoring*: The second application could be blade monitoring. The blades are the most critical components of the wind turbine. The blades are designed for a number of load cycles compliant with the life time of the turbine. However the deviation of load cycles encountered by different turbines is very large. When the loads encountered are known for all wind turbines individually, the design margins can be lowered or the life time can be adapted.
   For the load counting, the processing can be done off line, which is a relaxation of the requirements compared with 1, where the measurement is real time. On the other hand, for load counting, the load ranges are accumulated over the life time, which implies that when a faulty signal is processed in the accumulated data, the result can become useless. This can not be repaired. This implies that the reliability of the signal is very important.
3. *Flight leader*: The third application is to use load measurements for the "flight leader principle" [Ref. 7]. In this application, the load measurements of one or two suitable turbines are used to estimate the loads encountered by other turbines of the same wind park. This approach can be efficient for offshore applications because only a limited number of turbines has to be equipped with extensive instrumentation.

The current project is focussed on 2 and 3, which are both off-line applications.

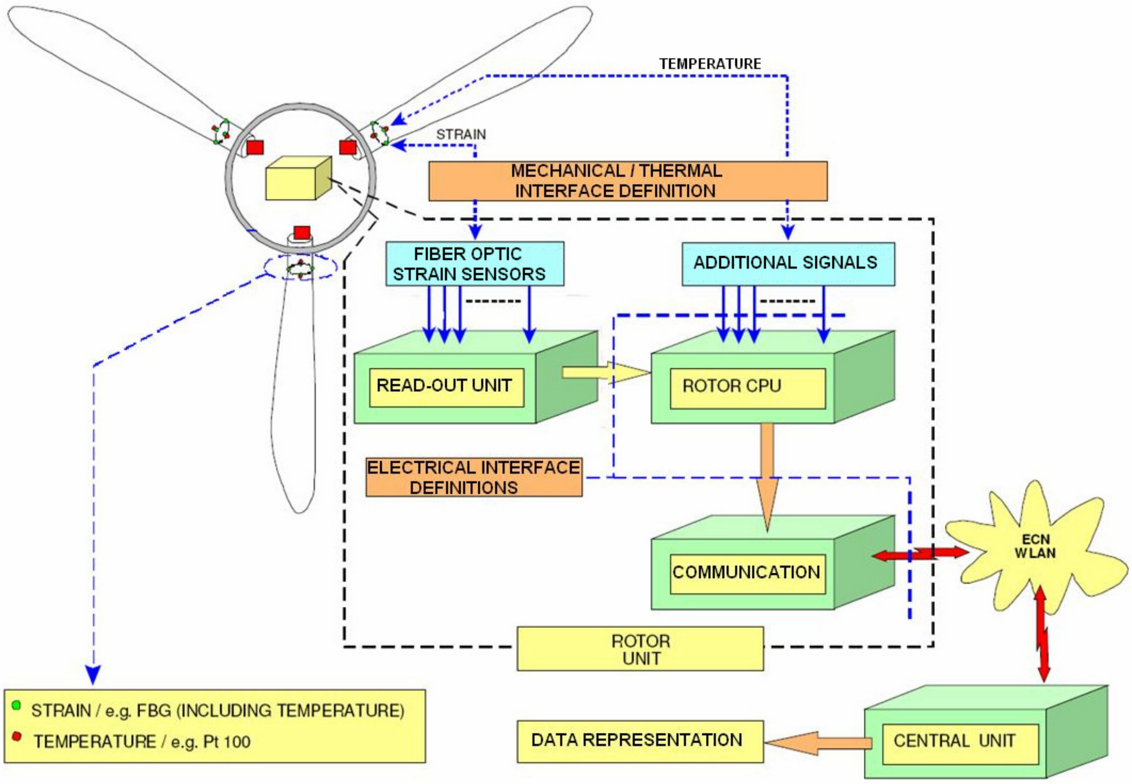


Figure 1: General lay-out of measurement system

A general set up of the measurement system applicable for all three applications, is given in Figure 1. The blades are equipped with strain sensors and temperature sensors. For both type of sensors, Bragg gratings are used. However, an option is kept open to extend the system with PT-100 sensors for additional temperature measurement. The Fibre optic sensors are connected with a read out unit (interrogator). All measurement information is collected in a synchronised form and sent to a central unit via a WLAN-system. In the central system, the rotor measurements are combined with other turbine signals (e.g. rotor rpm, wind velocity, etc.) for further processing.

The load sensors are installed in the blades, while the processing will be done in the turbine. This implies that there is always and interface necessary between the rotor and turbine. This can be a wireless interface or a slip ring. When a load measurement system is installed as real time system for control purposes (option 1), the system will be integrated in the turbine design and the measurement data will be part of the regular data interface between rotor and turbine. For the other two applications, the system should be considered as an add-on, so that the regular interface cannot be used. Communication via WLAN is then the most likely option.

3. Fibre Optic sensing

3.1 General

For optical strain measurements, Fibre Bragg gratings are the most promising technology for load measurements in wind turbines. The basic principle is that light is sent into an optical fibre provided with a Bragg grating. The Bragg grating reflects only a narrow portion of the spectrum. The reflected wavelength depends on the properties and state of the Bragg grating.

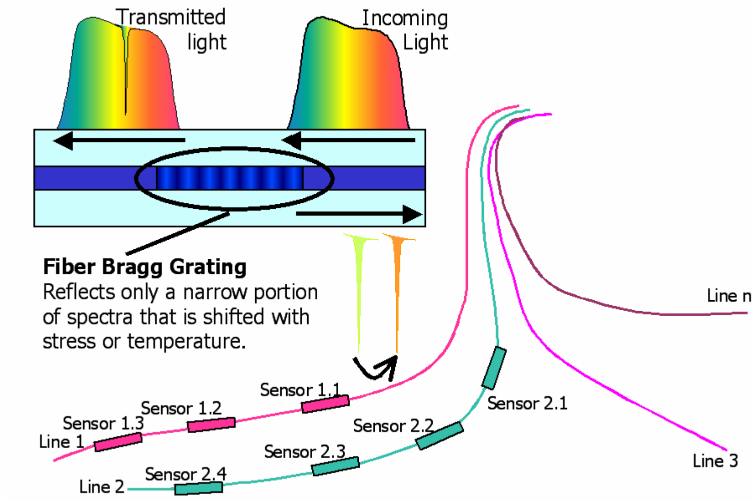


Figure 2: Basic principle of Fibre Optic strain measurements

For the Bragg gratings, the reflected wave length is sensitive for the strain, temperature and pressure. However, the sensitivity for pressure changes (≈-8.66E-6 pm/mbar) is far less than the temperature and strain sensitivities and can be neglected for this application. This implies that (similar to classical strain gauges), the sensors are sensitive for strain but also for temperature. The sensitivity for strain is ≈1.2 pm/με, while the sensitivity for temperature is 10.2 pm/^{o}C. This roughly implies that 1^{o}C in temperature change is equivalent with 8.5 με! Because temperature changes are large and mutual difference between the locations are also not negligible, compensation is necessary.
Basically it is possible to have more Bragg gratings in a fibre. When there are more Bragg gratings in series in a fibre, each Bragg grating will reflect the light of a certain wavelength depending of its properties. There are two different approaches for having the sensors in series:

- Wave length Division Multiplexing (WDM)
- Time Division Multiplexing (TDM)

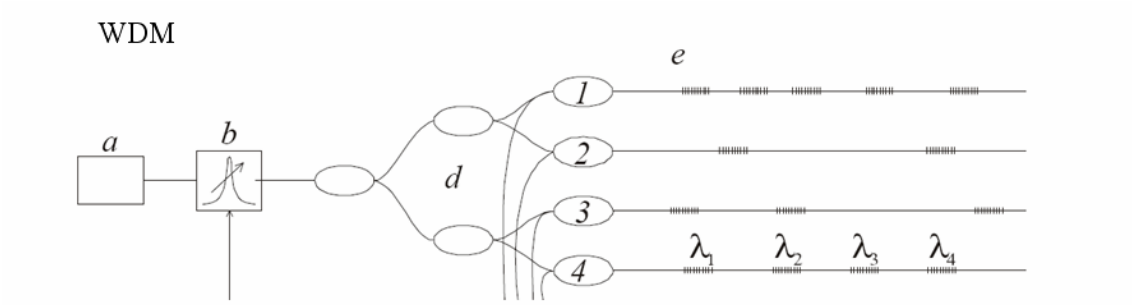


Figure 3: Wavelength division multiplexing

For WDM, each Bragg grating in a string has a different nominal reflective wavelength, which can deviate within a certain interval depending on the strain and temperature. The number of sensors in a string is limited by the number of intervals which can be defined with the total wavelength range (typically 8 for load measurements).

