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Report

D 2.3.01/02/04 Sensors for condition monitoring of different components of (offshore-)wind power plants

Possibilities for further evaluation in Nowitech and beyond

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ABSTRACT

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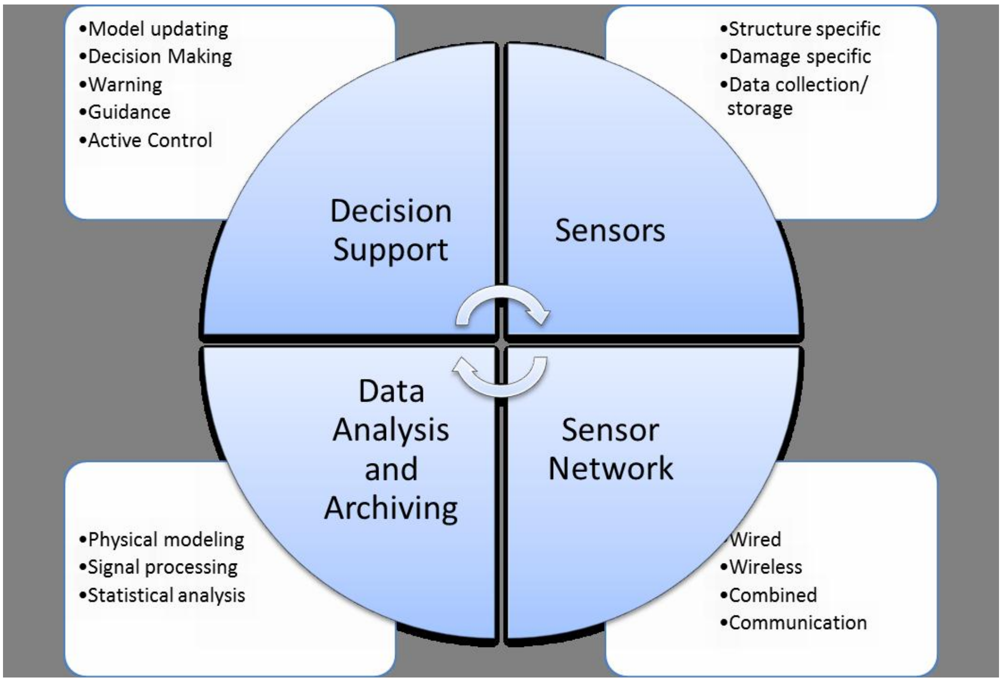

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Microsystems and Nanotechnology

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1 Introduction

Offshore wind power plants are costly to maintain. Maintenance requires a special offshore ship or a helicopter to reach the offshore plants with a specialised crew. A current update on the maintenance effort for the Alpha Ventus plants in the German North sea is 450 maintenance hours/year for every turbine. It is stated that this effort needs to be below 150 hours/year in order to be economically viable [1].

Condition monitoring of different parts of a wind power plant/wind farm might help to reduce maintenance costs together with advanced models for failure prediction and maintenance optimization algorithms [2]. Commercially available equipment based on traditional sensors that is currently used is indicated in e.g. Figure 1-1 below, from [3]. Condition monitoring of the various rotating parts of the wind turbine may be done using both specific sensors and indirect measures such as output power and signal noise in related data.

Apart from such "traditional" condition monitoring, another important issue is to monitor the structural health of the "building" construction, the related support structures and the critical components of the turbines, including the rotor blades. The rotor blades, increasingly termed "wings" or "airfoils", have quite complex aerodynamics and variable loads resulting in increasing use of modelling and advanced designs and better materials. The turbine "wings", typically over 40 m in length, are exposed to tremendous forces and even small damages in the wing structure might lead to total destruction of the turbine construction in a heavy storm. Current advances in control systems, materials and designs aim at avoiding excessive loads throughout the structures.

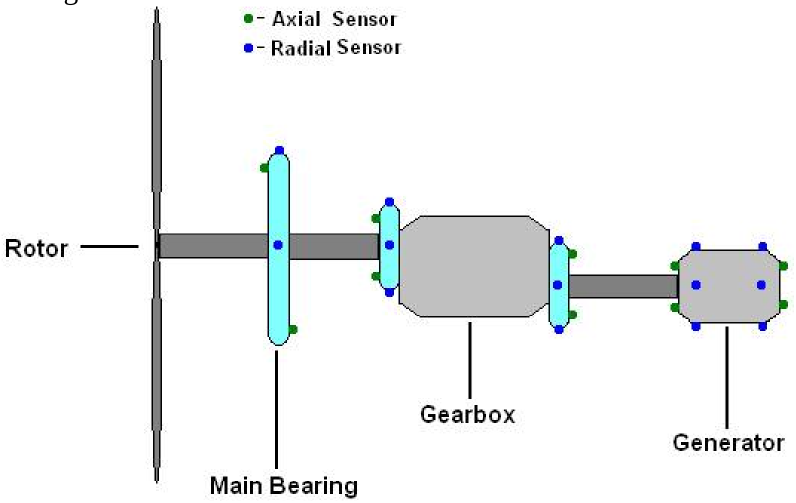


Figure 1-1: Examples of where sensors can be placed on different rotating parts of the wind turbine (from [3])

The present report is a result of Task 2.3 (WP2 in Nowitech) in which some effort is made to combine present current knowledge on possible sensors for materials testing and a condition monitoring system.

2 Possible Sensor Types

There are many available sensing principles for mechanical sensing, from simple strain gauges to innovative (un-proven) technologies based on e.g. nano-technology.

We need to state a few definitions:
"Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure. It is a major component of predictive maintenance. The use of conditional monitoring allows maintenance to be scheduled, or other actions to be taken to avoid

the consequences of failure, before the failure occurs. Nevertheless, a deviation from a reference value (e.g. temperature or vibration behavior) must occur to identify impeding damages." [4]
"The process of implementing a damage detection and characterization strategy for engineering structures is referred to as **Structural Health Monitoring** (SHM). Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments." [5]

A structural health monitoring system and its parts is described in [6]. Structural Health Monitoring (SHM) incorporates four, more established technologies for Operations and Maintenance (O&M) of electromechanical systems such offshore wind turbines (OWT):

- Condition Monitoring (definition above)
- Non-destructive evaluation/testing
- Statistical process control
- Damage prognosis

The functions of a SHM system including the above are all based on reliable, robust measurements and sensors that may be operated autonomously, i.e. without the need for trained personnel for routine measurement.

Apart from challenging specifications on robustness and reliability for the sensors and their system(s), one of the main obstacles for deploying a monitoring system are the variations in the environmental and operational conditions, and indeed, variations in the structures/components to be monitored. The monitoring system will be sensitive to changes in the environmental and operational conditions of the structures, and to (unplanned) changes to the structures/components. Therefore, such ambient variations of the system need to be explicitly considered in the design, implementation and use (the process) of a structural health monitoring system. Another major challenge is to integrate the monitoring system in a cost-efficient manner. The question is also how to integrate the monitoring system so that future (unforeseen) system upgrades may be handled more effectively.

The state of the art in condition monitoring systems for wind turbines is the subject of following section, largely based on recent studies including the UpWind project (www.upwind.eu). The UpWind project also looked at various design possibilities and control strategies for large scale wind turbines, including (extreme) load control and load reduction by advanced blade control. Control strategies might include high speed pitch control, the use of flaps or more advanced concepts for morphing (bend-twist coupling) of the rotor blades. Decentralised control systems/strategies involving local sensors and actuators seems interesting, and have been briefly investigated in Nowitech. The possibility of using advanced materials such as wires/sheets of shape memory alloys and thermoplastic blades gives new options for designing smart rotor blades. Obviously, the choice of sensors, actuators and control systems is deeply linked with design, materials and fabrication methods.

In the following we concentrate on a few possible sensor types that are more or less available. Our presentation will be limited to what we believe are the most promising candidates for (offshore) WT's based on available knowledge in Nowitech, the literature and some information from a few of the stake-holders and suppliers of commercial structural health monitoring systems today.

3 State-of-the-art in Condition Monitoring for Wind Turbines

As stated in [6], we should focus on **systems integration**, including operations and maintenance, and the likely deployment of SHM systems/techniques proven in other applications to reduce costs. However, the application of SHM systems **Off-shore**, in particular to OWTs introduces several new aspects including higher loading and corrosion (storms, waves), possibly new designs and materials while there is a need for more reliable systems, due to the high cost of maintenance compared to land based WTs or related civil engineering.

A structural health monitoring system and its parts is described in some detail and can be found in [6], re-stated here for reference:
"A SHM system is composed of components in a well functioning system for monitoring several specified hazards according to previously fixed levels. These components grouped according to their functionality and implementations include:

1. The structure to be devised, in this case a tower and/ or a substructure.
2. Sensors, including not only the electronic devices for measuring, but also electrical energy sources. These should be chosen after a deep analysis of hazards and their physical mechanisms of sources, progress and impact on the functional state of the structure.
3. Data acquisition systems, where the measured signals are conditioned
4. Data transfer architecture and mechanisms. Generally several kinds of communication links are used in a WTP. First, we define an internal communication network which includes wired and wireless components as well as acoustic modems for OWTPs. Second, the external communication with a remote data centre is built through a long range wireless protocol (GSM, GPRS, …)
5. Data storage and management (SW+HW).
6. Data interpretation and diagnosis (SW+HW). This part is the key of the whole intelligent functionality, including a wide range of different SW tools
   1) Modeling the system, classified into one of the major two groups:
      a) System Identification through non physical models.
      b) Structural and physical models to be compared / updated. For this purpose specific simulation tools will be deployed. Currently a great effort aims to integrate these initially independent simulation modules into holistic tools (Wind + Wave + structure e.g.)
   2) Structural condition assessment module for finding and possibly localizing damage.
   3) Prediction of remaining service life modules which work in relation with a failure model/data base, and estimate in which point of the damage process we are.

The optimal SHM solution tends to integrate the listed components in the early phase, so that an optimized design of the structure can be performed."

3.1 Current status on CM/SHM for WTs

Condition monitoring based (preventive) maintenance strategies for wind power plants is a current topic of application oriented research both with respect to more theoretical, statistics based models [7], [8] as well as a more practical approach combining statistics with empirical data from expert questionnaires [9]. However, these strategies are based on a CM system available in the wind power plant. In today's wind power plants data is available from different sources, but no comprehensive CM/SHM monitoring system is implemented, that allows the online diagnosis and prediction for all critical parts of the plant. This is basically due to the fact that sensors in the power plant are mostly used for feedback and not for surveillance, and sensors are not available on all critical parts.

3.2 Traditional wired sensors at critical point locations

Commercially available equipment based on traditional sensors that is currently used is indicated in e.g. Figure 1-1, from [3]. Condition monitoring of the various rotating parts of the wind turbine may be done using both specific sensors (often those which are already available for feedback control) and indirect measures such as output power and signal noise in related data. Wired sensors represent the benchmark of condition monitoring, optical sensors not included.

3.3 Microsensors/MEMS and optical fibers/FBG's

We include separate sections later on what we believe are the two most promising sensor approaches for large scale use of CM/SHM of WT's offshore, i.e. optical fibers embedded in or on the components (section 4) and/or arrays of networked, small sensors integrated in/on the surfaces of the same components, section 5. Micromachining offers the potential for fabricating a range of sensors and systems, (micro electro-mechanical systems, MEMS) for structural applications including load, vibration and acoustics characterization and monitoring. Optical fibers including FBG's are also very promising sensors for CM and SHM. Microsensors are extremely small; they can be embedded into structural materials, can be mass-produced and are therefore potentially low cost. Additionally a range of sensor types can be integrated onto a single chip with built-in electronics and ASIC (Application Specific Integrated Circuit), providing a very low power Microsystem [10], suitable for distributed wireless sensor networks, see section 5.

In recent years, progress has been made to reduce the complexity of systems using MEMS sensors and devices, while increasing the connectivity to the macroscopic world. One example is **microfluidics**, where MEMS devices such as pressure and flow sensors and actuators may be integrated with flow channels. The Australian company SMSystems (www.smsystems.com.au) provides crack-detection sensors and a portable unit used for pressurizing/vacuum monitoring using an emerging NDT technology known as Comparative Vacuum Monitoring (CVM). Microfluidic channels are structured using MEMS-type technology in polymer stamps/foils bonded to structural parts. MEMS devices and (polymer based) microfluidics provide more reliable and lower cost microfluidic handling and read-out systems.

3.4 Surface Mounted Sensors/Smart Layer/Large area application of sensors

The SMART Layer® concept, currently under development by the Stanford start-up company Acellent Inc. (www.acellent.com) is largely based on small, thin piezoceramic transducer discs included in thin, flexible, dielectric layers including printed electrical connections, as used for flexible printed circuits. The concept seems particularly well suited for ultrasound based SHM of composites. Strain gauges and FBG fibers may also be included in such "smart" layers [11], and e.g. MEMS-based accelerometers could be packaged/integrated in a similar way. A typical commercially available **MEMS sensor package** will likely build too much height (1-2 mm) to be directly applicable in thin foils. In order to reduce the build height of the sensors in the foil/smart layer, “unpackaged” MEMS-sensors may be used if the polyimide/kapton-foil or similar is used as part of the actual (application specific) MEMS-package. Various smart sensors may also include polymer based sensors printed or otherwise directly integrated in or on one or more fabrication layers or steps in the backing foil. The latter technique is explored for production of RFID-type tags as a part of emerging printed (often polymer/organic materials based) electronics.

3.5 Surface Embedded Sensors

Sensors and related signal analysis for condition monitoring of rotating components/ machinery is fairly well established compared to SHM. The idea to embed sensors in the working surfaces of e.g. cutting tools and bearings seems promising, in particular for surfaces with a functional thin film coating for increased wear resistance/lower friction. The challenge is to deposit and pattern high quality thin films on non-conventional substrates including 3D-surfaces with rough topology. Further development in this field is being carried out in several groups, e.g. in the EU project IC2 (www.ic2-eu.org) demonstrating Pt-100 type temperature sensors deposited in rapid-prototyping tools.

3.6 Monitoring of wind turbine rotor blades

Sensor based monitoring of wind turbine blades can be divided in two main categories: 1) Operational control monitoring, linked to simple or advanced control strategies and 2) condition monitoring (CM) and structural health monitoring (SHM). The purpose of operational control monitoring is to provide information of blade loads to optimize the operational state, typically by pitch control, to maximize power output or to reduce loads in case of strong winds. SHM/CM on the other hand aims at monitoring the reduction in structural health or strength due to the repeatable fatigue loads expired by the blade, impact events or lightning strikes. Operational control monitoring is standard on modern wind turbines and mostly based on blade root moment measurements and in some cases on input from strain gauges or accelerometers on the blades. SHM is performed on blades of operating wind turbines today but with limited details of information and the field is regarded as immature but emerging, with several methods being tested and developed. Vibration monitoring using standard time and frequency domain techniques for analysis, based on input from accelerometers or strain sensors (including FBG's), is currently favored in commercially available systems.