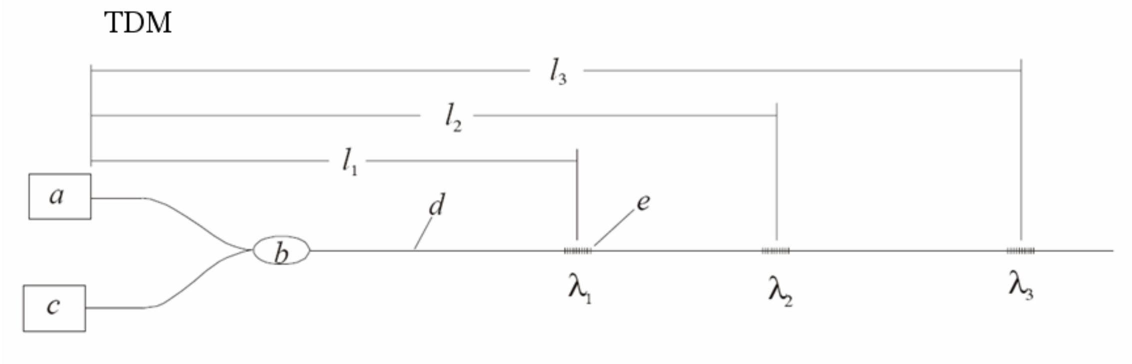


Figure 4: Time division multiplexing

In case of TDM, all gratings might have the same nominal frequency. The light is pulsed, and the time between transmitting and receiving is used to recognise the location of the sensor involved. Because each grating has the same nominal wavelength, the reflected light is attenuated depending on the location in the string (each grating causes a certain attenuation, depending on its properties). This is the limiting factor for the number of sensors which can be used within a string (normally more than 8).

Both approaches are used and instrumentation is also available for both. Interrogators are available for TDM, WDM and also for mixed configurations and are using different technologies.

3.2 State of the art

The instrumentation for fibre optic measurements is in the stage that all components are available more or less of the shelf. There are several suppliers, offering a rather wide range of products, interrogators as well as sensors in different forms.

Projects executed in the past by ECN often showed disappointing results. The measurement campaigns were interrupted for various reasons e.g.:

1. The interrogator often failed for unknown reasons, so that after long periods only a few time series were available.
2. The available time series often showed data interrupts because of timing problems.
3. The ranges/amplitudes of the strain signals of opposite sensors (suction/pressure side and trailing/front edge) often show large differences while they should be in the same order. This might be caused by the transfer of the strain of the blade material to the elongation of the Bragg sensor. Also composites are often not homogenous, while the sensor measures over a small length. This can also affect the results.
4. The temperature signals were disturbed by the strain. The strain was modulated on the temperature signal, so that this signal was not suitable for temperature compensation of the strain signal. For a correct temperature measurement, the Bragg grating should have good thermal contact with the object, while it should not be affected by the strain. In practise this is difficult to realize.

Because the problems were related to the sensors, the interrogator as well as to the software, it is not possible to develop a robust load measurement system without knowing the properties of the interrogator in sufficient detail and having suitable sensors. For the software development, a reliable interrogator and robust sensors are necessary. For these reasons, the following subjects are treated individually:

1. An interrogator should be selected and tested in the laboratory in order to get good insight in the properties with respect to accuracy and environmental conditions. For three

interrogators as selected, which fulfil most of the requirements theoretically, experiments are necessary for validation.

2. A sensor should be developed, suitable to measure the strain of not-homogenous materials. The available sensors on the market based on Bragg grating are often embedded in composite patches. These sensors can be glued on the surface of the component to be measured. The relation between the actual strain and the elongation of the grating is not always well defined. Apart from that the strain of the composite can be locally different due to the structure of the material. For load measurements only, the effects are less important because the differences are compensated by the calibration. However, for condition monitoring, the absolute strains are also of interest so that a more direct measurement is preferred.

3. Software should be developed, which also includes extensive data handling and which can operate fully automatically. This software is not available at this moment and should be developed. For development of this software a reliable measurement system is of major importance.

4. Read out unit (interrogator)

The read out unit forms the interface between the optical sensors and the "electrical/numerical" part of the measurement system. It translates the measured wavelength shift of the Bragg sensors (see Figure 5, where the read out unit is indicated) into numerical values.

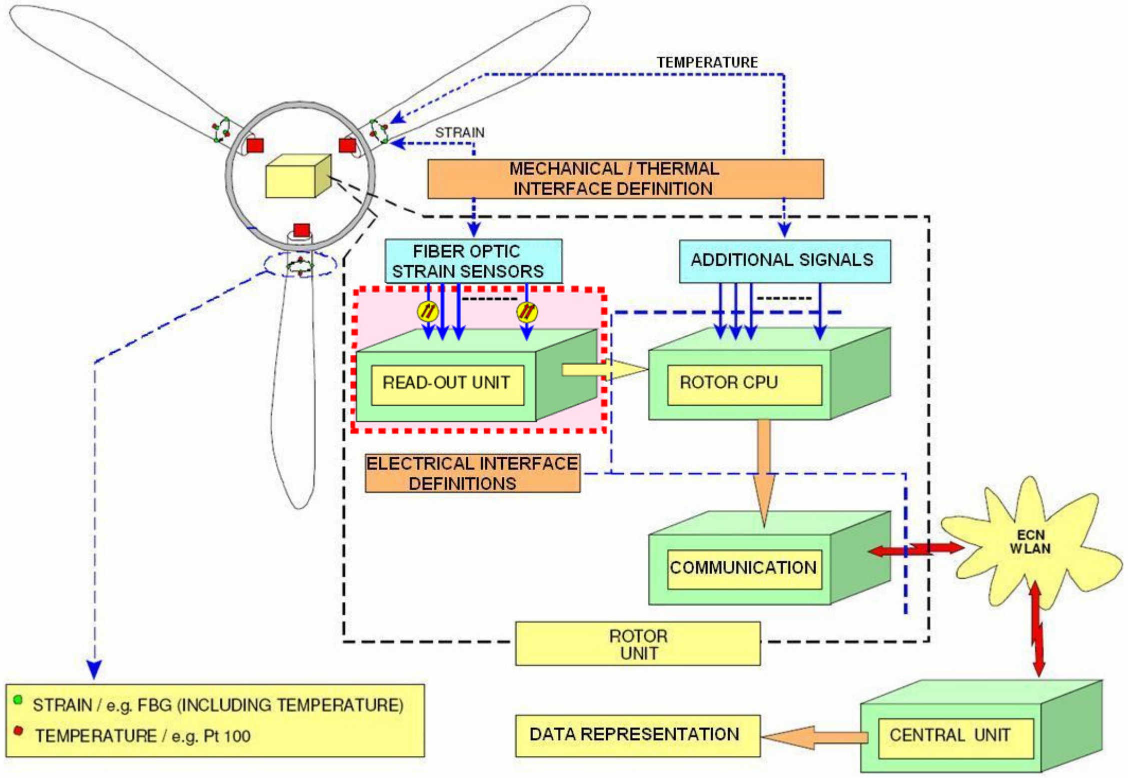


Figure 5: Read out unit as part of the measurement system

The properties of the read out unit (or interrogator) are of major importance for the quality of the measurements. These units are more or less standard available from suppliers, however specifications often promise more than can be realised. For this reason the selection of a reliable interrogator was a major part of the project.

The selection was based upon:

1. A desk study about available interrogator on the market [Ref. 1]
2. An extensive laboratory test with some interrogators [Ref. 3]

4.1 Desk study interrogators

A desk study has been done in order to get more insight in the instrumentation available on the market [Ref. 1]. With respect to the interrogator the following specifications are used for the desk study:

Strain resolution	:	1 με
Strain accuracy / stability	:	better than 5 με
Maximum strain level	:	-1000 ….+1000 με
Frequency	:	>16 Hz
Sensors per blade	:	4 stain sensors / 4 temperature sensors

The resolution and stability requirements are rather demanding in relation with the total range. However, the accuracy of classical measurement systems based on electrical strain gauges is even better than 5 με. Reason for the strict requirements is that the strains in the blade root related to the driving torque are in the order of 50 με, while the strains related to other loads (wind and weight) are much higher. For condition monitoring, the relation between driving torque and other turbine parameters can be of interest.
Apart from that, for the development of sensors the accuracy of the interrogator should be better than the requirements of the system to be developed. Because of economic reasons, the interrogator to be selected should be suitable for the sensor development as well as for field experiments. For sensor development the requirements should be considered as a bottom line.

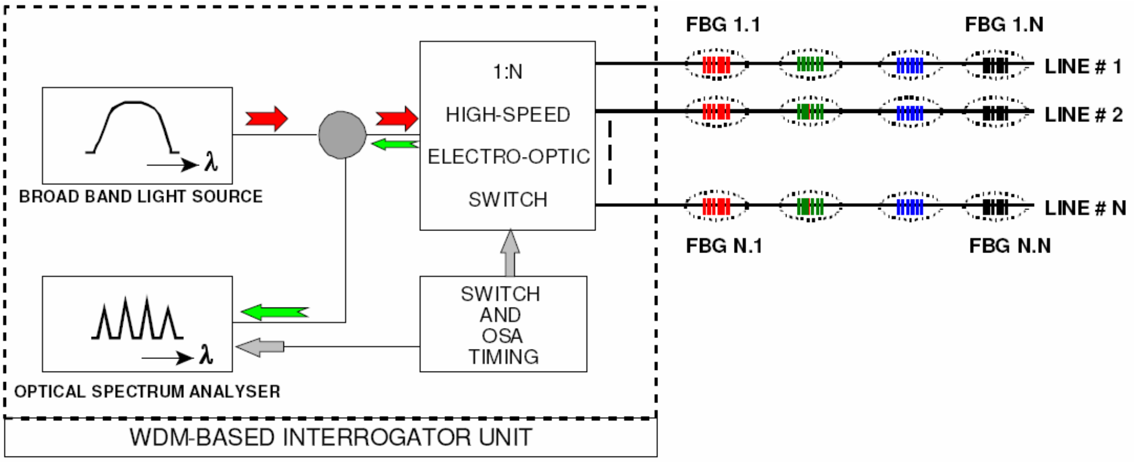


Figure 6: Multi-channel system

Because of the temperature sensitivity of optical sensors temperature compensation is necessary. Not only the temperature can vary over a wide range, also the temperature differences between the measurement locations can vary considerably (order of 10 ^{o}C). This implies that at each measurement location a strain sensor as well as a temperature sensor is needed. With four measurement locations per blade, 8 sensors per blade are needed. With a multi channel interrogator (see example Figure 6), each channel can accommodate the eight sensors of one blade, so that three channels are used. The range of the wavelength light source and analyser should be sufficient to cover to requirement measurement range of the eight sensors. This is a limiting factor for the WDM-systems, where overlap of the wavelength ranges of the individual gratings within a string is not allowed.

The desk study gives an overview of available interrogators, the used technologies and properties. A short overview is given in Table 1.

Table 1: Overview of systems as examined during the desk study

Supplier	Model	Resolution [pm[1]]	Accuracy/stability [pm[1]]	WDM/ TDM
Micron Optics	Sm130-200[2]	0.5	2-5	WDM
HBM[3]	1-DI-101	0.5	2-5	WDM
Welltech	FBG3000-8	1	5	WDM
FOS&S[3]	FOS&S- X1	1	10	WDM
FOS&S	FOS&S- X2	1	10	WDM
FIBERPRO	IS7000	1-2	5	WDM
Technobis	TFT4[4]	1-2	Not specified	TDM
Technobis	Deminsys	2	Not specified	WDM
Insensys	WT-1010	0.8 /2/5	'a few με'	TDM
Smart Fibres	T4	6	20	TDM

(1) 1 με = 1,2 pm

(2) This is a 1-channel instrument, which can accommodate 12 sensors.
(3) HBM and FOS&S both use relabeled products of Micron Optics
(4) The TFT4 of Technobis is a modified version of the T4 of Smart Fibres

From the table above can be learned that a wide variety of instrumentation is available which gives the impression that a suitable interrogators can be obtained of the shelf. However for some aspects, the product specifications are not known and questions can often not be answered by the supplier directly, which implies that testing is necessary. Another finding is that HBM as well as FOS&S offer instruments which are based on Micron Optic products. Micron Optics should be considered as the leading company with respect to fibre optic interrogators. Their products can be found by different suppliers as relabelled instruments. Technobis offers a low cost instrument, which is a modified version of the T4 of Smart fibre. This instrument is not available, but could be developed for the project.

Smart Fibres has a long history with wind applications and was the first supplier of these systems. Insensys was founded by Smart Fibre employees and developed a range of measurement systems especially focussed on wind applications. At this moment they are the leading company for wind turbine applications. The products of Welltech and Fibrepro comply with the specifications for a large part, however a track record of these companies was not known.

4.2 Laboratory tests interrogators

Based on the desk study, the following instruments were selected for testing:

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.

Figure 7: Interrogators as tested: HBM, Insensys and Smart Fibres

With these suppliers was agreed that the instruments should be available for these tests free of charge, under the conditions of confidentiality and individually reporting. Also a test plan has been proposed and agreed upon with the individual suppliers.

4.2.1 Testplan

A general test plan was prepared for all 3 devices, in which the types of tests have been described. This test plan has also been discussed with the suppliers. The performance requirements can be affected by several conditions as indicated in Figure 8.

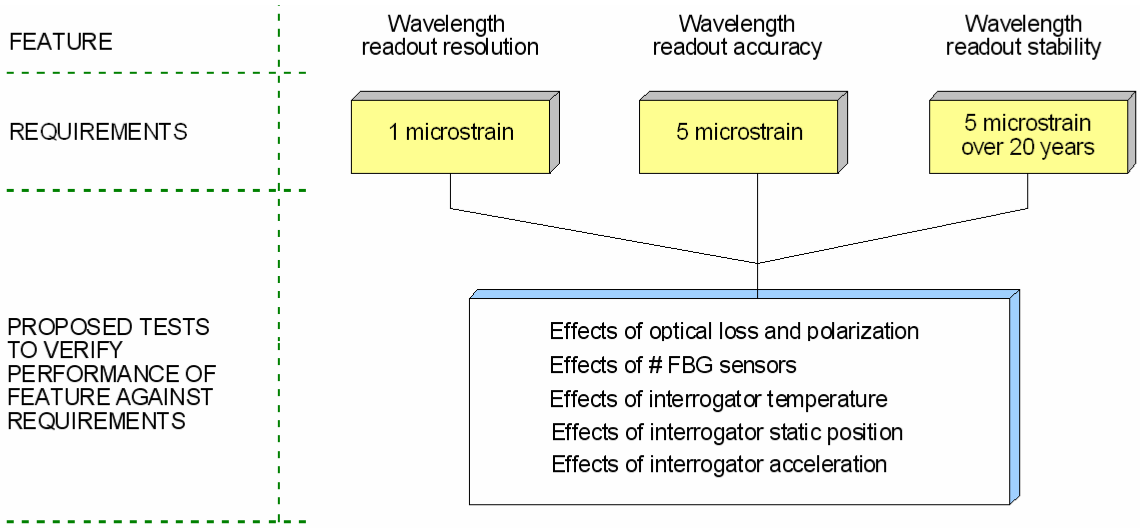


Figure 8: Performance requirements and tests

The effects of polarization and attenuation can be 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 splicing of fibres and connectors. 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.

In a string, several gratings are put in a series. Depending on the technology (TDM or WDM), using more gratings (8 in our case) might 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 proposed:

- 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

4.2.2 Test equipment

In order to execute the laboratory tests, special test equipment is needed. The following equipment was used:

Test strip

A test strip, equipped with several strain sensors, suitable for all three interrogators was used for static and dynamic testing. Aluminium was chosen because the material properties are well defined.

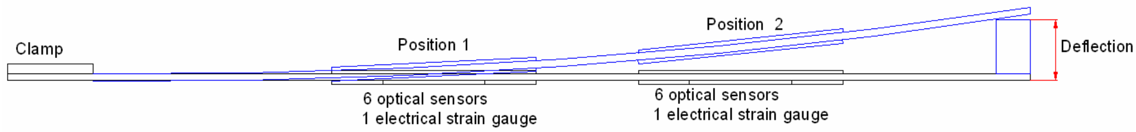


Figure 9: Sensors aluminium test strip

The test strip can be clamped at one side, while the deflection is done at the other side. This deflection can be done statically (block of 10, 24 and 50 mm) or by a dynamic excitator with adjustable amplitude and frequency.

The aluminium test strip has been instrumented with the following sensors:

- 4 Bragg grating for three interrogators (12 in total)
- 2 electrical strain gauges
- 1 PT-100 temperature sensor

Fibre Bragg grating sensor strings

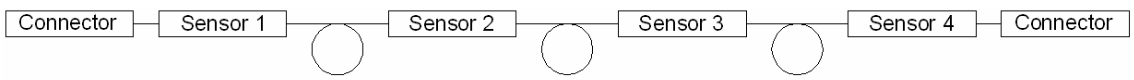


Figure 10: Sensor string

For each interrogator, all four sensors are located in one string with connectors at both ends. This implies that the strings can be connected to the interrogator from each side and can also be used as part of a larger string. For the TDM-systems a minimum distance (3 meter for the Insensys, 10 meter for Smart Fibres) between the sensors is required which results in windings of the fibre between the sensors.

All three interrogators have specific requirements with respect to the properties of the Bragg gratings. For this reason, the gratings were also delivered by the suppliers of the interrogators.

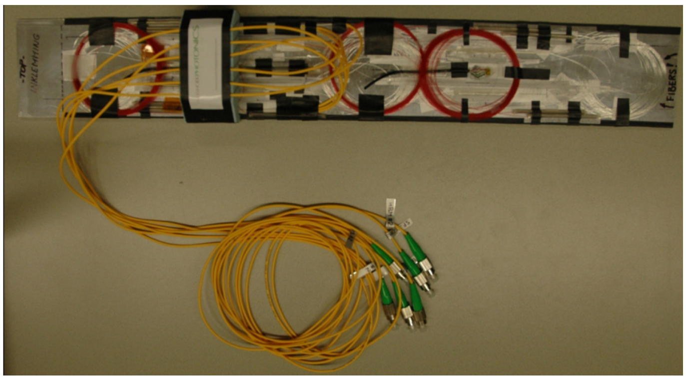


Figure 11: Photograph test strip

The photograph shows the realisation of the test strip. At several locations, windings of optical fibres can be seen, which are necessary for the TDM-systems.

Reference grating

In order to verify the stability and accuracy of the interrogator, a reference grating has been used. For the purpose of the test, a special device was purchased, which included two Thermal Stabilised FBGs, which covered the requirements of the three interrogators.