The complexity of SHM of WT blades is a consequence of them being large heterogeneous constructions subjected to complex loads leading to several different types of damage and failure modes.

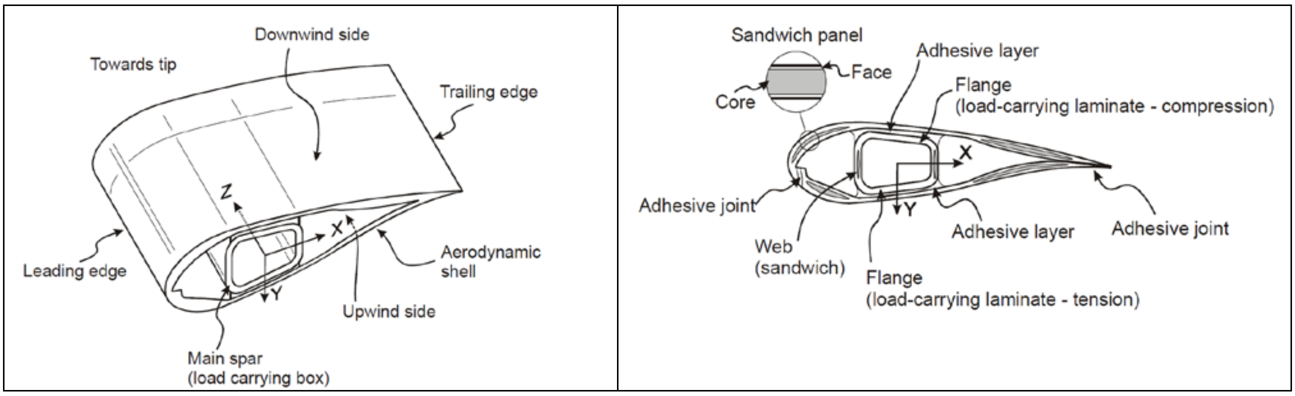


Figure 3-1: Sketch of a typical blade construction

Figure 3-1 illustrates the cross section of a typical wind turbine blade consisting of a combination of monolithic and sandwich composites joined by adhesives. The outside of the blade is protected by a gel coat. Typical failure modes include:

- Adhesive layer debonding
- Sandwich panel face/core debonding
- Delamination
- Matrix cracking
- Fiber or laminate failure
- Fiber pull-out
- Gel coat cracking
- Gel coat debonding

3.7 Methods for SHM of WT blades

The approaches for SHM of WT blades can be divided in three categories [12, 13]:

- Load monitoring
- Vibration monitoring
- Acoustic monitoring
- Excitation methods

In the following the principle of each method is discussed.

3.7.1 Load monitoring

The principle of load monitoring is to track the load history on the blade based on strain measurements by sensors at selected positions on the blade structure. The appearance of larger cracks or structural damage would be detectable in the vicinity of sensors. However, the potential of load monitoring is primarily to predict the cumulative fatigue damage propagation occurring in the structure. The fatigue damage propagation is predicted by processing recorded load data with a prior knowledge of fatigue behavior of materials, structural details (e.g. adhesive joints) and the entire blade structure based on extensive fatigue tests and simulation data.

3.7.2 Vibrational monitoring

WT blades in operation vibrate at characteristic frequencies and mode shapes [12-14]. The basis for this approach is that damages on the blade structure or disturbances as ice accumulation changes the structure's mechanical properties and thereby the vibration characteristics. Comparing the current vibrational state with that of the "virgin healthy" structure will disclose existence of damages or disturbances. Based on experience, test and simulations the severity of damages can be judged and inspection and repair carried out if necessary. Vibrations measurements of a rotor blade are commonly performed by instrumentation with accelerometers or FBG optical sensors. Vibrational monitoring has been shown to be an efficient tool to detect (major) damage and severe icing.
Vibration monitoring is based on mechanical response of the entire blade and therefore has limited capability of predicting type and position of damages. More advanced vibrational analyses involving modal shapes and frequency domain response functions in combination with accurate (inverse) structural modeling could perhaps account for this. However, the use of more sensors (MEMS, see section 5) in a network e.g. in a distributed WSN would enable monitoring of more complex modes, loads and possible damage, and is probably necessary in order to validate more complex models.

3.7.3 Acoustic emission monitoring

The principle of the passive method Acoustic emission (AE) is to measure waves generated in a structure due to damage events. In principle analysis of the wave pattern (Energy, frequency) can reveal damage type and size and if a number of sensors are used also position of events. The technique has been applied to various materials and applications and AE equipment is commercially available from several suppliers. AE to detect damages in WT blades was thoroughly investigated in the European research project AEGIS (1998-2002). In AEGIS software was developed to identify and grade different types of damage events, during static failure test of blades. Despite that AE has been regarded as promising for SHM of blades the method has not yet found use in operative turbines. This is likely due to the fact that a high number of sensors are required to cover a blade leading to complex data processing and high price [15]. In addition AE only detect damage growth and not the present size of failures, and the events occurring during operational fatigue will likely be less intense than those occurring during static tests or accelerated fatigue tests. However, the use of continuous sensors has shown potential to increase the sensitivity [13]. The largest potential of AE for WT blades is probably in combination with methods probing the present damage state.

3.7.4 Acoustic excitation methods

A widespread approach in NDT and SHM is to actively excite (consuming power) the structure and monitor how it responds or how induced waves propagates and transforms due to interferences. This concept is not widely explored for SHM of WT blades but a few studies applying acousto-ultrasonics are known [12], in addition to the SMART Layer concept (as described section 3.4 above) which may be used for both passive and active monitoring. The principle of these methods is to generate a wave signal propagating in the structure and detecting the signal at another position or the reflection of the signal returning to the emitting position. Changes and discontinuities in the structure as for example damages will change the detected waves compared to those detected in the virgin structure [16]. Variations in this type of methods includes the frequencies and waveforms applied, and the methods are most suited to detect larger defects as delamination, sandwich core-skin debonding and adhesive layer fracture. For the excitation and detection typically a configuration of piezoelectric transducers are used.

3.7.5 Combinations

A high performing SHM will probably rely on a combination of information from different types of sensors [11]. With respect to the large amount of sensors required to monitor a whole blade, the possibility to use the same sensors for different types of measurements is attractive [16]. Sandia laboratories, in collaboration with other research teams, performed fatigue tests of a prototype blade instrumented with a variety of sensor systems [17]. The study did not conclude on an optimal SHM system mainly due to failure occurring at an unexpected position not in reach of all of the sensor systems. This highlights the problem of covering a whole blade. Also, unwanted interference between the systems was observed, an issue that should be accounted for. Sensor mounting and installation issues must be addressed in the design phase, and it may be better to install sensors at difficult to reach locations even before the SHM/CM system is mature, as post-mounting sensors is very difficult and expensive. A high definition microphone and/or cameras may also be installed for simple "remote presence" at key locations in WTs, possibly including blades, and such sensors may also gather useful information on the state of the WT, and blades.

4 Embedded FBG in fiber reinforced polymer matrix

A recent study [18] reported the use of fiber-optic Bragg gratings (FBG) for load monitoring of a 4.5 MW WT in Germany. Ever since the advent and later break-through of fiber-optics in telecommunications in the 1970s and 1980s, the potential use of the technology in various sensing applications has been addressed by the research community. Fiber-optic sensors have since found numerous industrial, military, and civil applications in recent years. Since an optical fiber is very thin and flexible and immune to electromagnetic interference fiber-optic sensors are in particular attractive for applications in harsh environments. In addition low weight, small dimensions, explosion safety and possibility to transfer signals over long distances make them also attractive.

Fiber-Optic Bragg Gratings (FBG) has become a popular class of fiber-optic sensors. They are basically strain and temperature sensitive devices [19] and can be inscribed directly in an optical fiber at any position. Several of them can be configured in series or in parallel on different fibers and interrogated from the same light source enabling flexible sensor configurations. The length of an FBG is typically a few millimeters, and a series of Bragg gratings will function as a set of discrete point sensors at chosen positions. The same type of fiber as used in telecommunications is used, and the fiber acts as both discrete sensing elements and as transport of signals. Since FBG's are conveniently used in reflection, the light source and detection device can be instrumented in one unit so that all instrumentation is located in the same place. Low transmission losses of optical fibers enable remote sensing, i.e. the sensors may be placed up to several kilometers away from the instrumentation. These sensors have been successfully used in monitoring loads on various structures like bridges, ships and composite material devices among others.

4.1 FBG Background

A Bragg grating is conveniently formed in a standard telecommunications grade single-mode fiber. A virgin single-mode fiber consists of an ultra-clean thin rod of fused quarts with a core region in the centre formed by doping with other materials to raise the refractive index. Standard dimensions are 125 µm diameter for the entire fiber, the centered core region has a diameter around 9 µm, and a protective coating forms an outer layer. Excimer laser illumination (in the ultraviolet spectral range) inscribes a refractive index modulation in the core of the fiber with a periodic fringe pattern of the refractive index through a photomask which defines the periodicity. The principle is shown in Figure 4-1. When a grating is inscribed in a fiber, the fiber protective coating has to be stripped off around the grating position and recoated again after grating inscription. With this process one has the ability to precisely control the grating reflectivity, bandwidth and general spectral characteristics. An alternative and much faster way of inscribing Bragg gratings is with the so-called off the tower method. Here the gratings are inscribed directly during fiber drawing and the process of removing and restoring the coating is avoided. However, due to the fast drawing speed only single-shot laser illumination is possible for grating inscription. Such gratings have low reflectivity (typically up to 10 % compared to up to 100 % for gratings post-processed in a fiber), but on the other hand the mechanical strength is in general higher since the coating manipulation is eliminated. Once the grating is inscribed in the fiber it is annealed at high temperature and experience has shown that it is very stable over time.

In a measurement setup a broadband source (emitting a continuum of wavelengths), or, alternatively a swept laser source is coupled into an optical fiber. When the light hits the FBG, the wavelength matching the period of the grating is reflected and can be routed to a spectral detection unit via an optical coupler. A typical setup is shown in Figure 4-2. FBGs can be manufactured with reflectivity close to 100 % and the reflection strength and the spectral width of the reflected signal can be tailored by adjusting the grating length, the refractive index modulation strength and the profile of the modulation along the grating length.

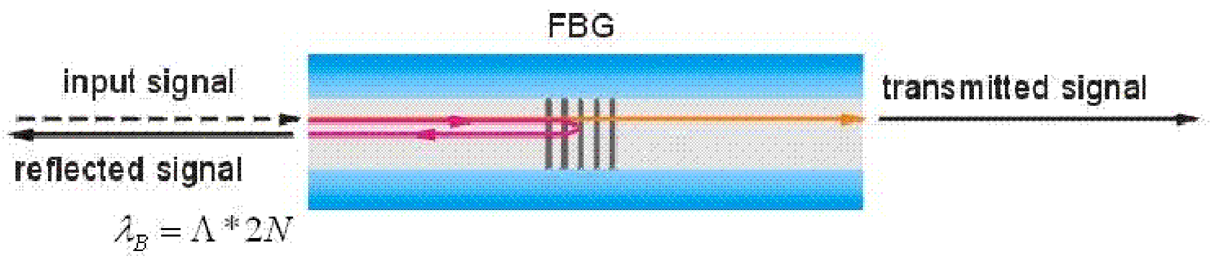


Figure 4-1: Periodic refractive index along core direction resulting in reflection at the Bragg wavelength.

The reflected wavelength is given by:

$$\lambda_B = 2n\Lambda$$

with n the effective refractive index of the fiber core and Λ the grating period. When the grating is strained the grating period will extend and the reflected wavelength peak will respond to this change in the grating period as illustrated in Figure 4-3. A similar behaviour occurs in compression where the reflection peak moves to lower wavelengths.

Several Bragg gratings can be inscribed along an optical fiber at any desired positions. In order to separate the responses each grating is inscribed with different period so that the reflected spectrum will become a series of discrete peaks. The separation between each grating must be tailored to the application and the expected maximum strain or compression so that the reflected peaks do not “collide” which will make the analysis meaningless.

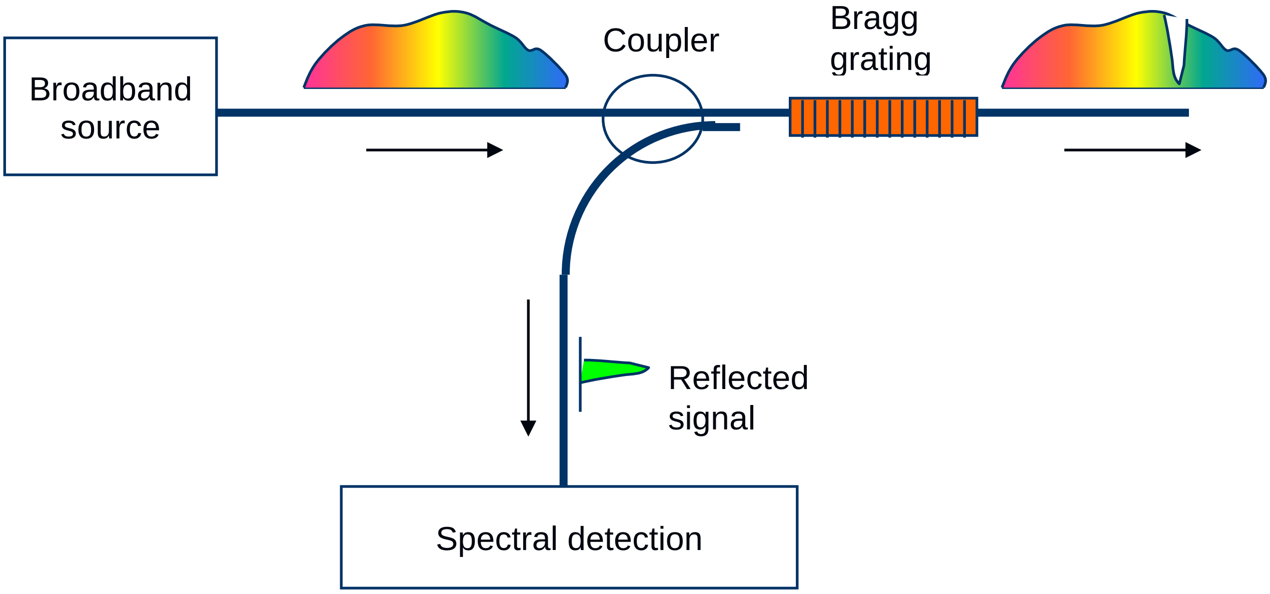


Figure 4-2: Measurement principle for Bragg gratings.