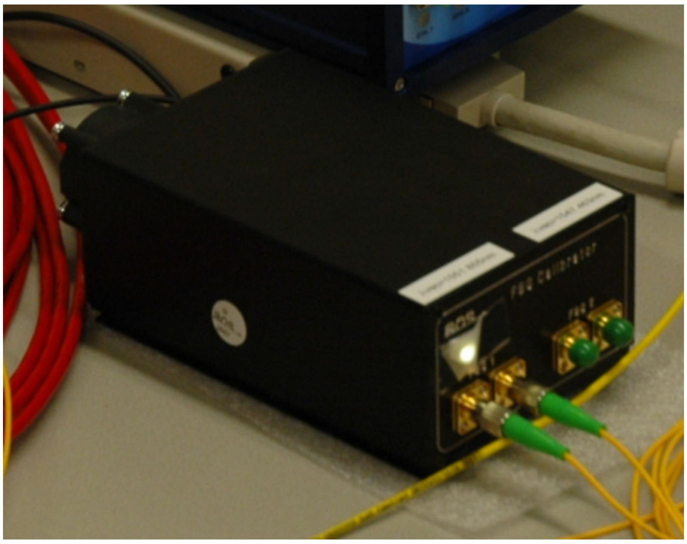
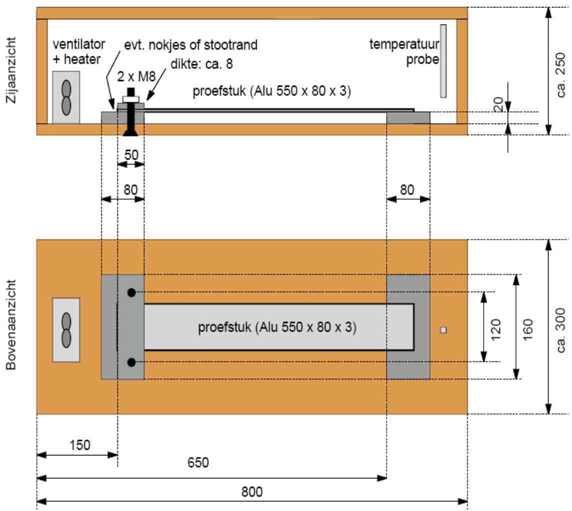


Figure 12: Reference grating devices

The reference gratings can also be connected at both sides, so that they can be combined with other gratings in one string of sensors.

Static bending device

The static device basically clamps the strip at one side. Bending is done by a displacement at the other side with a block of 10, 24 or 50 mm.



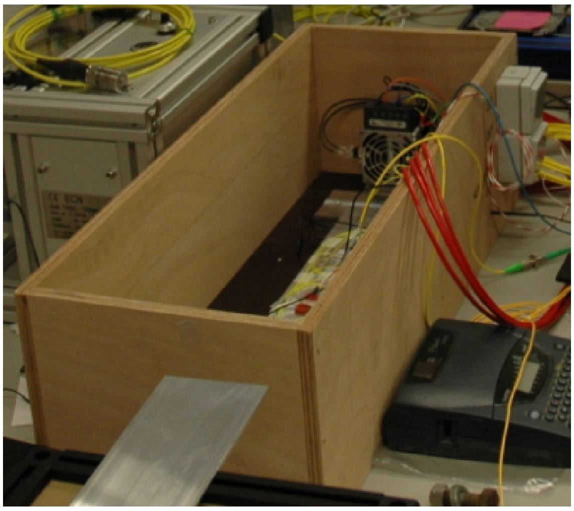


Figure 13: Test strip in temperature controlled cabinet

A fan, heater and a temperature probe, is installed in the cabinet so that the temperature can be varied during the tests.

Dynamic excitation device

A special device was built for the dynamic strip excitation as well as for the acceleration tests of the interrogators. The amplitude of the excitation as well as the frequency (motor speed) can be adjusted for both tests.

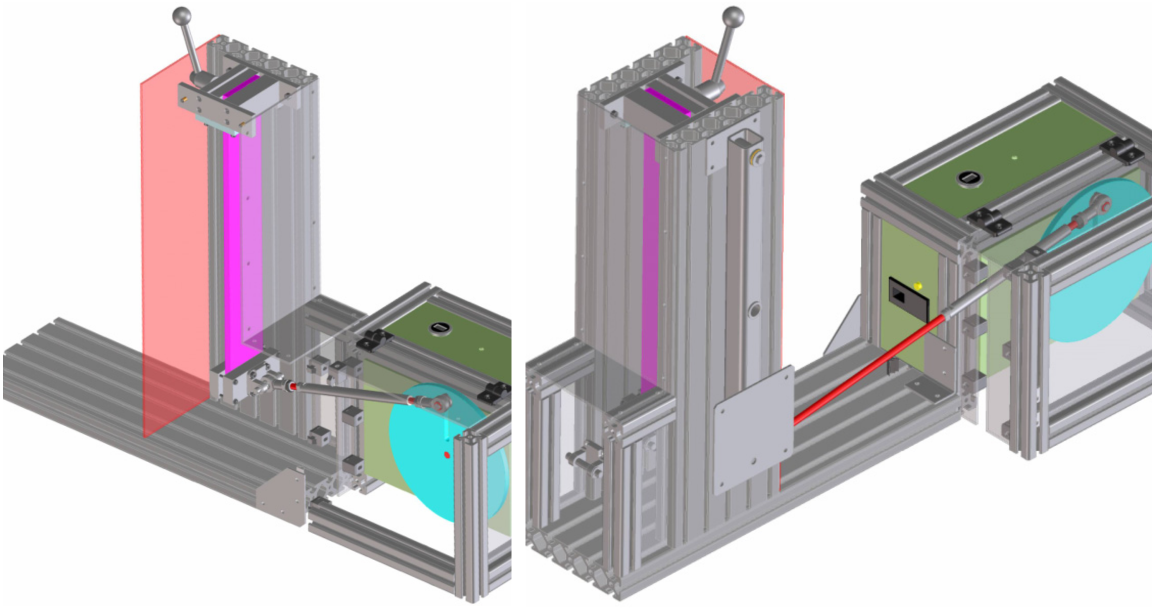


Figure 14: Dynamic excitation device: Strip bending (left) and interrogator acceleration (right)

The left configuration is used for bending of the strip, which can be clamped at the top side. The excitation is done at the bottom side of the strip by a crank.
For the acceleration test a crank can be mounted suitable to mount the interrogators is three different directions.

Few Micro strain Modulator

In order to test the resolution, it is necessary to have the possibility to elongate the grating with about 1 με. For this purpose a special device, Few Micro strain Modulator (FMM), was built.

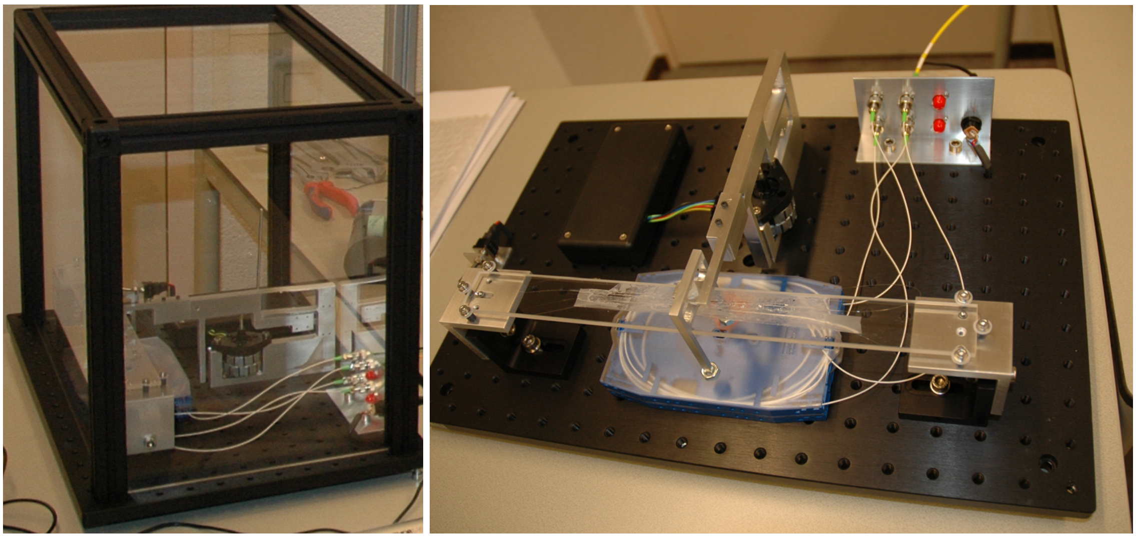


Figure 15: Few Micro strain Modulator

The FMM consists of a quartz strip, on which Bragg gratings are glued. The strip is supported at both ends on rollers. Bending is realised by placing a weight at the middle of 'top side' of the strip. The weight can be lowered or lifted by an electrical actuator, avoiding manual placing. The whole device is placed under a Perspex / PMMA cover. A temperature sensor is also included.

The quartz strip is provided with two different Bragg gratings in order to make it suitable for all three interrogators under test. The strings are also provided with connectors at both ends, so that they can easily be used as part of a string.

Climate room

A climate room was also available suitable to test the interrogators over the required temperature range.

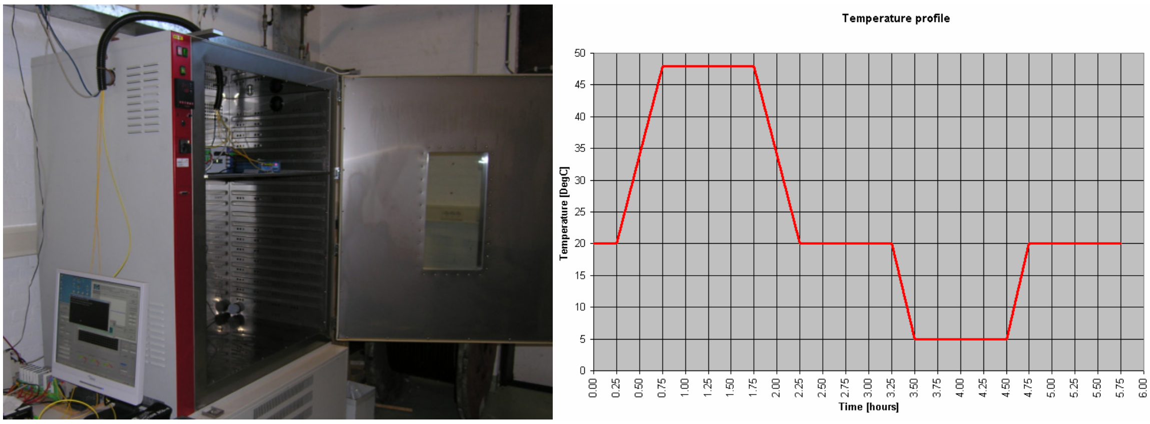


Figure 16: Climate room and example of applied temperature profile

The climate room was temperature controlled and large enough to test all three interrogators together.

4.2.3 Test results

The results of the test of the interrogators individually were confidential and only available for the suppliers. However the tests also resulted in specific knowledge which is not directly related to the interrogators individually.

General

There is quite a difference in performance between the three interrogators. Applying this measurement technology is not simply choosing for a certain device, but some knowledge about the technology is inevitable. The test resulted in the selection of a device with significant better performance. However also for this device shortcomings were identified.

For load measurements, the temperature sensitivity has an important impact on the measurement results. This is not typical for optical sensors, but also for electrical strain gauges. Temperature compensation is hindered by the variation in properties of the material of the object. When only the load range is of interest, than the temperature effects are less important as long as the temperatures are equally distributed over the measurement section. However, this is not always the case. For condition monitoring, not only the range, but also the absolute value is of interest, which implies that temperature compensation is necessary. A stable performance of the interrogator is essential to make this possible. The stability of the interrogator under varying temperature is not obvious.

Sensors

The properties of the Bragg grating appeared to be of major importance. Various types of Bragg gratings have been used along the test with different core diameters, reflection coefficients and coatings.

Bragg gratings can also be sensitive for the polarization. The impact of polarization on the results is significant, but measures can be taken to keep this at an acceptable level. The effect strongly depends on:

- The attenuation in the string. Increasing attenuation also increase the polarization effects. Attention should be given to splicing, connectors and core diameters.
- The uniformity of the properties of the sensors on a string is of importance. Differences in properties can result in different reflections levels which implies that the detection of the interrogator can not be optimized

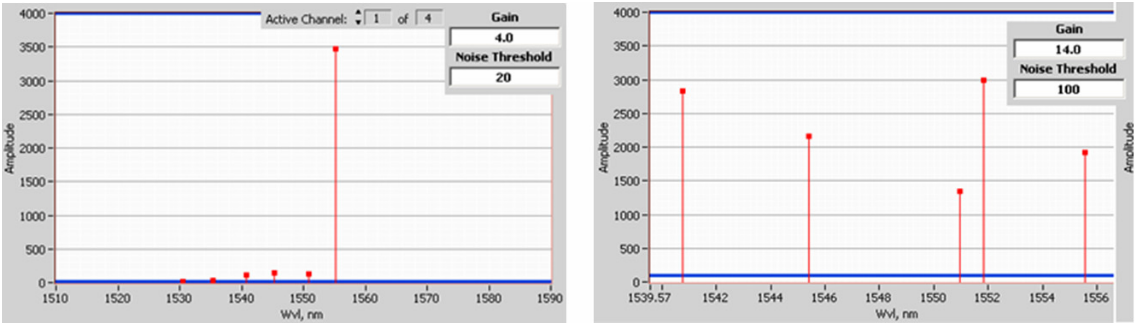


Figure 17: Non-uniform properties of sensors

In Figure 17an example of non uniform properties is shown. In a string with six sensors, indicated by the red bullet. Five have a low reflection, while the sixth has a high reflection. With a low gain, the signals for the grating with a low reflection are near to the noise threshold. A high gain results in an overflow of the high reflection sensor. In this example, the grating with high reflection is of another type, so that this can easily be prevented. However also within a group of gratings of the same type, the difference in amplitude is a factor 2, which has a negative affect the accuracy.

- Connecting fibres can also introduce or enlarge the polarization effects due to frequent change in bending and torsion with small radii.

After consultation of the supplier of Bragg gratings, a new batch of gratings was ordered for sensor development. The properties of this batch, as shown in Table 2, show that sensors can be produced with rather low deviation in reflection. Also the spacing between the gratings can be realised with 2 mm, which implies that splicing in between the gratings is not necessary. This implies that strings of gratings can be ordered, with specified wavelengths, reflection and spacing between the gratings without splices (the connectors used do not need splicing), so that the attenuation is kept minimal.

Table 2: Example of properties of recent batch

measurement values and evaluation

	Wavelength			Pulse width	Reflection
no	(nominal)	(actual)	(difference)	FWHM	1-T
	[nm]	[nm]	[nm]	[nm]	[%]
1	1516.03	1516.51	0.48	0.100	27.0
2	1520.64	1521.03	0.39	0.101	25.7
3	1533.78	1534.06	0.28	0.102	25.5
4	1538.39	1538.45	0.06	0.106	25.8
5	1569.28	1569.10	-0.18	0.107	24.4
6	1573.89	1573.75	-0.13	0.106	25.2

In the table above, the nominal wavelength is the wavelength as ordered and actual is the value as realized. The differences do not have any consequences for the sensor design. The pulse form, as represented by FWHM does also not show unacceptable differences. The reflection of the sensors is also acceptable.

Accuracy and resolution

Although the mutual differences are large, a resolution of 1 με is feasible for two of the three interrogators. Also the accuracy and stability together with the required frequency of 16 Hz cannot be met by two of the interrogators.

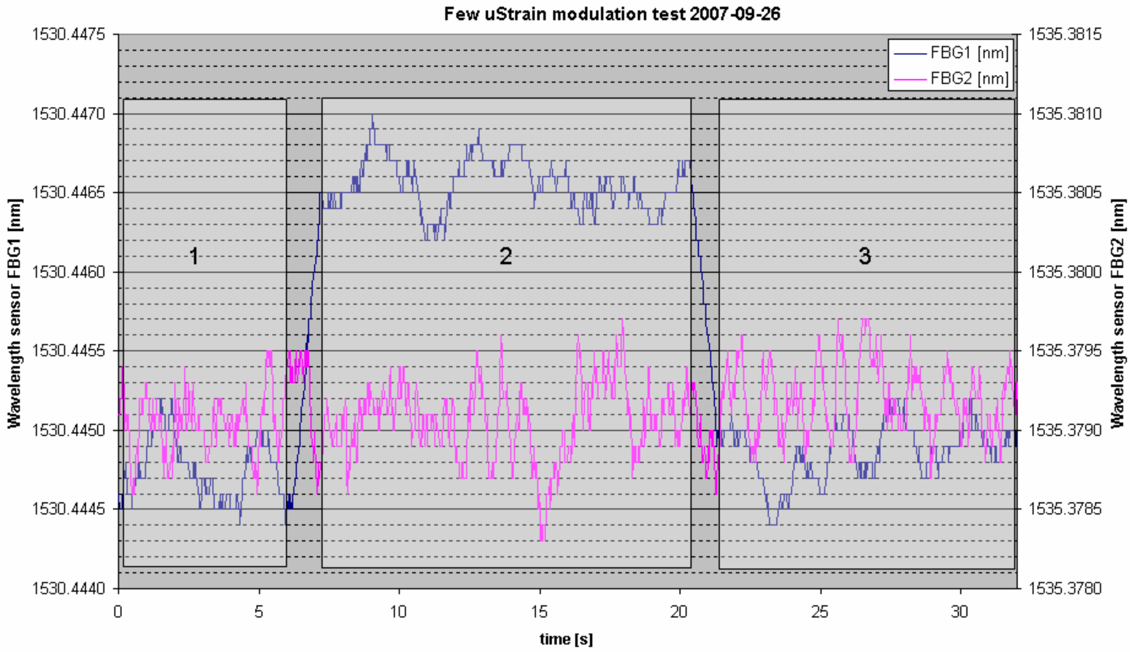


Figure 18: Example of resolution test

One interrogator showed a good result with respect to the resolution and accuracy test. In Figure 18 a strain of 1.25 με was applied on FBG1. This resulted in a step of 1.5 pm (conversion factor is 1.2. pm/με).

Polarization

Typical problem for fibre optic sensors is polarization. With an optimal sensor configuration, effects of polarization are at a level of 10 pm (8.3 με), which is not acceptable. Only one of the interrogators showed an effect less than 1 pm with a high reflection sensor. With low reflection sensors, the polarization effects increase also to the level of 10 pm. This implies that there is a strong need for improvement for all instruments.

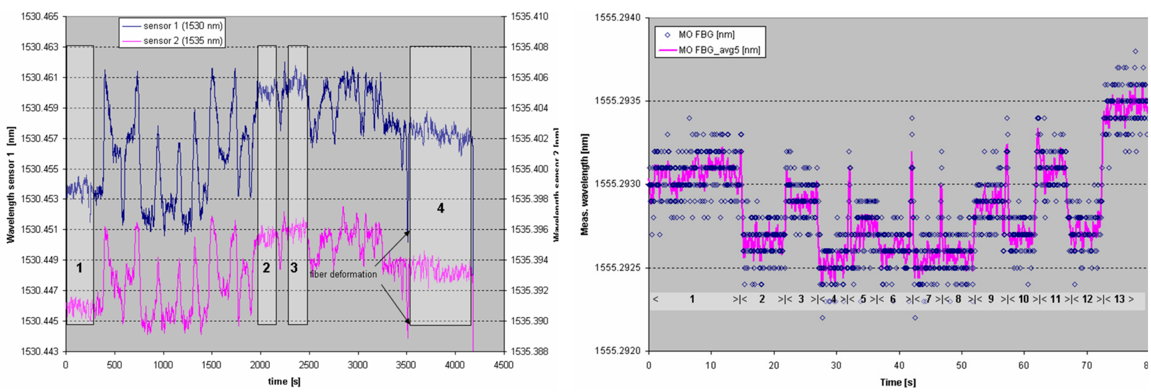


Figure 19: Polarization test for one interrogator with different sensor configuration

In Figure 19, the sensitivity for polarization effects of this technology is demonstrated. The test was done with the same interrogator. In the left graph, low reflection grating were used. The range within which the signal varies is in the order of 6 to 10 pm. In the right figure, a high reflection grating was used. The range is now reduced to 1 pm!