FBGs for strain sensing are conveniently used in the 1550 nm telecommunications window where components like couplers, detectors and light sources are readily available. The spectral width of the light source and the maximum expected strain for the application will determine how many FBGs that can be accommodated along a single fiber. However, one can configure FBG sensors along many parallel fibers so that a large amount of sensors can be interrogated simultaneously.

A virgin fiber with an inscribed FBG is sensitive to both strain (ε) and temperature and the peak wavelength (λ_B) (cf. Figure 4) depends on strain (ε) and change in temperature (ΔT) through the following relation:

$$\lambda_B = K_1\varepsilon + K_2\Delta T$$

K_1 and K_2 are constants that can easily be obtained from calibration measurements and for standard fibers they are typically: K_1=1.2 pm/με and K_2=10 pm/ºC (1 pm=10^{-12} m). A lot of experimental evidence shows that this linear dependence is valid for fairly large strain and temperature variations covering situations of practical interest. Thus, FBGs have similar attributes as ordinary strain gauges; a linear dependence on strain, but temperature compensation is usually needed. Strain measurements therefore become relatively simple by tracking the position of the reflected wavelength peak. When the fiber with the FBG is attached to or integrated in a structure the constants K_1 and K_2 will change due to the combined effects of the fiber glass and the structure. However, the linearity is still retained as evidenced by a large amount of experiments on various materials. For certain geometries and situations where the fiber is embedded in a composite material the constants can be calculated [20]. In particular the temperature constant (K_2) will be strongly influenced by the material to which the FBG is attached, while the strain constant (K_1) is close to that of the virgin fiber.

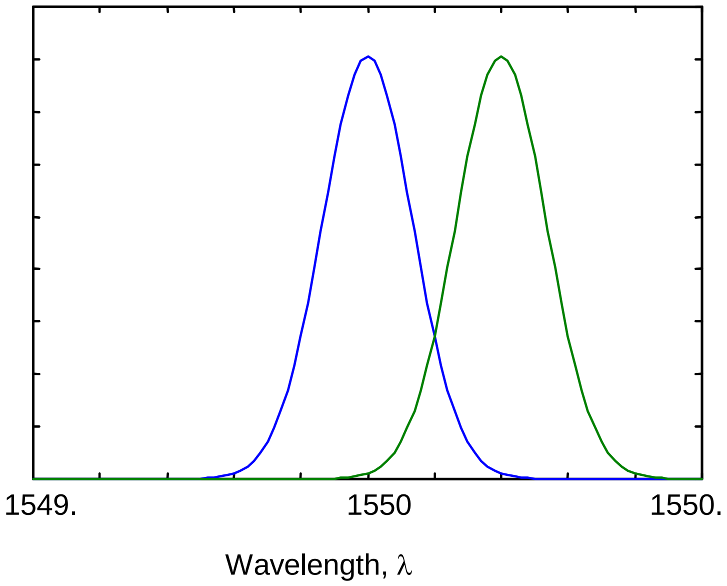


Figure 4-3: Illustration of FBG response for strained (green) and unstrained (blue) grating.

In general temperature compensation is necessary in strain measurements, and although some sophisticated methods have been suggested, it turns out that the simple solution by adding one or more reference FBG's that are not attached to the structure and positioned in the vicinity of the positions where strain is to be determined is the favoured way of overcoming the temperature dependence. These reference gratings only respond to temperature and by knowing the temperature constant the temperature contribution can be corrected in the strain measurement sensors.

Bragg gratings are now commercially available from many vendors world wide either as short fibers with inscribed gratings or in packages tailored to specific applications, in particular for strain or temperature sensing. Most vendors can offer products tailored to specific applications. Currently FBGs must be regarded as reliable and stable devices which have reached a high degree of maturity.

Interrogation instrumentation for FBG sensors is also commercially available from several vendors. These range from sophisticated and expensive instruments to small and simple portable devices. The main features of these instruments are a broadband source (superluminescent light emitting diode, swept laser or erbium amplified spontaneous emission fiber source) and a spectral detection device which determines the reflection wavelength. The instrumentation determines the types of measurements the interrogator can make, in terms of data rate, dynamic range, wavelength accuracy, repeatability, stability, and other key performance parameters. Most instruments have a software platform on which the interrogator core technology is deployed and determines the on-board data processing and storage capabilities of the interrogator.

4.2 Embedding fibers in composites

From the small size and their flexible nature it was early recognized that optical fibers could be attractive for embedding in composite materials for sensing purposes in view of their many advantages including insensitivity to electromagnetic interference, light weight, multiplexing capabilities and resistance to corrosion. Up to now there have been numerous tests and small scale deployments with fiber sensors, and Bragg grating sensor has been the favourable candidate for this purpose. The feedback from recorded loads, deformations and temperatures of (in particular inside) existing structures in real conditions, can lead to highly valuable information for design criteria as well as strain monitoring of an in-service structure which can greatly enhance the insight and confidence in the (long-term) behaviour of composite structures. The compatibility of these sensors with the manufacturing process of fibrous composite materials (pultrusion, co-braided with braided composites, laminates, etc.) is an extra advantage. By integrating an FBG into a structure, it becomes very robust and it can survive the sometimes harsh environment in which composite materials are used.

Once the fiber is integrated into the composite it can be considered stable and well protected. However, there are a couple of challenges that need to be addressed during the integration process.

First, a major issue is the entry point of the optical fiber lead in the composite material, which is prone to breaking. An overview of the literature on approaches to overcome this problem is given in [21]. Two main options exist to protect the fiber egress point in composite laminates: either integrating a fiber connector at the edge or surface of the laminate or integration of a protective fiber feed-through mechanism. Both methods enable the optical fiber to be led smoothly out of the stiff laminate (surface or edge) without excessive bending and curvature. In [22] a study has been performed with the aim of developing practical and robust methods for the access of embedded sensor fibers. Several approaches were tested and evaluated and one example consisting of a protection fixture at the egress point and a connection fixture is shown in Figure 4-4.

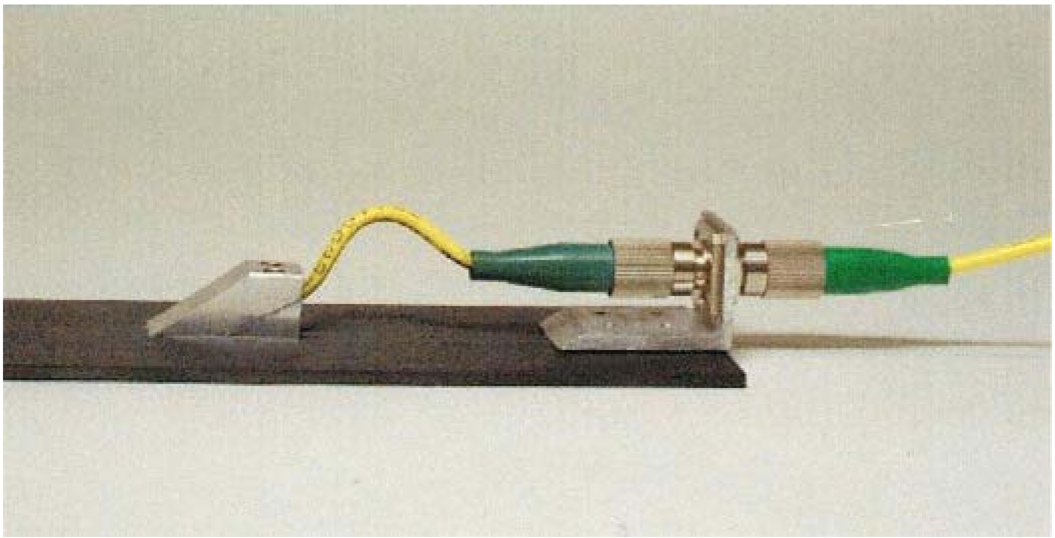


Figure 4-4: Horizontal connection using optical connection part fixture

Second, the distortion of the composite structure in the surroundings of the optical fiber is another issue. The diameter of the FBG is 125 μm (for a classical telecom fiber), but can be made smaller using special but more expensive fibers. In addition a protective coating such as polyimide (typically 15 μm) adds to the thickness. This is still one order of magnitude larger than the most commonly used reinforcement fibers (glass: 5–20 μm, carbon: 5–10 μm). Thus, the embedded optical fiber will inevitably cause a local distortion in the host material (Figure 4-5).

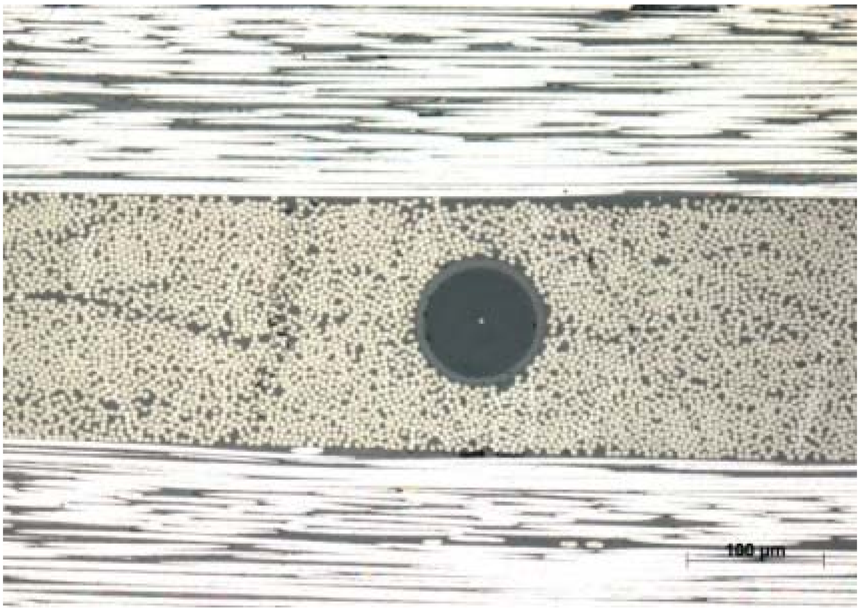


Figure 4-5: Fiber embedded in a cross-ply laminate.

In addition, the type of composite material (uni-directional, woven fabric, stitched, braided, etc.), and the relative alignment of the optical fiber with respect to the reinforcement fibers influences the distortion. However, research has proven that small diameter optical fibers do not cause any significant reduction in strength of composites, and standard 125 µm optical fibers produce a minimum perturbation of the host material when embedded parallel to the reinforcing fibers in laminates [23, 24]. In addition, resin-rich regions (resin pockets) can occur around the embedded fibers in some cases.

Furthermore, the strain measured with an embedded optical fiber sensor is not necessarily equal to the one present in the structure. A certain discrepancy will exist, depending on the material and geometrical properties of the sensor and the host structure. Although the linear strain response of bare FBG sensors is well documented, the relation between the strain of the host material and that measured by the embedded sensor needs to be established. Such data can in general be obtained from test samples with simple geometric shapes under controlled and known loads, where analytical or finite element calculations [25] can verify correct strain measurements of the composite from the sensor measurements.

As long as the FBG response displays a regular bell-shaped form as sketched in Figure 4, the determination of the center wavelength is simple. However, after embedding in a composite material, the response curve can sometimes be distorted and may display as a double-peak or even worse a multiple-peak shape. This may occur due to non-uniform stresses around the embedded fiber or transversal loading which introduces birefringence in the fiber resulting in a double peak. A fiber alignment parallel to the reinforcing fibers should be employed in order to minimize such effects. The optical fiber is usually provided with a protective coating such as for example polyimide. The coating will act as the interface between the optical fiber and the host material. This can also impact the transfer of strains from the matrix to the fiber and by choosing a proper coating the strain transfer can be improved in certain principal directions. For example, it is possible to choose a coating for which stress concentrations around the fiber can be avoided and composite distortion minimized.

Embedding of FBG sensors must be performed during blade and rotor/WT construction. For existing WT's it is convenient to surface mount the sensors for instance inside the blades. Surface mounting is done using a thin layer of adhesive to bond the FGB sensors to the surface. For extra protection a pad made up of some soft material can be overlaid the fibers. The relation of the strain of the sensor to that of the substrate for surface mounted FBG strain sensors is different from that of embedded strain sensors. In the first case, the adhesive layer thickness and mechanical properties of this layer have a certain influence on the strain transferred from the structure to the bonded FBG. The strain transfer is mainly dominated by adhesive thickness between the bottom of the fiber and the substrate and the bond length of the fiber. Embedded fibers are completely surrounded by the host material.

4.3 Monitoring of wind power plant components

4.3.1 Rotor blades

The rotating blades are the source of the generated power and can be subject to heavy loads during operation. As wind turbines become increasingly large, the blades are designed as slender and lighter structures and the flexibility of the blade is increased to reduce load. Accordingly, the importance of the dynamic stability of the structure has been emphasized for wind turbine blades, and therefore structural health monitoring is of importance to secure the reliability of the structures during operation. A condition monitoring system can be used in monitoring the instantaneous loading (strains with moments and forces derived), the structural health condition and prediction of the residual service life before failure. The structural health condition focusses on the detection of damages, their location and their severity at any time of the life of the blade. Vibration monitoring of rotor blades is a possible approach since damages and damage growth will affect structural stiffness and hence appear as changes in the structural vibration modes. The principle is to compare on-line measurements to the reference mode shapes of the undamaged rotor blade. The degree to which damages can be detected in size and location depends on the number and spacing of sensors in the rotor blade structure. FBG sensors can conveniently be used for vibration analysis.

For a practical arrangement the sensor configuration (number of sensors and positioning) must be determined, preferably from experience and known weak points in the structure, and embedding the sensors (for new blades/WT's) or surface mounting (for existing ones) at the pre-determined positions. Once the sensors are in place the required instrumentation must be placed and secured within the blade.
Power supply for the instrumentation is required. Data storage and possibly some data processing should be made locally. In addition, for on-line surveillance essential data can be transferred wireless to a convenient location on ground where the final data processing can be made.

4.3.2 Towers

Towers can be monitored in a similar way as the blades, and this is a much simpler task from a practical point of view since they are static constructions and easier to access. Otherwise, for sensor arrangements, data storage and transfer similar considerations to those for blades apply.

4.3.3 Rotating machinery

Figure 1-1 (in the introduction, section 1) showed an example where sensors can be placed on the main components of the rotating parts of the wind turbine; the main bearing, gearbox and the generator. There are numerous possible faults that can occur in these components and some were highlighted in the recent EU Upwind project (www.upwind.eu) as:

- Electrical asymmetries caused by generator faults
- Wear of slip rings and brushes leading to increased brush sparking
- Contacting faults from loose terminal screws/clamps or corrosion leading to increased temperature

- Erosion of contact plates in switching gear leading to increased resistance and temperature increase.