A conclusion could be to use only gratings with a high reflection. However other factors make the low reflection grating attractive, such as lower costs and much higher strength of the fibre.

Temperature effects

The temperature range within which the interrogator should operate is 0 - 60 ^{o}C. The tests were executed between 5 and 48 ^{o}C. One interrogator stopped operating at 38 ^{o}C and did not immediately recover after lowering the temperature.

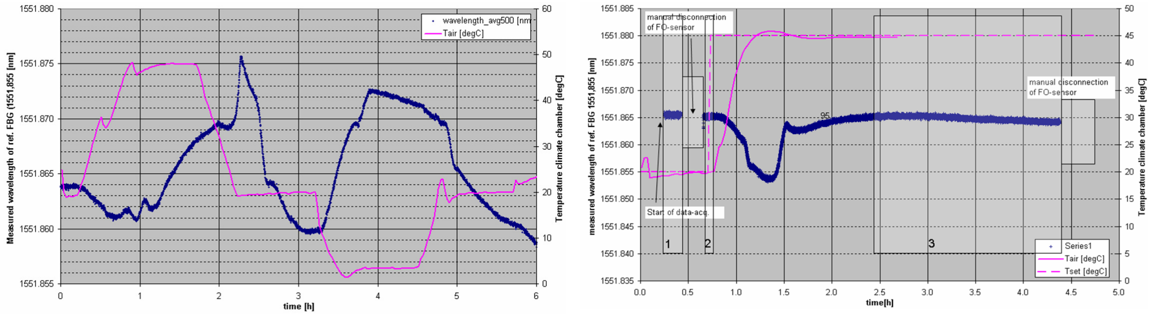


Figure 20: Example of a temperature test in the climate room

A second interrogator showed a large offset during the temperature change and recovered slowly over a period of an hour. This behaviour is illustrated in Figure 20. In the left graph, a temperature profile was applied, which results in large deviations of the wavelength read out. In the right figure, a step response shows that the wavelength read out initially reduces with about 20 pm and recovers in a time span of more than 1 hour.

Acceleration tests

The accelerations tests, as executed, did not show significant effects on the performance of the instruments.

5. Sensors

In order to measure the strain in wind turbine blades, two approaches can be followed:
- Integration of the sensor in the blade material
- Attachment of a sensor at the surface of the blade.

During the development of applications where load measurements are used, it is much more practical to use external sensor rather than integrated sensors. Integration of the sensor in the blade material will be a serious option at the longer term. However it requires quite different skills than usually required for blade manufacturing. Also other problems have to be overcome such as failure of sensors, damage of sensors during installation, etc. This requires much development time which hinders the development of the application.

Figure 21: Example of sensors: Micron Optics, FOS&S, FOS WindPower

External sensors are available in many forms at an attractive price level. They can also be installed in existing turbines, which implies that a measurement system can easily be installed after choosing the right interrogator and sensors. However practical applications show that the sensors and their installation also cause a lot of troubles:
- The time required for installation is long (at least 1 day per blade)
- Installation requires skilled personnel
- Installed sensors often fail, while repair also requires skilled personnel
- Relation between actual and measured strain is not well defined
- The strain is measured over a small distance, while the material is not homogeneous
- Installation of sensors for temperature compensation doubles the installation effort
- Calibration for load monitoring is required, also after repair action
- Temperature sensors should be free of loads in longitudinal direction, which is difficult to realise.

For a successful application of fibre optics in a wind turbine, sensors should be available which do not have these disadvantages. For this reason a desk study has been done [Ref. 1]. Apart from the requirements for the accuracy, additional desired properties were formulated:
- 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 be blade and should be done by regular maintenance staff without special skills for fibre optics (Plug and Play)
- There should be no calibration on site required after replacement of the sensor
- The fixation of the sensor should be rigid and stable over the life time 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 study included some options with respect to sensors installed on the surface of the blade as well as sensors integrated in the blade material. From this study it was concluded that sensors,

which meet the requirements above, are not directly available. For this reason several options for a new sensor assembly were proposed.
Because of the specific requirements for this application, it was decided to develop a sensor assembly in accordance with the specifications as listed above. For the development, most important items are:

- Choice of the Bragg gratings and optical fibers
- The installation aspects of the sensors in the blade
- The sensor assembly

5.1 Choice of Bragg gratings and optical fibers

The interrogator as used for further testing works in accordance with the WDM-principle and has four channels. This implies that the nominal wavelength of each grating within a string should be different and the ranges of the grating should not overlap over the whole load range. The values of the nominal wavelengths should be chosen accurately taking into account the possible pretension of the strain sensors and the load in the blade during installation and operation. For each blade four strain sensors and four temperature sensors are foreseen and they are planned in one string. The maximum range of the wavelength is 70 nm (1515…..1585 nm) which has to be split up over the eight sensors and margins in between. For the temperature sensors, a range of 70 ^{o}C is chosen, for the strain sensors 2500με. These ranges can be accommodated within the range of 70 nm.

5.2 Installation aspects of the sensors in the blade

The sensor assembly with the Bragg sensors should be installed on the inner surface of the blade. This should be realised in such a way that replaceability of the sensors is easily possible, without the need for recalibration. Fasteners like screws are not allowed for attachment to the blade material.

With respect to the installation there are some restrictions:

- The mounting of the sensors should be possible within a short time frame. For the three blades, all sensors should be installed within 1 day. This means about 2 hours per blade, half an hour per sensor assembly!
- The connection should withstand the loading of the sensor assembly. The device is mounted with pretension in order to improve the accuracy.
- The connection should withstand the cyclic loading of the blade. The loading of the blade results in strain in the blade material, which also cause a load on the connection between the device and the blade material.
- The connection should be stable over the life time of the turbine (creep < 0.5 μm). Creep causes an offset in the measurements and when this is too large, regular calibration is necessary. This should be prevented.
- Installation of the complete assembly should only require one access per blade. This implies that after mounting the device, the sensors should be connected immediately.
- The sensors should be mounted by gluing, because screwing in the blade is not allowed
- The adhesive area should be small, so that the impact of the connection on the measurement is minimal.

Several alternatives have been tested under loading conditions (static and dynamic) and finally resulted in a design and installation procedure which meets these requirements.

A procedure has been defined so that the installation of all load sensors in the blades is possible on site within eight hours by two persons. The design of the sensor assembly and the installation procedure does not require special skills with respect to fibre optics and meet all the requirements above.

5.3 The sensor assembly

Although no details can be published at this moment due to the process of getting a patent, the development resulted in a carrier which meets the requirements. Figure 22 shows an early principle of the sensor assembly.

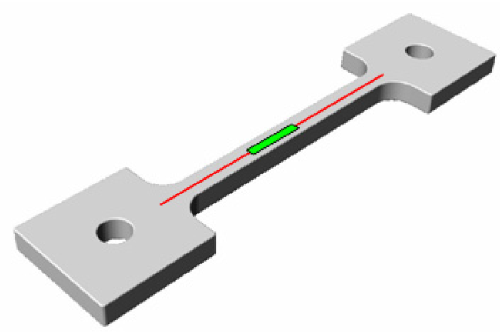


Figure 22: Carrier for fibre optic sensors (principle)

Based on this principle, several design options have been considered, which resulted in an experimental carrier. In this design the following properties have been realised:

- The strain sensor measures the distance changes between supports directly and accurately.
- On the assembly, a temperature sensor can be added in an area without any deformation caused by strain. The temperature sensor only measures temperature effects (thermal temperature expansion of the fibre and the sensor assembly and the change of the breaking index).
- The optical connection is realised by optical connectors, which are insensitive for dirt and which can easily be connected.
- Installation of the sensor assemblies on the supports can be done without special skills with respect to optical techniques.
- The strains in the sensor assembly are sufficiently low to survive during the lifetime of the turbine.
- The choice of the optical fibre, together with the coating, results in a very low probability of failure.

However the first model also learned that the connection of the sensor included some critical properties, which made several design alternatives necessary. Problems which have been encountered were:

- The handling of the fibres and sensors during mounting of the fibres on the carrier was difficult and time consuming.
- The pretension in the fibre with the strain sensor appeared to be a complicating factor during mounting of the fibre string.
- The active measurement length (narrower part of the sensor assembly) resulted in an unfavourable ratio between strain measurement range and used wavelength range
- The protection of intermediate fibres was not always ensured. This made mounting and replacement risky.
- Experiments showed large hysteresis in the strain measurement.

For these reasons other design options have been worked out. This resulted in a modified design with improved properties.

- The carrier can easily be mounted and replaced.
- After replacement of the sensor the difference in measurement value was lower than 10 με.

- The ratio between the measurement range and the wavelength range is more favourable
- The hysteresis in the measurements was lower significantly. However with respect to this property there is still room for further improvement.
- The sensor assembly can be calibrated in the laboratory and needs no further calibration on site

The modified design is suitable to continue further experiments, such as dynamic testing. Calibration of the carrier itself might be the most difficult part. Although this design can not be qualified as a production model, it has potential for further design simplifications and cost optimisation. Also features for improved handling can be realised without reduction of the performance.

5.4 Supports

5.4.1 Type of adhesive

Several adhesives and combinations have been used for the connection of the supports. Static and dynamic tests have been executed. Important criteria for the choice of the adhesive were:

- The curing time
- Handiness during installation
- Durability under static and dynamic loading conditions

The selection of the adhesives should be considered in connection with the installation procedure. A two-stage installation procedure was initially proposed because adhesives with a long curing time (order of 12 hours, depending on the temperature) were advised by suppliers for reasons of durability. However from installation point of view, the procedure should be as simple as possible, so making the connection in one step is always preferred. An adhesive was found with a low curing time in combination with sufficient strength for the long term fixation. (see Table 3).

Table 3: Curing time of applied adhesive

Times to minimum shear strength

Temperature	°C	10	15	23	40
Cure time to reach	hours	-	-	-	-
LSS > 1MPa	minutes	20	12	8	2
Cure time to reach	hours	-	-	-	-
LSS > 10MPa	minutes	30	25	18	5

LSS = Lap shear strength. Note that the adhesive will reduce in volume by ca. 13% during cure.

5.4.2 Materials and surface treatment

For the sensor support, three different materials and preparation methods were used:

- RVS. This material is also used for the carrier. It has a high E-modulus, compared with the blade material, which implies high tensions in the glue connection. Before cleaning and gluing the surface was treated in order to ensure good connection between the adhesive and the metal.
- Aluminium. This material has an E-modulus closer to the blade material than RVS. For aluminium a suitable surface treatment is also essential.
- Reinforced plastic. This is the same material as used for the blade.

All three options have been tested extensively.

5.4.3 Static experiments

Static experiments have been executed using test items connected to a block of reinforced plastic. The figure below shows the test configuration as used.

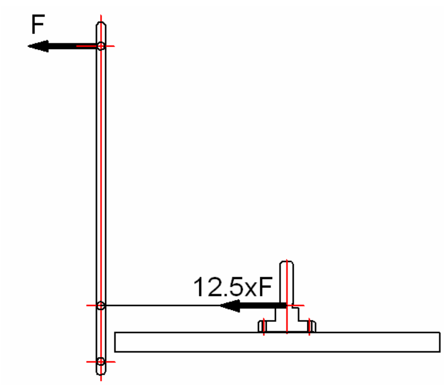


Figure 23: Test configuration static tests

The test item is glued on a block of reinforced epoxy. A static load is applied on the test item via a hinge. The forced applied on the hinge is measured by a tension meter. The upper limit of the tension meter was 500 N. With a ratio 12.5, the maximum force on the test item is 6250 N. The expected loading of the sensor assembly is in the order of 20 N. Worst case is that persons might use a stud as support, which results in high loads.

The static test showed that the ultimate load on the test item is larger than 2000 N for the different adhesives. One of the adhesive showed an ultimate load of 6000 N.

5.4.4 Dynamic experiments

The deformation of the blade material and the high E-modulus of the RVS test items cause shear loads within the glue seam. In order to examine the behaviour of the connection under cyclic loading, three series of tests have been done on a test machine of WMC [Ref. 6]. For each of the tests, a number of test items were installed on an epoxy block. An example of a test block is shown in Figure 24.

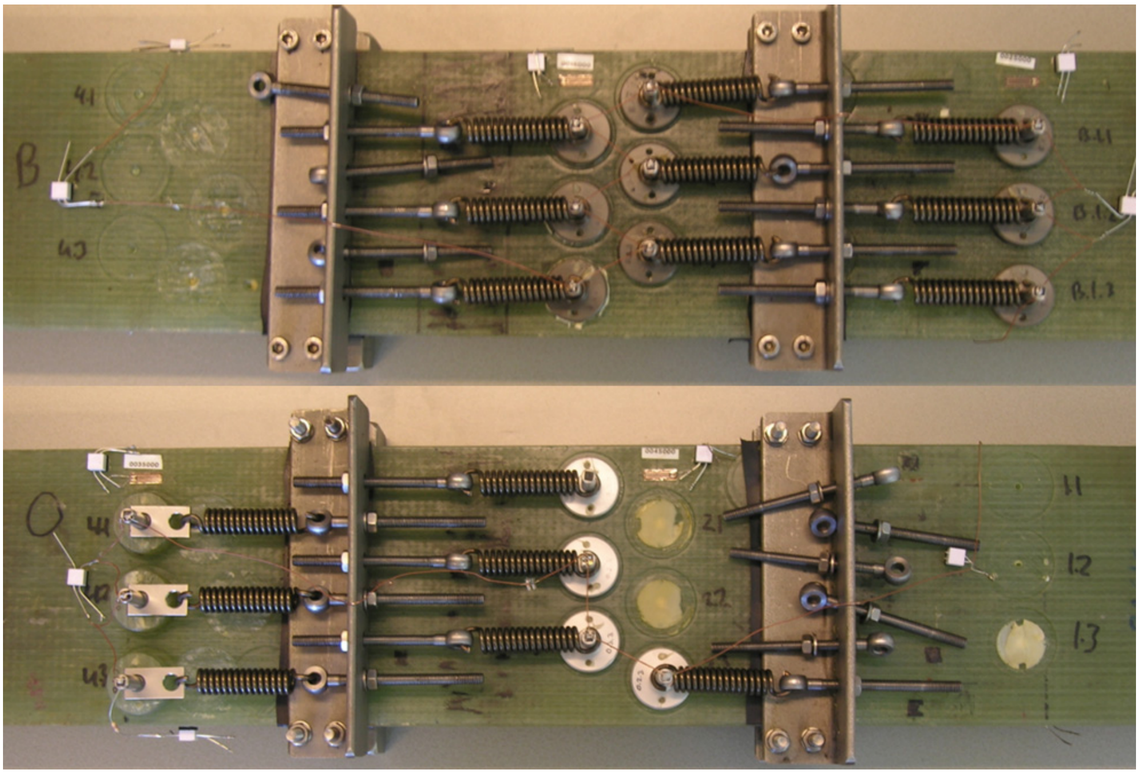


Figure 24: Test block for dynamic testing

For each of the tests, several groups of three identical test items are installed. Within each group the loads and method of connection are also identical. For each group the following parameters have been changed:

- Types of adhesives, for positioning as well as for fixation
- Type of surface treatment of the stud and the block
- Level of static loading (20, 60, 100, 150, 200 N)
- Cyclic strain levels (±1000, 0..2000, 0..-2000, 0..2500 $\mu\varepsilon$)
- Frequency (1 Hz and 1.5 Hz)

The range of the strain applied is larger than the maximum strain expected during turbine operation. The applied static load on the stud is about 10 times the load as expected during operation (expected 20 N). This implies that the test conditions are severe compared with the application.

The test has been performed over more than 10 million load cycles with 8 different configurations. Five configurations survived the test. Also the adhesive with the highest static strength survived the dynamic test.

5.4.5 Final design

An adhesive was found suitable for installation of the studs in the blades. This adhesive survived the dynamic test and showed the highest static strength. Apart from that the curing time appeared to be suitable for installation in one stage while the handling is also simple enough for on site installation activities.
The selected adhesive could be combined with the material as used for the sensor assembly as well, while the required surface treatment is simple and effective.

6. Data processing

Within the scope of this project, the load measurements are used for load monitoring of the blades. The load monitoring 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 not increase the tasks needed for operations. This implies that the system should operate fully automatically.

A major problem of measurement systems (in general) is that the raw measurement data is contaminated with all kinds 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 that will ruin the cumulative loads spectra. Moreover, because of the strongly varying operating conditions it is not sufficient to perform a simple validation, e.g. by looking at daily cumulative loads spectra. So the measurement data should be carefully validated, taking into account the operational conditions, before it is processed and added to cumulative loads spectra.

Because of the vast data amounts of these monitoring systems manual data validation by the operators is practically impossible. The validation should be performed automatically. When data appear to be unreliable, possibilities for recovery should be examined. Only when the processing software has to reject data, manual intervention can be considered. This rejected data can be stored for that purpose. For practical reasons the amount of rejected data should be very limited, which implies that the measurement system should be very reliable.

The processing software should be suitable for various turbines and measurement systems. Various turbines are operated differently with respect to starting, stopping and power production. Status information of the turbine is not standardised, which implies that a specific interface between the turbine control system and the data processing is always necessary. For the measurement system, the interface is defined by an interface specification. This specification describes the output file generated by the measurement system (= input file for the data processing). All measurements should be available in physical units and synchronised. Application of the data processing software in other turbines and for other measurement systems, only requires a specific interface module with the turbine.

For the development a software specification has been prepared, which focuses on:

- The validation of the measurements with respect to file integrity, signal quality
- The operational modes of the turbines and the split up of the measurements in single mode parts
- Safeguarding and level detection
- Load cycle counting and frequency analysis

6.1 Data validation and processing

The overall structure for the blade load monitoring system is depicted in Figure 25, where two main processes can be distinguished.

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.