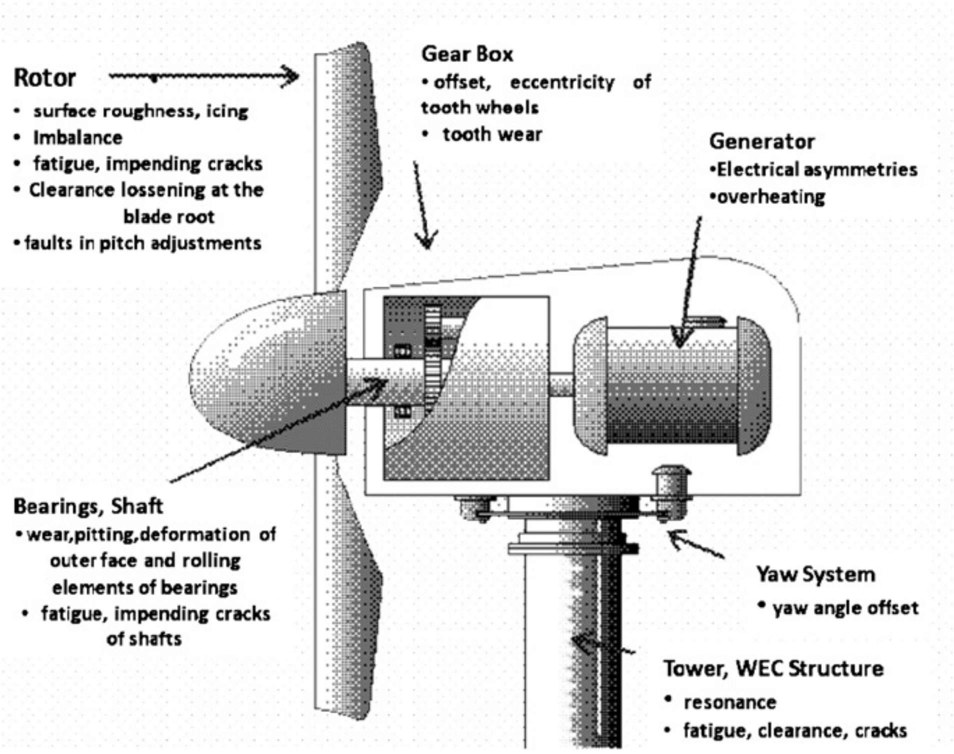


Figure 4-6: Illustration of some possible faults in rotating machinery (from [13])

Some of these are highlighted in Figure 4-6. In addition monitoring of oscillations and vibration of the rotating machinery parts can provide early warning signals when deviating behaviour is detected.

Since FBG sensor are small and flexible and accessible on parts that otherwise may be difficult to access with other sensors, they should be excellent candidates to perform at least some monitoring functions of possible problems listed above. Several possible faults listed above will lead to temperature rise, and for these cases FBG used as temperature sensors can monitor excessive heat. For these cases a sensor packaging dedicated to temperature sensing should be used. Monitoring vibrations are also in general feasible depending on vibration levels and frequency. Hence, FBG sensors should offer a potential for monitoring critical parts in rotating machinery both as temperature or strain/vibration sensing.

4.4 Experimental experience

Some tests of WT blades, both as scaled models and real structures have been reported in the literature and a brief summary of the results are given below.

In [26] a down-scaled wind turbine blade was fabricated using glass and carbon fiber materials for the skin and stiffener, respectively. An array of five FBG sensors was embedded in the composite laminates for structural health monitoring. The blade length was 3.5 m (three blades total for the structure), and the blade was designed to operate at a rated speed of 180 rpm between the cut-in and cut-out wind speeds of 3 m/s and 24 m/s, respectively. After fabrication of the blade, the FBG array was used to monitor the structural conditions, including structural dynamic behaviour during testing of the blade. The results of the tests showed that the measured natural frequencies and mode shapes by the FBG array matched the results obtained from the FE analysis and conventional accelerometers. It was found that the extracted flapwise bending mode shapes and natural frequencies (in the range 8-55 Hz) coincide well with the results of FE analysis and accelerometers.

In [27] a real-time FBG monitoring system was designed and applied to monitor the 42.65 m long rotor blade of a 2 MW wind turbine in South Korea. The wind turbine performance is analysed during various operating conditions. Figure 4-7 below shows the set-up. The FBG interrogator is fastened in the rotor hub, and the measurement results are processed, displayed and stored in a laptop computer (PC1) installed with driving software. PC1 is directly controlled using the remote control software on the ground computer (PC2). The power supply (220 V/60 Hz) was available in the rotating hub. Data were collected at 100 Hz sampling rate. The FBG sensors with acrylate protective coating are located on the inside of the blade and surface mounted parallel to the neutral axis of the blade, except one near the trailing edge. One additional FBG sensor was employed for temperature compensation and not fastened to the structure. Unidirectional E-glass tape was used to laminate FBG sensors onto the blade surface by the hand lay-up process.

The finite element method and fast Fourier transform were used to determine modal characteristics of rotor blades. Flapwise and chordwise natural frequencies were obtained accurately from the FFT analysed yawing signals, and these results were compared with the FE modal analysis results of the GFRP-based composite rotor blade. Deviations were typically within 3 %.

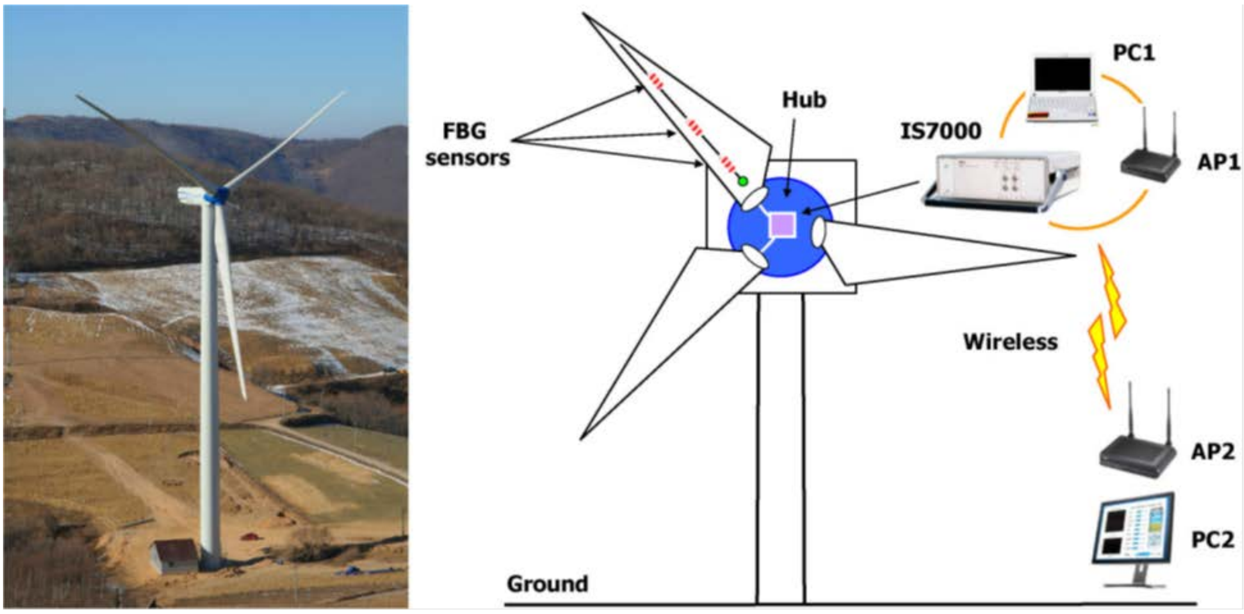


Figure 4-7: 2 MW wind turbine with a wireless network.

Another paper [18] describes an FBG measurement system which is monitoring the 53m long rotor blade of a 4.5MWwind turbine in Germany. In this test the power supply (220 V/50 Hz) is available in the rotating nacelle. The data transmission from the FBG interrogator located in the wind turbine rotor to the data handling computer in the stator is carried out via a wireless transfer. Also in this installation, the FBG strain sensors have been integrated after finishing the rotor blade. A sensor pad (Figure 4-8) has been developed consisting of a GFRP substrate, with the FBG strain sensors attached frictionally stable to it, and a cord grip, providing strain relief to the fiber-optic signal transmission cables at both ends of the pad. All attachments between FBG sensors and blade use adhesives over the whole FBG length to the pad and over the whole pad area to the blade surface, respectively.

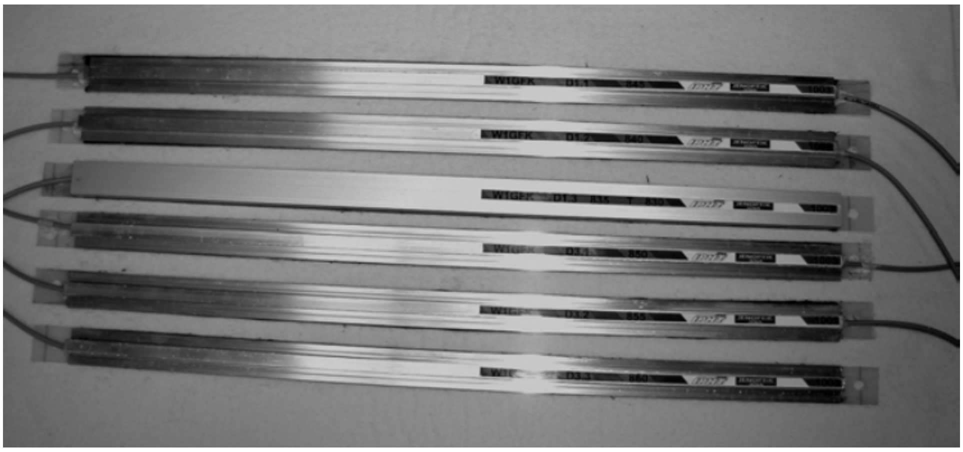


Figure 4-8: Six sensor pads for strain monitoring of rotor blade. The third pad includes a temperature sensor (from [18])

Three strain sensor pads each have been attached to both the windward and the leeward internal surfaces of the blade, on opposite symmetrical positions. After upgrading, the system collected data with a rate of 50 measurements per second. The digital signal processor performs the Bragg wavelength calculations on-board resulting in the faster transmission rate of the sensor data already calculated. The measurements provided detailed strain data showing significant differences between the strain characteristics at different sensor positions along the blade. At the time of publication the system has operated reliably for more than two years delivering continuous load monitoring. The data will be used for safety monitoring and active safety control of the blades and for load monitoring of the whole turbine.

In the EU project "Upwind" optical fiber FBG strain measurement systems are described. The objective of the assessment was to investigate the performance of embedded and surface mounted optical fibers for strain measurement, notably in fatigue. Several test specimens were made and the test results were compared to similar tests without optical fibers, to detect any potential influence of the presence of the optical fiber in the laminate. In addition, optical fibers were surface-mounted on the sides of the specimens and tested in the same testing regime. Strain measurements were compared to measurements using more conventional technologies, such as extensometers and strain gauges.

The main conclusions from these tests were as follows. Embedding fibers in 4-layer and 6 layer laminates was successful after taking the necessary precautions against leakage via the cable protective mantle and ensuring proper alignment of the fibers in the mould. However, the optical fibers were quite sensitive to external loads, which resulted in some of the sensors being destroyed during the preparation of the plates and specimens. No detrimental effect of surface-mounted fibers on fatigue life was detected.
Also, no significant detrimental effect of embedding fibers was found and embedded fibers gave relatively reliable measurements. Surface mounted optical fibers seemed to suffer from the degradation of the adhesive bond between fibers and specimen surface. An alternative bonding method might give better performance, e.g. bonding over a longer length of the optical fiber.

So far there seems to be no real installations with embedded FBG sensors, while there are some where FBG sensors have been post-installed with surface mounting as shown in the examples above. Installation of embedded sensors must be performed during WT/blade construction.

4.5 Roadmap for tests and commercialization

Despite some drawbacks and challenges in embedding fibers in composite materials, FBG sensors are judged to be the best choice for this purpose, if not wireless sensors can be used. Their multiplexing capability can greatly reduce wiring and connections compared to ordinary strain gauges where each one requires two wires.

When embedding an optical fiber in a composite laminate, there are several effects which must be taken into consideration. Once embedded, it is not possible to remove, repair or otherwise modify the optical fiber, and therefore a high degree of reliability is necessary during production, or the embedded sensors are wasted. In addition concerns still remain about the survivability of the sensors during the embedding process and laminate curing stages. Concerns of sensor survivability include the mechanical survival of the optical fiber as well as any optical degradation of the fiber due to the heat of the curing process. Secondly, an embedded standard optical fiber with a diameter of 125 µm still has a significant impact on the laminate. Including the fiber in the laminate creates a stress concentration in the laminate; it disrupts the location of the composite fibers, causing a resin rich region and can ultimately compromise both the static and fatigue strengths of the laminate. How these factors affect the long-term reliability and stability of a wind turbine should be investigated before embedding sensors in blades.

In view of the challenges listed above, a possible roadmap for development of FBG sensors integrated in WT blades should comprise the following steps. **First a reliable and reproducible way of integrating the fibers during blade construction must be worked out.** Test samples as for example composite panels made up in the same way as real blades or scaled-down versions of real blades suitable for a laboratory environment can be used for testing basic embedding issues. Using many samples one can get data for successful integration rates in terms of failed sensors, distortion of FBG response after curing and detrimental effects on the composite samples. Mechanical tests of samples with embedded fibers compared to similar samples without fibers should reveal any possible strength degradation due to the embedded fiber. When, after such tests an installation procedure has produced satisfactory results, the procedure should be qualified and ready to be employed in real structures. Still, some tests of real structures should be carried out in order to verify the qualification procedure. Very large blades will generally be manufactured in separate sections that are assembled into the finished blade. In this case it is very difficult to use one single fiber sensor covering the total length since it is a problem to splice fibers in connecting different blade sections. In this case each section should be instrumented separately. Most interrogation systems can handle several parallel fibers so this solution should not become a limitation.

Once the procedure for embedding of fibers is worked out, the organization of connection fibers, choice and secure placement of the interrogator and its power supply and data storage and transfer must be taken care of. A solution as described in [27] where the FBG interrogator is fastened in the rotor hub where power supply is available should be an advantageous solution. The choice of interrogator depends primarily on the desired number of sensors and the interrogation rate which must be sufficiently high in order to monitor vibrations and dynamics of the structure. Most interrogators employ separation of each sensor by assigning a wavelength band for each one and the limitation of the number of sensors here is the spectral width of the light source and the expected variance in sensor response from external forces while in operation. A larger number of sensors can be interrogated using a TDM (time division multiplexing) technique. However, each sensor must here be separated by a long enough length of fiber in between each one which may cause an excess length of fibers in the structure.

Data storage and transfer solutions must be decided according to the needs of the operator. The solution described in [27] where a local processing unit located in the hub and transfer of essential data to a central computer can be a practical way of serving the purpose. For off-shore installations data transfer to shore can be made with fiber-optic communication cables integrated with the power cable which is common practice in many off-shore installations.

Finally, and most important, will be the question on how to relate the measured data to the condition of the monitored structure. A strategy for identification of failures in terms of existence, location, type and extent and their effect on the overall reliability of the structure would be an ultimate goal of a structural health monitoring system. Finite element models (FEM) of the structure with and without damage combined with smart algorithms should be an important supplement in order to interpret measured data. This combination can become a key step for the extraction of information from sensor data, i.e. the identification of the damage-sensitive properties, derived from the measured dynamic response, which allows distinguishing between the undamaged and damaged structures. The combination of FBG sensors, FEM data and smart algorithms can thus together provide a diagnostic tool for obtaining knowledge about a possible damage situation. In this way, with the help of algorithms and FEM data, it should allow for a physical interpretation of sensor data. This would make it possible for the damage not only to be detected, but also characterized, located and quantified.

Recently a FiberSensing WindMETER system [28] is introduced as a complete monitoring solution specifically designed to be installed in WT blades. The system consists of a low-power consumption interrogation unit and FBG strain and temperature sensors. The system claims high resolution to be attained even for long fiber leads and connections with losses. The interrogator is prepared to perform under rough environmental conditions. Fast continuous swept laser scanning enables simultaneous acquisition of tens of sensors up-to 100 Hz sampling rate. The packaging of the sensors is lightweight and ruggedized due to the ability to embed the optical fiber FBG in GFRP material. These sensors are protected with a polyurethane rubber layer, being suited for surface application directly in wind generator blades. The interrogator is prepared for real time and remote operation via Ethernet interface, allowing its connection to any industrial computer or PLC through TCP/IP or optionally with RS232, RS485 or CAN interfaces. The system can also be integrated with a wireless router for long range wireless transmission.

5 Distributed Wireless Sensor Network

A network of small sensors is needed to monitor large areas or surfaces. The SMART Layer® concept is a promising (and patent-protected) technology currently under development, as described previously in section 3.3. Wired solutions pose obvious challenges for low-cost installation and use, but are reliable and may be integrated in or on a structure if possible in the design and later fabrication phase, similar to that described for FBG above- but more wires give increasingly complex installation unless "smart" techniques are used. Post-installation on site is very costly and probably not possible for OWT's. A more flexible, yet still complex, solution is to establish a network of wireless sensors.

Distributed wireless sensor networks consist of sensor nodes, possibly relay nodes, and a base station. The use of relay nodes and e.g. "hopping connections" generally define a "distributed" network.
The sensor nodes consist basically of at least one sensor, readout electronics, processing electronics, RF-electronics (incl. filter etc.), antenna and a power supply. The power supply is quite often a battery, but might also include energy harvesting solutions using available energy from the surroundings (e.g. solar power, vibration energy etc.). The maintenance free operation of the sensor nodes is normally a question of the reliability of the different components and, obviously, of the battery lifetime.

It is difficult to imagine a cost effective wireless sensor network without the use of MEMS.
Small sensors, typically MEMS may be more easily integrated in a type of networked configuration suitable for large scale SHM-systems. The key features of (wireless) sensor nodes are:

- Size,
- Power consumption and battery lifetime ,
- Accuracy,
- Reliability,
- Cost

5.1 MEMS background

Microelectromechanical systems (MEMS), are also known as microsystems or micromachines. Typically MEMS are used as sensors and can measure different physical entities:

- Mechanical sensors (Pressure, acceleration/vibration, angular rate, flow, tactile)
- Thermal sensors (temperature, flow)
- Chemical sensors (pH, gas, reagents)
- Optical sensors (spectrometer, pyrometer)
- Magnetic sensors (Hall effect, magnetometer)

However, the same technology can also be used for micro actuators (e.g. digital mirror displays) and energy harvesting devices. These systems can sense, control, and activate mechanical processes on the micro scale. MEMS are a promising technology for SHM applications. The latest developments have led to a remarkable reduction in size, cost and power consumption of these sensors. They can be mass produced, are small enough to be used in applications where conventional sensors would be intrusive, and are often combined with systems for wireless data transmission. There is now a variety of different MEMS sensors on the market directly available off-the-shelf. The main application areas of standard MEMS sensors are automotive (airbag sensors, tyre pressure monitoring, ABS/ESP etc.), consumer (mobile phones, Nintendo WII etc.) and industrial (condition monitoring, process control etc.) applications. However, for different application areas with special requirements it might be necessary to develop a tailored MEMS solution, e.g. a special type of MEMS accelerometer with a specific sensitivity [10]. MEMS sensors may also be used to monitor parameters such as crack initiation, propagation and corrosion etc.

Small sensors may be more easily integrated in a type of networked configuration suitable for large scale SHM-systems. Most MEMS sensors for SHM applications are based on vibration sensing performed with MEMS accelerometers, but many other measurements are also possible.
The field of **MEMS accelerometers** can be segregated into two dominant microsystem architectures: capacitive and piezoresistive. Capacitive accelerometers employ a differential capacitor whose balance is disrupted by the movement of the proof mass. Piezoresistive accelerometers generally rely on strain induced within a flexural element that attaches the proof mass to the sensor housing for identification of the mass movement. Capacitive-based MEMS accelerometers, such as the ADXL iMEMS series (Analog Devices, Norwood, Mass.) have enjoyed great commercial success and dominate the market. However, with new processes available and old processes improved, a low-cost, high performance piezoresistive accelerometer is possible [10].

As an example of other possible uses of MEMS for SHM, a resonant capacitive MEMS transducer was recently developed for use as **acoustic emission detectors** [29]. The 1-cm square device contains six independent transducers in the frequency range between 100 kHz and 500 kHz, and a seventh transducer at 1 MHz. Each transducer is a parallel plate capacitor with one plate free to vibrate, see Figure 5-1, thereby causing a capacitance change which creates an output signal in the form of a current under DC bias voltage. The device was used to detect acoustic emissions associated with crack initiation and growth in weld metal. In a side-by-side comparison with a commercial piezoceramic transducer, fewer acoustic emission events were detected by the MEMS transducer. This was a consequence of the somewhat worse signal-to-noise ratio of the MEMS transducer, in part as a result of electrical interference. The signal-to-noise ratio might be improved with better packaging and shielding.

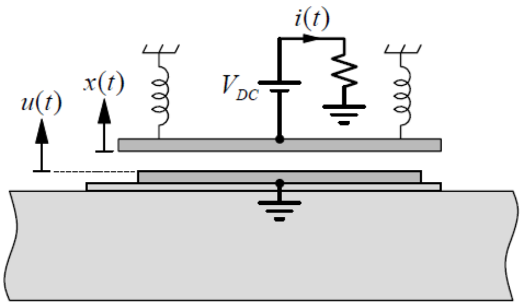


Figure 5-1: Schematic of acoustic emission transducer showing both mechanical and electrical elements [29].

MEMS can be operated as single sensors, or as integrated multiple MEMS sensors for performing measurements in high dynamic environments. Multiple sensors can be configurations of identical, nearly identical or different sensors. The theoretical advantage of arrays of identical sensors is the enhancement of the signals by a factor N, where N is the number of the identical sensors, while the random noise of a combination of N sensors should increase proportional to the square root of N. An array of multi-ranged accelerometers is an example of similar sensors. Each accelerometer is designed with a certain dynamic range. These sensors are incorporated together to give a combined larger dynamic range. A more common example of different sensors in a MEMS package is a pressure sensor with temperature compensation in the same module.

In [30] the roving hammer and MEMS array methods are compared by testing a composite vertical stabilizer (tail plane) from an Airbus A320 aircraft. In the roving hammer technique a small number of accelerometers, typically about four, is installed on the structure and the structure is then excited at a large array of test points. Frequency response functions are individually measured between each excitation point and the reference accelerometers, and the required operating curvature shapes are determined from the resulting array of frequency response functions. While setup of the experiment is reasonably quick, data acquisition can be time consuming and it is not easily amenable to automation. The MEMS technique is an alternative approach, which relies on the reciprocity theorem. An array of response transducers is installed on the structure, and then only a few locations are excited. Despite the different test procedures, and the lower quality of the MEMS transducers, it is shown that an array of low cost MEMS transducers can determine results comparable with those obtained using high performance transducers. The MEMS testing was accomplished by installing a sub-array of 30 ADXL202 MEMS accelerometers (Analog Devices, Inc.) and completing the data acquisition. MEMS accelerometers type ADXL202 were selected for the MEMS array test primarily because of their low cost and small size and weight, leading to the possibility of embedding them in future composite structures during manufacture. A comparison of the 353B33 ICP, a rather typical bulk piezoelectric transducer, and the ADXL202 MEMS transducers is shown in Table 1.

Table 1: Comparison of transducers.

	Precision Quartz Shear ICP 353B33	MEMS ADXL202
Manufacturer	PCB, Inc.	Analog Devices, Inc.
Catalog price[a]	$315	$14.55
Mass[b]	27 g	1.55 g
Approximate size[b]	19 mm diameter × 24 mm	5 mm × 5 mm × 2 mm
Maximum bandwidth (3 dB)	12 kHz	5 kHz
Peak acceleration	50 g	2 g
Sensitivity	100 mV/g	312 mV/g
Resolution	0.0005 g	0.005 g
Noise density	6.4 $\mu g/\sqrt{Hz}$ @ 1 kHz	500–1000 $\mu g/\sqrt{Hz}$ average across frequency range

[a] Phone quotes June 13, 2006 for single item purchase.
[b] Mass and size exclude cables and connectors.

MEMS sensors are commonly integrated with circuits for signal conditioning, preferably with an ASIC (application specific integrated circuit) chip. Such a basic configuration may further be packaged with increasingly capable systems and sub-systems as required for a complete, and application specific sensor system. Since MEMS-sensors are used for a vast number of applications a whole **MEMS-packaging** industry exists with related, application specific technologies.

In the figure below, a block diagram of an automotive tire pressure monitoring system (TPMS) shows the basic system requirements for a complete node in a "state-of-the-art" wireless sensor system, including a possible energy harvesting/scavenging capability.

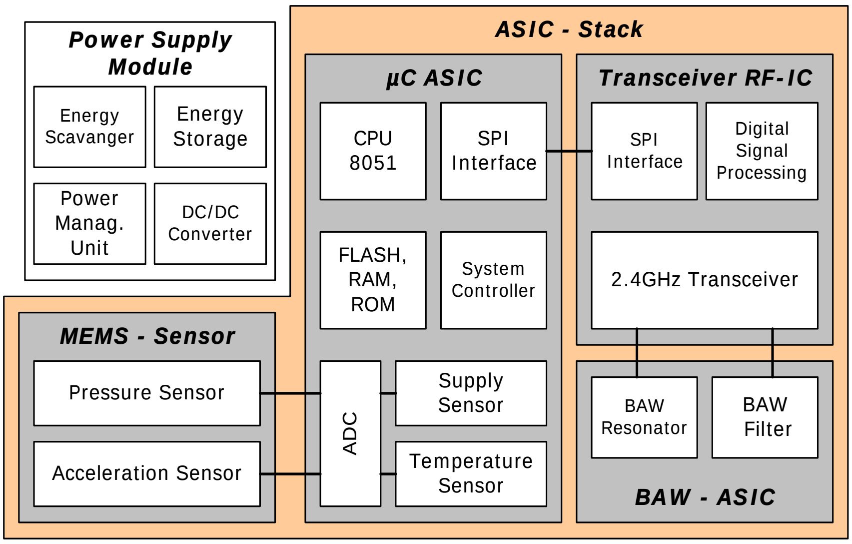


Figure 5-2: TPMS block diagram as an example of the system requirements for a node in a wireless sensor network, as presented and detailed in [31].

The block diagram above includes a (MEMS-based) energy scavenger/harvester as a sub-system of the power supply module in order to possibly complement the batteries and capacitors (energy supply and storage). Such energy harvesters could provide energy to the system to match the lifetime of the system- thus avoiding external battery replacement or charging [31]. **Energy harvesting and power generation** is now a major research field in the MEMS world [32, 33] while better battery technology may also be expected in the future. Estimated power requirements for the above mentioned TPMS may also serve as an example of the typical (advanced) node in a state-of-the-art wireless sensor system.

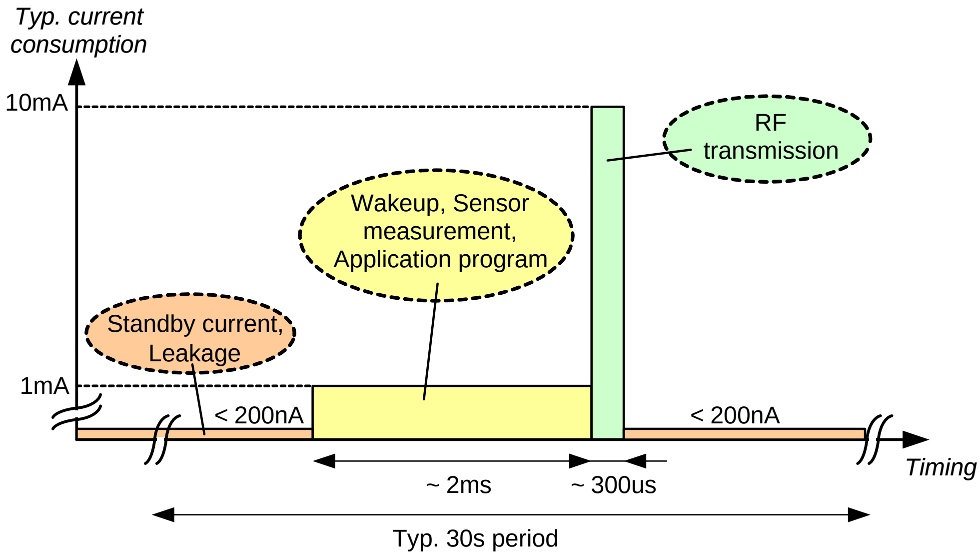


Figure 5-3: Typical current consumption of a (state-of-the-art) TPMS node.

Obviously, in order to drive antennae and send/receive signals in a possibly noisy environment the radio transmissions in a WSN need to be of relatively high power for the system as a whole. However, recent advances in low-power radio circuits [31] and in micro-controllers commercially available from e.g. Texas Instruments or Energy Micro (www.energymicro.com) and innovative radio/antenna- technology including RF-MEMS (another very active MEMS-research field) will likely further reduce the power requirements for more applications to soon match that available from available or emerging (MEMS-based) energy harvesters [32].