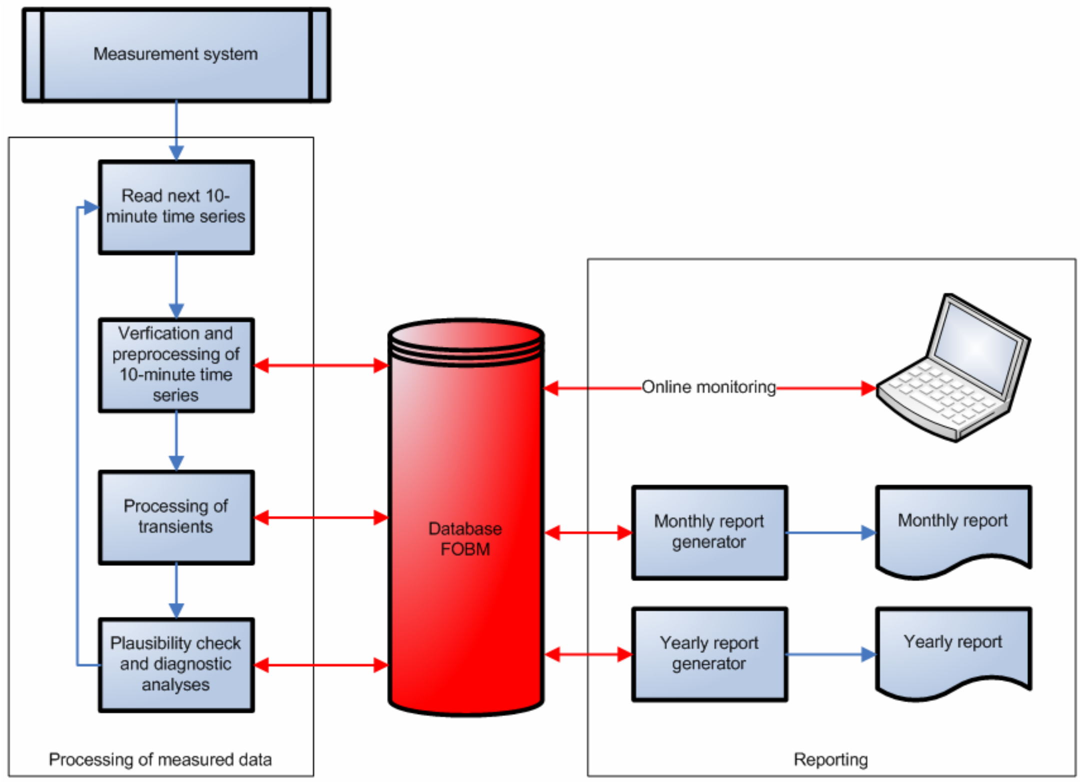


Figure 25: Overall structure data processing and information retrieval

The time series will normally not be stored in the database for longer periods. After processing the data, the time series will be deleted. Only when further automatic processing of the data series is not possible or when the measurement data is not reliable, these time series are stored for a certain period of time. If relevant, these time series should be judged by an operator/analyst who decides what to do with these. So the storage is limited to:

- Data processing information
- Logging information
- Operator warnings
- Statistical values of 10-minute files
- Cumulative data
- Frequency analysis results
- Capture matrix and related time series
- Rejected measurement data

In a first attempt for fully automatic operation, the approach is based on a reliable measurement system, where failure of data is exceptional. In this case the number time series to be stored is limited and the impact on the results is small and easy to compensate. When frequent measurement failures occur (e.g. more than 1% of the 10-minute time series), compensation will become more difficult and the results are less reliable. If this situation occurs, improvement/repair of the measurement system is more logical than focussing on the processing software.

The data processing includes the following parts:

1. Read next 10-minute time series
   A new measurement file is imported every 10 minutes
2. Verification and pre-processing of 10-minute time series
   The structure of the file should be in line with the specified format and the individual signals should be reliable.

3. Processing of transients
   Transients, such as (emergency-)stops are treated separately.
4. Plausibility check and diagnostic analysis
   Plausibility checks are carried out in order to verify whether the loads are within the expected ranges.
5. Direct warning/reports to the users is also foreseen in case of exceeding limit values. This will be done by sending e-mails.

6.2 Data retrieval

The stored information can be used for data retrieval. In the data base the following information is stored:

- On line monitoring / warnings
- Statistical values of relevant signals per 10 minute file
- Capture matrix with time series involved
- Equivalent loads over each time series
- Markov load counting matrices for each time series
- Frequency plots of certain time series
- Capture matrix with reference files
- Log file information

This information is used for reporting on a regular basis or on request. The report should give condensed information which is helpful for the users to perform his task e.g. maintenance planning.
This information could be:

- Results of frequency analysis. The eigen frequency might be an indicator for the health of blade materials. Shifts in the eigen frequency indicate a change of the structural properties of the blades. Threshold values should be determined on the based of selected time series, which can be considered as representative for certain conditions.
- Accumulated loads. The load changes as monitored can be accumulated over the life time of the turbine. This is an indication for the encountered loads which can be compared with the design values.
- The equivalent loads can be calculated over the lifetime, which is a simple indication for the encountered loads. This can also be compared with the design values.

The reporting should be defined in detail during the follow up of the project.

7. Conclusions

The load monitoring of wind turbine blades, using fibre optic measurement technology has been split up in the reading equipment, the sensors and the data processing. The fibre optic measurement technology is suitable for application for load measurements over the life time of the turbine, however some disadvantages have to be solved before the application will break through. The price of the measurement system is still high, while the handling requires special tools and skills which hinder the application. There are only one or two suppliers, which have an interrogator, specially designed for wind turbine application. The design is robust and installation in the hub does not require additional protection. Interrogators from other suppliers are often not designed for installation in severe environments.

7.1 Test of interrogators

The tests have been performed with three interrogators. The chosen models should be considered as leading for wind turbine applications.
All three interrogators have undergone the same test programme. The test results showed some very interesting results:

- One interrogator failed several times during the test. The measurement results of this interrogator were poor. After the test the model was withdrawn from the delivery program of the supplier.
- The other two interrogators in combination with the recommended Bragg grating appeared to be very sensitive for polarization. Polarization can easily be introduced by moving the fibres. The measurement fault introduced by polarization only could be in the order 0f 10 pm (8 $\mu\varepsilon$).
- One of the interrogators also showed to be sensitive for the environmental temperature. Deviations were in the order of 20 pm.
- The polarisation effect is strongly dependent of the attenuation. Attenuation is caused by the connecting fibres, in particular at sharp bendings, splices and connectors. Also the core diameter of the fibre is of major importance. It is not also evident that the core diameter is constant, because some types of Bragg gratings are written in fibres with a small core diameter while for the connecting fibres larger diameters are common. So the choice of the sensor properties and the lay out of the sensor configuration is of major importance.
- One of the interrogators showed to be less sensitive for polarisation by using other sensors than recommended by the supplier.

The test resulted in the choice of one specific interrogator, which showed clearly better performance than the other model. It was decided to purchase this interrogator for executing of further experiments.

7.2 Sensor development

The sensor development should result in an assembly which: (1) measures the strain and temperature accurately, (2) can easily be installed and replaced, (3) requires minimal calibration and (4) should survive the life time of the blade.

The current prototype has the following properties:

- The expected life time of the sensor is larger than 20 years. Results of fatigue tests of fibres and sensors of the same type show longer life times even at higher strain levels. The adhesive connection with the blade survived 7 million cycles in a test environment, but the strongly depends on the workmanship. Application of alternatives depends on permissions of the blade manufacturer.

- The sensor can be easily installed in the rotor blades. The on site installation of a sensor assembly takes 15 to 30 minutes, which implies that a turbine can be equipped with a load measurement system in the rotor within one day. This minimizes the down time of the turbine.
- The sensor is designed for easy maintenance. A failure can easily be detected and the sensor can be replaced within five minutes. Calibration of the sensor can be done during production. On site calibration after replacement is not necessary, which implies "Plug-and Play".
- Temperature compensation is included with respect to sensor properties. Optical strain sensors are sensitive for temperature changes and compensation is necessary for measuring the absolute values.
- Installation and maintenance can be done by technicians that are trained for regular wind turbine maintenance. Special skills with respect to fiber optics are not required.
- The sensor is also compliant with respect to resolution and accuracy and does not show drift.

The sensor has also been made and assembled. The sensor appeared to be stable over the time which means that the connection of the fibre does withstand the tension in the fibre and that the coating of the fibre also doesn't show creep. Initial tests with replacement of the sensor resulted in minimal differences [less than 10 pm].

Static tests over the whole measurement range showed deviation in the order of 10 pm, which corresponds to and distance difference between the supports of 1 μm. This deviation can be caused by the sensor, but it can also be introduced by the calibration tool and measurement device.

Dynamic test has not been executed up to now. A patent for the sensor design is pending.

7.3 Software development

Load measurement systems produce large amount of data, which is difficult to handle by the operators. The project resulted in a concept for automatic data processing and providing key figures to the operator to make decisions for maintenance. This improves the cost effectiveness of the maintenance. The concept is described in a specification and the software is in development.

The software has the following features:

- The measurement system converts the strain measurements into bending moments. A well defined interface between measurement system and data processing enables the use of the software in combination with other measurement systems.
- The software automatically generates load spectra and equivalent loads in accordance with the relevant IEC-61400 standards and taking into account the operational conditions.
- The measurements are validated automatically.
- The measurements can be processed directly, which implies that storage of large amounts of measurement data is not necessary.
- The software allows comparison of loads between the individual turbines in order to prioritize maintenance and inspection schemes.
- Although an interface between the wind turbine and the measurement system is required with respect to the PLC-signals, the data processing is suitable for all types of turbines.
- The data processing also includes automatic warning and detailed event analysis.

The software development did not yet result in version ready for application. The requirements are available for a wide extend. The development is hindered by the complexity of large variations in loading in combination with unreliability of measurement data. Although the measurement system should generate reliable data, faults can have strong effects on analysis results. This implies that a lot of effort should be laid in this part of the data processing. The implementation of the software is now in execution.

8. References

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