An example of innovative wafer-level packaging, or so-called "3-D integration", of the physical layers needed for extremely small nodes in future WSNs is described in some detail in [31], and was the topic of a recent large integrated EU project (www.e-cubes.org).

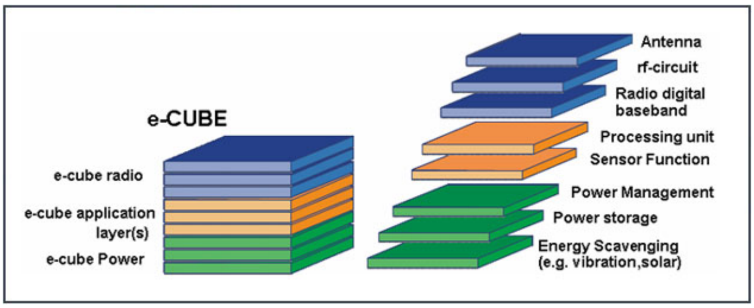


Figure 5-4: Figure from the e-CUBES project (www.e-cubes.org) illustrating the physical layers (wafer-level) needed for a complete wireless node.

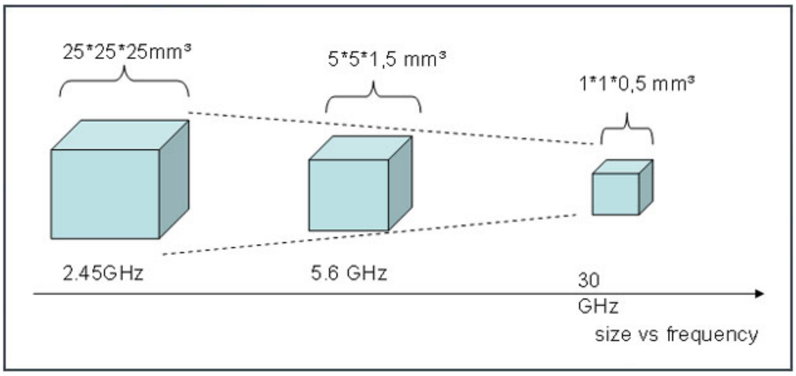


Figure 5-5: Figure from the e-CUBES project (www.e-cubes.org) illustrating the possible (near future) size of wireless sensor nodes and the scaling law of the integrated antenna.

The required physical layers of a node in a WSN will typically include those illustrated in the e-CUBES concept in the figure above.

The **physical size of a node** is determined by three main factors:

1. The size of the integrated circuits including microcontroller, signal conditioning, radio circuits etc. and power management.
2. The minimum size of the antenna required for power-efficient communication
3. The power storage/battery and/or energy harvesting subsystem.

Since integrated circuit technologies allow increasingly complex circuits in smaller sizes and with lower power levels, the main size limitations are therefore the antenna size and the power system. Given the integrated circuit technology, with respect to die size, power consumption and frequency capabilities, the achieved target size for the e-CUBES - project was about 1 cm^3 (see Figure above), while targeting less than 1mm^3 dimensions in the future. The optimum shape or “form factor” will probably not be cubic for most applications- though such a shape would be ideal for a full wafer-level packaging concept such as the vision of e-CUBES. Such a future "e-CUBE" could be integrated in a polymer-based “patch” for integration in a tire for tire pressure monitoring or for so-called RFID-tags. Larger polymer patches/tags enable practical handling and bonding to a suitable device or i.e. airframe or wind turbine blade substrate, while exploiting the increased packaging area to enable efficient antennas and power harvesting including e.g. a flexible photovoltaic cell. Large area electronics could be used including low-cost technology developed for “RFID-patches”, suitable for lower frequency RF-radio communications.

5.2 Sensor Networks

A short discussion on the use of wired vs. wireless networks was previously stated. MicroStrain Inc. (www.microstrain.com, based in Vermont, USA) provide a wireless sensor network solution based on the IEEE802.15.4 standard protocol in which each node in the wireless network is assigned a unique 16 bit address or an optional 96 bit EPC code for self-powered active sensor-RFID. ZigBee and WirelessHART are other network solutions providing both high level (user level) and low level (physical layer functions) protocols based on the basic 802.15.4 protocol. As an example of "state-of-the-art" wireless sensor networks (WSN) the reader is referred to a "white paper" on the distributed wireless network developed for gas detection by the SINTEF technology spin-off GasSecure AS, available at the company web-site (www.gassecure.com).

In [34] several different sensor network paradigms for SHM are discussed and evaluated, using retrofitting in buildings as an example application.

A so-called *Decentralized Processing with Hybrid connection (*Figure 5-8*)* is argued to be a good choice for buildings, but also seems to be relevant for a hybrid sensor network for aircraft or rotorcraft and might also be interesting for wind power plants. At the first level, several sensors are connected to a relay-based piece of hardware, which can serve as both a multiplexer and general-purpose signal router. At the highest level, multiple data processing stations are linked to a central monitoring station (or smart node) that delivers a damage report back to the user (or SHM system). Hierarchal in nature, this sensing network can efficiently interrogate large numbers of distributed sensors and layers with groups/arrays of sensors (as for example implemented in a SMART Layer as described elsewhere), while reducing the number of physical radio-capable nodes as necessary.

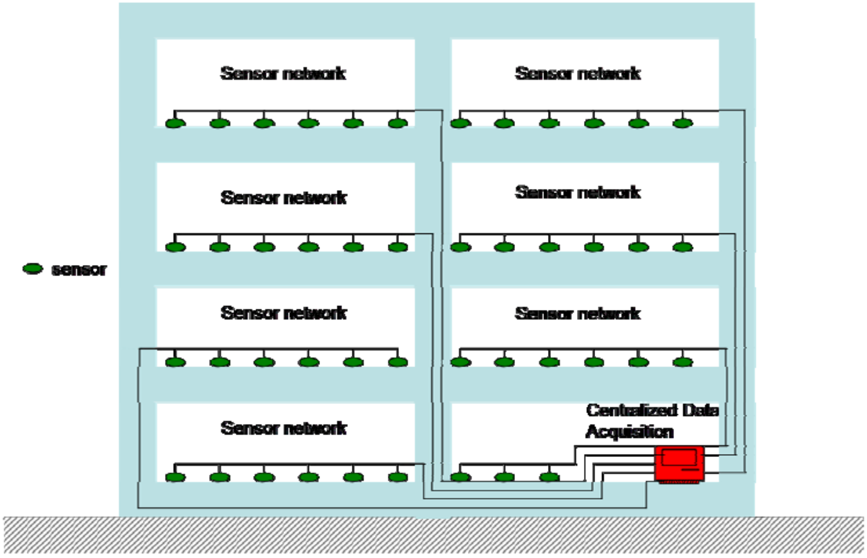


Figure 5-6: The wired sensing network of a typical sensor system (for buildings).

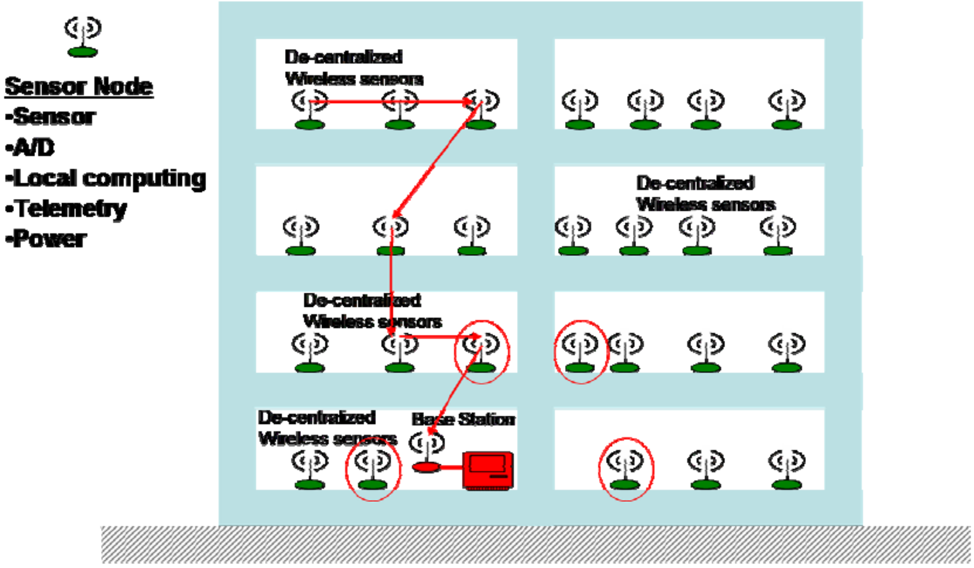


Figure 5-7: De-centralized wireless SHM system with hopping connection, greatly reduces installation costs, but the potential loss of data during transmission is an issue.

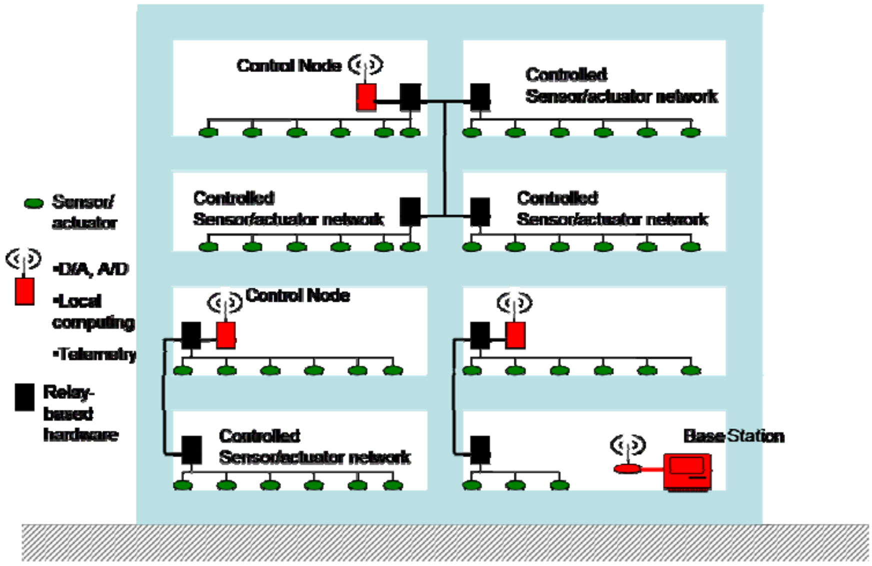


Figure 5-8: De-centralized wireless SHM system with hybrid connection combines most of the advantages of wireless systems (cost and flexibility) with increased reliability and robustness.

5.3 Sensor Integration

Data interrogation procedures (feature extraction and statistical modelling for feature classification) are necessary components of a SHM system that convert the sensor data into information about the structural condition. *Statistical modelling for feature classification* is concerned with the implementation of the algorithms that analyze the distributions of the extracted features in an effort to determine the damage state of the structure. A non-sensor-type-specific discussion of this topic is presented in [34].

An important aspect in designing and in programming a (wireless) sensor node is to minimize its overall power consumption [31, 35]. As a first step it is recommended to look for (or develop) an optimized hardware. There are a lot of power consuming components like the sensors, the A/D-conversion-module, the radio module, the sensor-CPU, and the memory which require energy to work properly (see table 1). If low power consumption is considered it is suggested to limit the voltage range of these components to a maximum value of 5 Volt or better of about 3 Volt or even lower. In a next step it is recommended that the system components operate in sleep or power down mode as often as possible.
The wake up time itself could be of importance. Especially if the measurement task is acoustic emission analysis a very fast wake up time of a few µs is required for some of the components. Another high power consuming part is represented by the sampling rate and the amount of handled data, e.g. high sampling rates and high amplitude resolution result in high power consumption.
Average energy required per transmitted bit and maximum data transfer rate for several wireless technologies are given in Figure 5-10.

Component	*Sleep mode*	*Full operation*
8bit-Processor @20MHz	24 µW	24 mW
Memory	6 µW	45 mW (writing)
		12 mW (reading)
Radio module (RF)	6 µW	24 mW (receiving)
		36 mW (transmitting)
Signal conditioning and A/D-conversion		
100kHz, 12 bit	-	0.6 to 2 mW
MEMS-Sensors		
Acceleration 2kHz, 12 bit	15 µW	6 to 15 mW
Humidity & Temperature	1 µW	1.5 mW

Figure 5-9: Average energy required for different components (at 3V) [35].

Communication standard	*12 m distance*	*30 m distance*	*Max. Transfer rate*
IEEE 802.11b (WLAN)	200 nJ/bit	300 nJ/bit	11 Mbps
Bluetooth™	2.5 µJ/bit	-	0.8 Mbps
Zigbee™	7 µJ/bit	7 µJ/bit	20 to 250 kbps
Home-RF (example)	1 µJ/bit	2 µJ/bit	0.8 to 2 Mbps
nanoNET (CSS)	60 nJ/bit	80 nJ/bit	2 Mbps

Figure 5-10: Average energy required per transmitted bit and maximum data transfer rate [35].

The SMART Layer concept, described in section 3.4, is an innovative example of a networked system of (wired) small sensors. It seems particularly well suited for acoustic based structural health monitoring of composites with small piezoelectric transducers. The concept is based on reliable and tested materials for packaging, wiring and laminations of the layer. Combinations of wired and non-wired nodes may be cost- and power-effective for SHM of e.g. WT blades.

MEMS, in particular those qualified for "automotive" (proven, tough specifications and low cost) seem ideal for use in "embedded" WSNs, e.g. for networked, wireless sensing for structural health monitoring applications. However, the "wireless packaging" of sensors, e.g. performed by many research groups, is usually for demonstration use and is much less integrated than that required for tough applications. The vision, however, is of many low-power “motes” (miniaturized, smart sensor nodes) embedded throughout the structure with a smaller number of higher capacity/power nodes that can provide local excitation, data processing, routing etc. The challenge is to develop both the networking algorithms to reliably communicate within the network, and distributed algorithms to monitor the state of the structure [37]. Many research groups are looking into wireless data transmission, as well as energy scavenging and low power battery driven sensors. Motes (or smart nodes) integrate a microprocessor, memory, and a radio transmitter together and can be outfitted with a plethora of industry standard sensory devices with little or no modification. The implication of this conglomerated setup is that it can be used to reduce, store, and ship data at the acquisition site, see Figure 5-11.

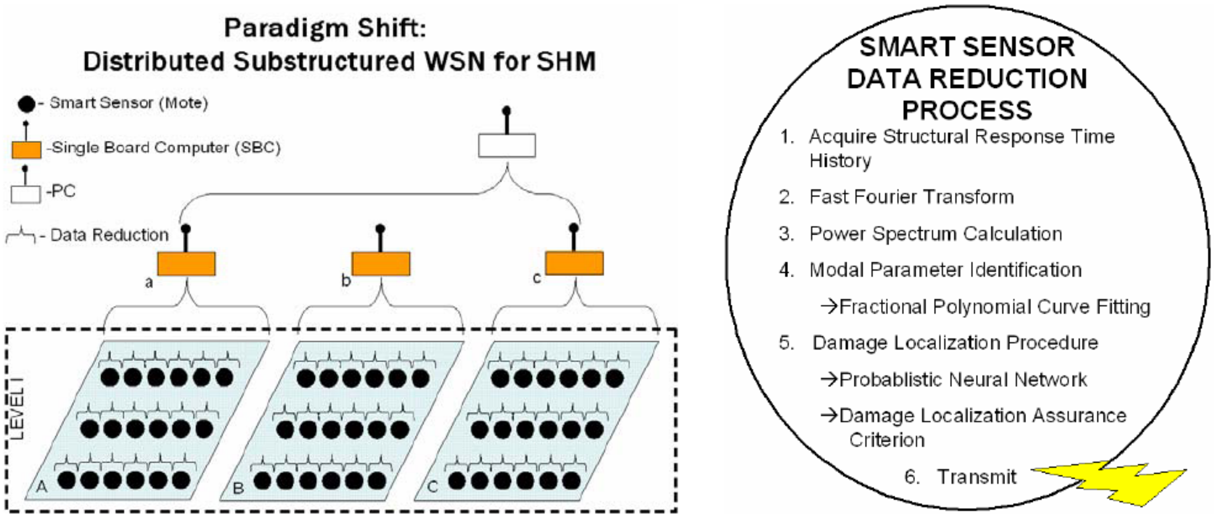


Figure 5-11: A Distributed and sub-structured Wireless Sensor Network for Structural Health Monitoring. Level I of this WSN paradigm for SHM relates to data reduction at the acquisition site.

The sensor motes are the main components of a wireless monitoring system, see Figure 5-12. There are different tasks a sensor mote has to perform, which are to collect and digitize data from different sensors, to store sensor data, to analyse data with simple algorithms, to send and receive selective and relevant data to and from other nodes as well as the central unit and to work for an adequate time period without a wired power supply. Therefore a sensor mote consists of a CPU or DSP with sufficient memory, a low power radio, an aligned analog to digital conversion module (ADC), a power supply and one or more diverse sensors.

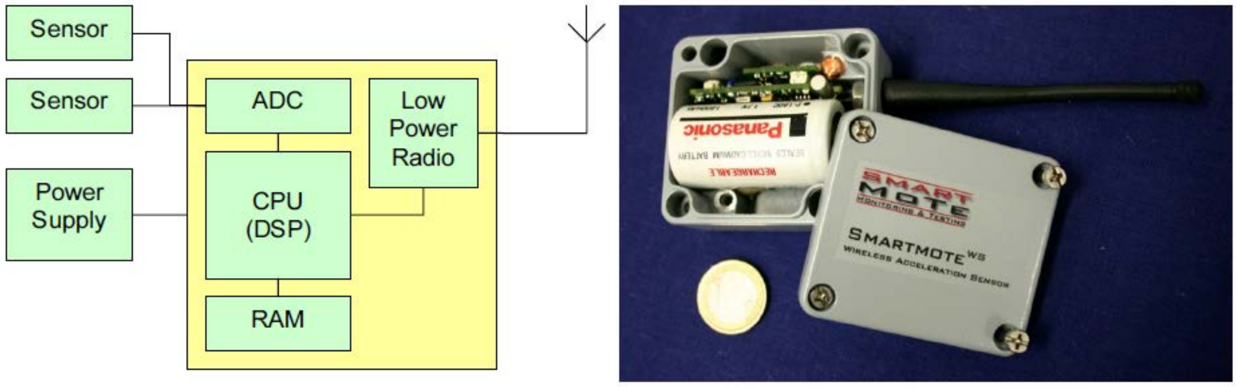
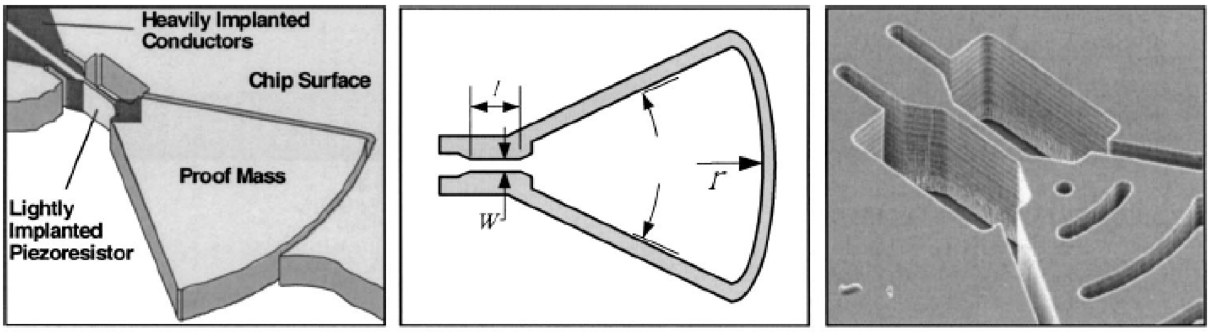


Figure 5-12: Schematic layout of a sensor mote and prototype (©Smartmote [35]).

The sensor much be chosen to suite the application, and the location and number of sensors should be chosen on the basis of knowledge of known "hot-spots" if possible. The sensitivity of a piezoresistive accelerometer (see e.g. Figure 5-13) are typically in the range as those that are commercially available, e.g. Analog Devices capacitive MEMS accelerometers are typically on the order of 100 mV/g, see Table 2. In comparison, traditional piezoelectric accelerometers, e.g. quartz tuning forks, shear mode crystals, piezoceramic bulk transducers etc, are (still) state of the art for many precision (high cost) applications. An overview of the cost and other parameters of some of the Analog Devices capacitive MEMS accelerometers are presented in Table 2. A piezoresistive MEMS accelerometer is shown in Figure 5-13 below.

Table 2: Low g iMEMS Accelerometers from Analog Devices (www.analog.com).

Part# Results: 10	# of Axes	Range	Sensitivity	Sensitivity Accuracy (%)	Output Type	Typical Bandwidth (kHz)	Noise Density (µg/rtHz)	Voltage Supply (V)	Supply Current	Temp Range (°C)	Package	Price* (1000 pcs.)
ADXL325	3	+/- 5g	174 mV/g	±10	Analog	1.6	250	1.8 to 3.6	350µA	-40 to 85°C	4mm x 4mm LFCSP	$2.38
ADXL326	3	+/- 16g	57 mV/g	±10	Analog	1.6	250	1.8 to 3.6	350µA	-40 to 85°C	4mm x 4mm LFCSP	$2.38
ADXL327	3	+/- 2g	420 mV/g	±10	Analog	1.6	250	1.8 to 3.6	350µA	-40 to 85°C	4mm x 4mm LFCSP	$2.38
ADXL335	3	+/- 3g	300 mV/g	±10	Analog	1.6	300	1.8 to 3.6	350µA	-40 to 85°C	4mm x 4mm LFCSP	$2.38
ADXL345	3	+/- 2/4/8/16g	up to 256 LSB/g	±10	Digital	1.6	-	2.0 to 3.6	145µA	-40 to 85°C	3mm x 5mm x 1mm LGA	$3.04
ADXL346	3	+/- 2/4/8/16g	up to 256 LSB/g	±10	Digital	1.6	-	1.7 to 2.75	145µA	-40 to 85	3mm x 3mm x 0.95 mm LGA	$3.04
ADXL321	2	+/- 18g	57 mV/g	±10	Analog	2.5	320	2.4 to 6	0.49mA	-20 to 70°C	4mm x 4mm LFCSP	$8.13
ADXL103	1	+/- 1.7g	1000 mV/g	±4	Analog	2.5	110	3 to 6	0.7mA	-40 to 125° C	5mm x 5mm x 2mm LCC	$8.19
ADXL203	2	+/- 1.7g	1000 mV/g	±4	Analog	2.5	110	3 to 6	0.7mA	-40 to 125° C	5mm x 5mm x 2mm LCC	$9.85
ADXL213	2	+/- 1.2g	30 %/g	±10	PWM	2.5	160	3 to 6	0.7mA	-40 to 85°C	5mm x 5mm x	$9.85



(a) (b) (c)

Figure 5-13: Piezoresistive Accelerometer (a) Design illustration; (b) physical dimensions and; (c) SEM image of planar piezoresistive accelerometer[36].

5.4 Cost and Availability issues

Mass production of MEMS and microprocessors for a variety of applications have reduced their cost to a level of tens of dollars, and with their increasing popularity, costs may be reduced to fractions of a dollar [38] for consumer and automotive products. The improvement in the technologies for other important components, such as memory, radio transmitters, and batteries, will allow more capable and long lasting devices, reducing their maintenance cost.

A review of wireless sensors for SHM is given in [39]. The obvious main benefit of wireless structural monitoring systems is that they are inexpensive to install because extensive wiring is no longer required between sensors and the data acquisition system. Monitoring of rotating components also becomes more feasible. Examples of commercial wireless sensing prototypes are presented in the Appendix, Table 3 for further reference.

6 Discussion on Materials and Sensor Integration in and on Wind Turbine Components

Critical point locations must be determined through the design-phase in cooperation with the manufacturer by either using simulation data (e.g. FEM simulations) or load testing. When such "hot-spots" are not well known, the solution is to employ more sensors and more modelling in the testing and qualification phase. Often the right answer to such critical point locations can only be achieved by experience after a certain time period in full operation.

Integrated sensors make it possible to follow the structure through its lifetime and give input back into the design iteration process (of new designs). This is probably crucial when the designs are novel and the operational conditions are extreme, as for very large OWT's.

6.1 Sensor Data for Model Validation and Wind Turbine Development

Recent, unpublished modelling results in Nowitech indicate that wing/blade damage is dominated by tensile stress due to inferior tensile fatigue characteristics of the shell glass fiber material. Improved materials (graphite based) will very likely improve these characteristics, as modelled, but a SHM/CM system including sensors embedded in or on the surface could also indicate excessive fatigue/loading before critical damage occurs. A fatigue life model including (non-complete) composite laminate theory also needs empirical data for validation and improvement. Conversely, we also argue that good models are needed in order to decide the correct quality and quantity of sensors in or on the structures to be monitored, and to extract trusted information from the sensor data. Simple algorithms should be embedded in sensors and related microcontrollers in order to reduce the amount of data that needs to be transmitted (and analysed) in a WSN during operations. Full data analysis, data fusion and data mining techniques must also be considered when suitable.

7 Discussion on critical condition and structural health parameters (with input from industry)

Two interviews with Norwegian wind power plant operators have been performed: Statkraft and Statoil. In the following the essence of the interviews will be noted:

- Wind power plants show often quite different failure modes though the turbines are (should be) identical (as manufactured and installed). Therefore, failure prediction seems to be quite difficult even with more statistical data.
- Temperature gradients especially in the IGBT converter modules seem to be a measure for failure modes. This would be interesting to monitor in operation to predict failure. This is also a quite common failure.
- Rotor blades are critical components and monitoring seems to be quite attractive e.g. noise measurements, icing etc. Nevertheless, the composite material should be understood better for prediction of failure modes.
- Future concepts of off-shore power plants work with lighter structures (easier installation and lower costs) and new bearing concepts (conical bearings). It seems that gearless concepts or quite simple gearboxes will be introduced. Life-time and failure models are either not available or not shared by the producers for these new concepts/components for wind power plants. It would be interesting to monitor (using integrated sensors) these next generation power plants right from the start to get an understanding of the failure modes.

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- It might also be interesting to monitor other structural parts, corrosion, lubricants and oil leakage as well as gas monitoring in the nacelle for clearance of the maintenance personnel.

8 Discussion on Condition Monitoring System

The term "Reliability-Centered Maintenance based on Statistical Analysis" is perhaps more accurate than "preventive maintenance". A sensor-based condition monitoring system should greatly reduce the need for manual inspections. An autonomous (sensor-based) system would make as many decisions as possible without involving the supervising/ managing people. However, as a first step, sensor networks should be installed and models should be developed for the decision support of the maintenance personnel, which would be a big step forward compared to today's available systems.

An overview, outlining most of the key factors of a smart structural (health) monitoring system is presented below, [40]:

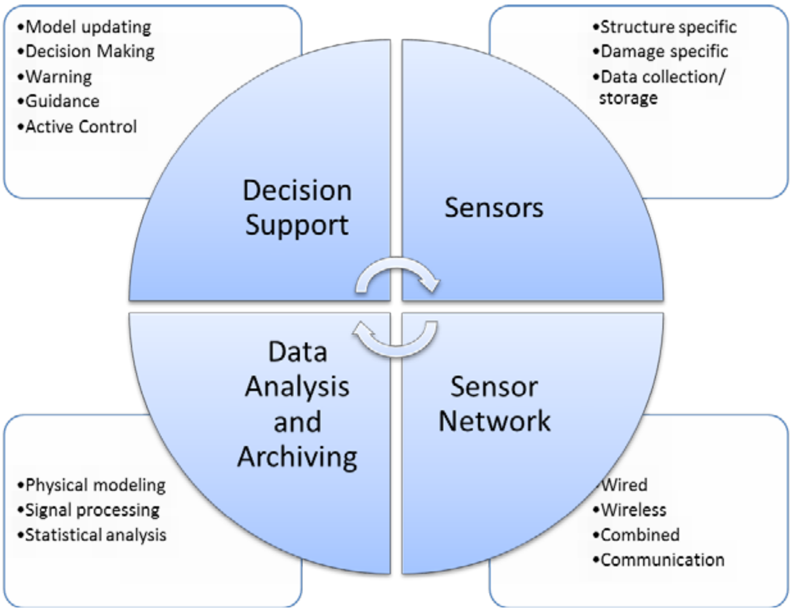

Figure 8-1: Smart Structural Monitoring System, redrawn from [40], outlined as a cyclical process of data flow and decision making as relevant for a wind turbine power plant.

The term "Decision Support System" is often used for modern smart, integrated (complex) systems where the user interface and user needs are in focus, e.g. for the systems developed for Integrated Operations of Offshore installations in Norway (IO). The components of such a decision support system [ref. above] include solutions to monitor the sensors and the sensor communications system. The decision support system should serve as the communications environment between the manager (decision maker) and the system, and as the information delivery environment for periodic queries or during major events. The strategic research agenda (SRA) of Ærto's OMO project [41] describes a roadmap of operation and maintenance strategies for offshore wind parks towards the year 2030. Among other things predictive health monitoring, load and condition monitoring, sensor technologies and wireless communication are mentioned as important research fields of the future on the area.

The two main points in [40] may be summarized as: 1) Wireless monitoring systems are an inevitable part of the future and 2) The Key to a successful system is providing information and decision support, not just data.

8.1 Input to "Data Based Decision Support Tools in Maintenance Management"

Condition monitoring based maintenance strategies for wind power plants is a current topic of application oriented research both with respect to more theoretical, statistics based models [7, 8], as well as a more practical approach combining statistics with empirical data from expert questionnaires [9].

Work on aspects of Operation and Management (O&M) in Nowitech includes a goal to develop a useful decision support tool/model that covers the whole life-cycle of an offshore wind farm, and in particular an approach to get a comprehensive cost-benefit model. A "smart structural health monitoring system" should be included as a feature in such model.

8.2 Input to Maintenance Training of Technical Personnel

The availability of simulation tools based on validated models (need sensor data) would be most valuable for training at all levels. A training feature should thus also be included in the decision support system for O&M. The need for hands-on training *vs* cost reduction of such training drove the development of "flight simulation" in the aviation industry, where it is an established and mandatory training tool. A flight simulator for OWT's could be very useful for both "pilots" and "mechanics" of the OWT Plants also, i.e. the managers, control and maintenance personnel.

9 Conclusion

This report gives an overview over different possibilities for using "new" types of sensors for structural health monitoring (SHM) and condition monitoring (CM) of wind power plants. The sensors presented should be further evaluated in a comprehensive cost-benefit analysis in the design phase of a wind turbine plant (WTP). The main motivation for this work is that the maintenance and periodic inspection effort of offshore wind power plants must be reduced due to very high costs to get personnel and equipment for maintenance on the offshore sites. This cost is directly coupled to the economical break-even point of offshore wind projects. Another motivation for new, reliable sensor types is the possibility to get information about the structural behaviour under operation of the power plants which may be used as input to upgraded structures and next generation wind power plants. This is especially important for the gigantic composite material based blades of the wind power plants due to the fact that fatigue etc. of these materials/structures is not, yet, well understood. More sensors would also enable improved operational control strategies, in which the structural state (i.e. fatigue damage level) is used to set the peak power generation allowed before the blades are pitched to reduce loads.

The main sensor technologies that are discussed in the report are optical fiber Bragg gratings (FBG) sensors and micro electro mechanical system (MEMS) sensors. Both sensor types have the advantage that they can be used in matrix configurations using a certain number of sensors to monitor structural elements and measure different parameters. FBG sensors might be directly embedded into the fiber glass matrix of the composite materials. MEMS sensors can be attached on the surface or be embedded in the structure and can be connected wirelessly with each other and/or a base station on the structure to form wireless sensor networks (WSN). MEMS sensors possess the advantage that they are less bulky than traditional sensors and that they require less energy, i.e. that they can operate longer without maintenance (e.g. changing batteries). However, for both FBG's and MEMS the installation method and materials used for integration will be critical for reliable long term operation- and we have presented discussions on possible solutions and limitations. Also, the data they generate must provide real decision support.

The basis of all measurement effort is that the critical points and parameters can be identified and that it is possible to mount sensors at these locations, and if a direct measurement parameter is difficult to attain, well-determined, correlated secondary parameters must be used. Two wind power operators have been interviewed and some critical points could be identified. However, until now there doesn't seem to be enough knowledge to point out obvious parameters and possibilities for SHM and CM, even though the interviewed persons see a great potential in this field. Nevertheless, known failure modes of composite rotor blades and monitoring possibilities of these failure modes have been described in some detail in the report. On the specifications for a (sensor-based) condition monitoring system we support the two main points being:

- **Wireless monitoring systems are an inevitable part of the future**
- **The Key to a successful system is providing information and decision support, not just data**

As a logical next step the possibilities for the using "new" sensor types for structural health monitoring should be further investigated by including such sensors in test structures (for e.g. blades) and test power plants (e.g. power converters) which are equipped with either FBG sensors or MEMS-based (wireless) sensors or both. A combination of two or more sensor types is preferred for various reasons, including self-test capabilities, reliability and redundancy.

At the present, there is still a lack of reliable data about the eigenmodes, frequencies and typical amplitudes of tower and rotor. The statistics for failure modes of these components is also scarce. Still, we would like to make some suggestions to how future wind power plants should be instrumented to allow structural health monitoring at the right level of complexity:

1. The rotating machinery, should be equipped with accelerometers and temperature sensors to monitor vibration levels and patterns as well as possible overheating
2. The rotor (and possibly also the tower) should be equipped to monitor the stress levels of the full rotor blade (and possibly tower). To achieve this one has to monitor the major modes of the structure this will involve something in the range of 10 – 100 sensors per structure.

At this level of instrumentation, one will be able to detect cracks and wear only after it has started to affect the overall behavior of the structure, but still early enough to allow corrective maintenance. Furthermore, such a system will give enough information about the actual loads occurring locally on the structure to allow for statistical prediction of remaining lifetime and scheduling of preventive maintenance. Finally, the system will give more detailed information to the control system.
For the instrumentation of blades (and possibly tower) we believe that the best solution is to use fiber Bragg gratings integrated in the composite structure. The output of such a system will be the strain levels in the structure which are directly linked to the stress experienced in the structure. Provided that the technical issues of fiber integration are solved in a reliable and cost effective way this will be an extremely robust system. Such a system can only be developed in close collaboration with a blade manufacturer.
If the problem of fiber integration cannot be solved in a satisfactory way, we believe that a very good alternative solution is to equip the structures with a wireless network of acceleration sensors. These sensors are small, cheap and easy to retrofit to virtually any structure. The drawback is that a fair amount of data processing is required to get the actual stress levels in the structure.

10 Outlook

We argue that sensors and sensor networks should be further evaluated, and that such efforts should be done in cooperation with other relevant efforts including materials testing and research, design and modelling and systems integration.

Limited evaluation tests could be performed inside Nowitech on e.g. rotor blade material (in the lab) or for data collection on specific turbine components (in the field). More involved tests and evaluations would have to be a part of a more complete project outside Nowitech.

10.1 Possible project beyond NOWITECH

In a larger project, preliminary tests could be extended to other (sub)-structures and integrated in a data fusion system with the data from other already available sensors in an integrated "smart system for decision support" to optimise operations and maintenance of OWT's. All this should be done in cooperation with the component/power plant manufacturers and operators.

Such a project should have several aims:

1. Check of viability of the proposed sensors for measurement of the right parameters.
2. Check of the viability of several wireless communication networks and protocols for offshore power plants.
3. Implementation of a SHM/CM system based on the available sensor data.
4. "Teaching" of the system in a pilot power plant (onshore)
5. Check of viability of the system in a few offshore power plants (perhaps on different sites)

A possible project would likely have to be considered for one or more of the following funding instruments with relevant calls for proposals:

- EU FP7: NMP call for Smart Energy harvesting materials (i.e. for distributed wireless sensor networks)
- NRC/RENERGIX: A possible complementary or competitive project to "WindSense"
- EERA or ERA-Net: Cooperative research, needs additional national or European level financing.

11 List of Abbreviations

ADC: Analog – Digital Converter
AE: Acoustic Emission
CM: Condition Monitoring
CPU: Central Processing Unit
CVM: Comparative Vacuum Monitoring
DSP: Digital Signal Processor
FBG: (Optical) Fiber Bragg Grating
FEM: Finite Element Method
HW: HardWare
MEMS: Micro Electro Mechanical System
NDT/E: Non Destructive Testing/Evaluation
O&M: Operation & Maintenance (Management)
OWT: Off-shore Wind Turbine
OWTP: Off-shore Wind Turbine Park/Plant
RFID: Radio Frequency Identification Device
SHM: Structural Health Monitoring
SW: SoftWare
WSN: Wireless Sensor Network
WT: Wind Turbine
WTP: Wind Turbine Park/Plant

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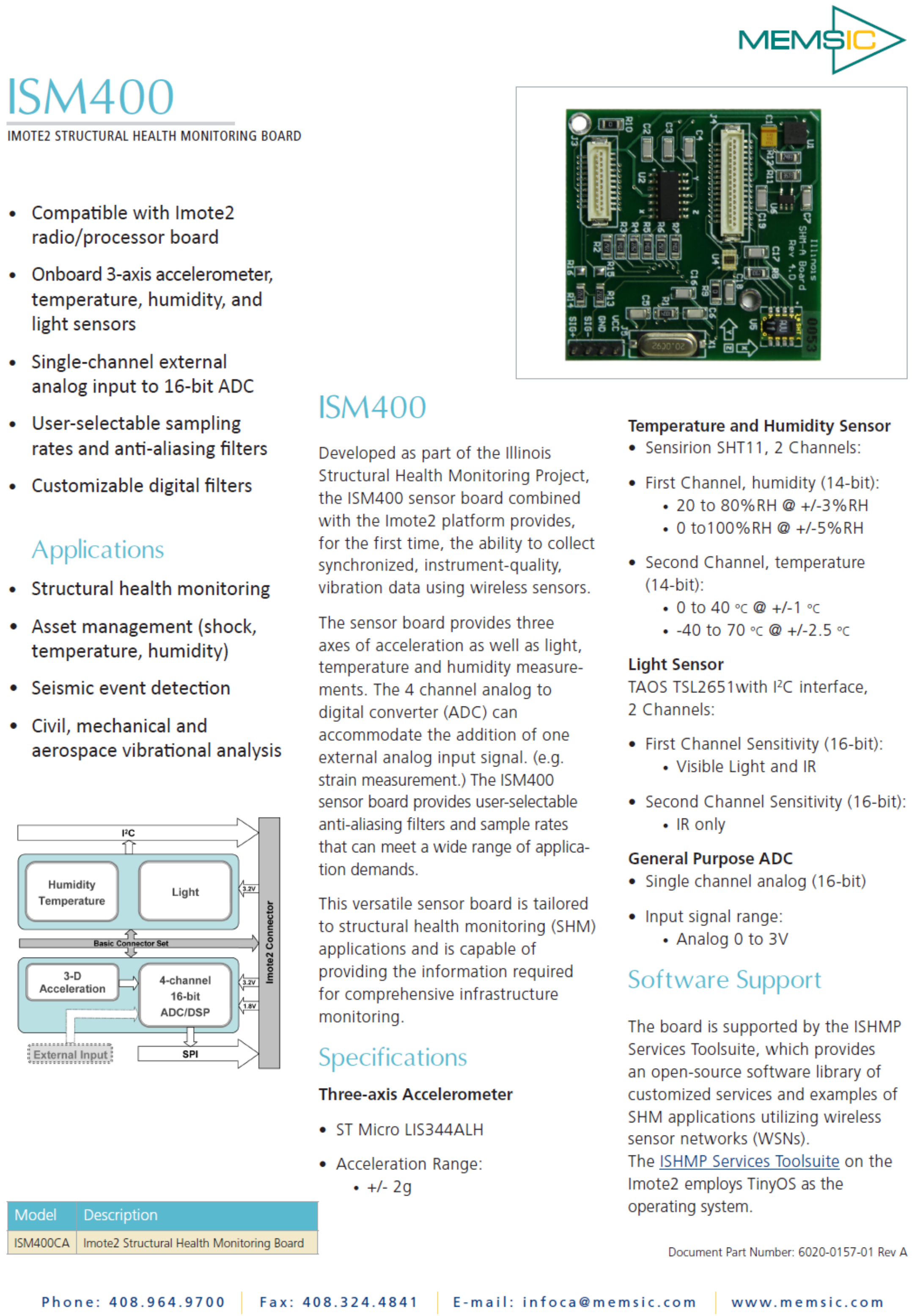
A Appendix

Table 3 below gives an overview of motes (smart nodes) from both research groups and commercial companies.
As an example of a commercially available (MEMS-based) sensor node for SHM is the ISM400 sensor board, from MEMSIC Inc., which offers a compact, power efficient solution due to its integration of vibration, temperature, humidity and light detection functionality into one platform. The key component of the ISM400 board is the Quickfilter QF4A512, a versatile 4-channel ADC and programmable signal conditioner with user-selectable sampling rates and programmable digital filters. The board interfaces with the Imote2 via SPI and I2C I/O and has a three-axis analog accelerometer for vibration measurement, one general analog input, as well as digital temperature, humidity and light sensors.

Table 3: Summary of commercial wireless sensing unit prototypes [39].

	UC Berkeley-Crossbow WeC (1999)	UC Berkeley-Crossbow Rene (2000)	UC Berkeley-Crossbow MICA (2002)	UC Berkeley-Crossbow MICA2 (2003)	Intel iMote, Kling (2003)	Microstrain, Galbreath et al. (2003)	Rockwell, Agre et al. (1999)
DATA ACQUISITION SPECIFICATIONS							
A/D Channels	8	8	8	8		8	4
Sample Rate	1 kHz	1 kHz	1 kHz	1 kHz		1.7 kHz (one channel)	400 Hz
A/D Resolution	10-bit	10-bit	10-bit	10-bit		12-bit	20-bit
Digital Inputs							
EMBEDDED COMPUTING SPECIFICATIONS							
Processor	Atmel AT90LS8535	Atmel Atmega163L	Atmel ATmega103L	Atmel ATmega128L	Zeevo ARM7TDMI	MicroChip PIC16F877	Intel StrongARM 1100
Bus Size	8-bit	8-bit	8-bit	8-bit	32-bit	8-bit	32-bit
Clock Speed	4 MHz	4 MHz	4 MHz	7.383 MHz	12 MHz		133 MHz
Program Memory	8 kB	16 kB	128 kB	128 kB	64 kB		1 MB
Data Memory	32 kB	32 kB	512 kB	512 kB	512 kB	2 MB	128 kB
WIRELESS CHANNEL SPECIFICATIONS							
Radio	TR1000	TR1000	TR1000	Chipcon CC1000	Wireless BT Zeevo	RF Monolithics DR-3000-1	Conexant RDSSS9M
Frequency Band	868 / 916 MHz	868 / 916 MHz	868 / 916 MHz	315, 433, or 868 / 916MHz	2.4 GHz	916.5 MHz	916 MHz
Wireless Standard					IEEE 802.15.1		
Spread Spectrum	No	No	No	Yes (Software)	Yes		Yes
Outdoor Range							
Enclosed Range							100 m
Data Rate	10 kbps	10 kbps	40 kbps	38.4 kbps	600 kbps	75 kbps	100 kbps
FINAL ASSEMBLED UNIT ATTRIBUTES							
Dimensions	2.5 x 2.5 x 1.3 cm						7.3 x 7.3 x 8.9 cm
Power	575 mAh	2850 mAh	2850 mAh	1000 mAh			
Power Source	Coin Cell	Battery (3V)	Battery (3V)	Coin Cell	Battery	Battery (3.6V)	Battery (two 9V)



MEMSIC

ISM400

IMOTE2 STRUCTURAL HEALTH MONITORING BOARD

- Compatible with Imote2 radio/processor board
- Onboard 3-axis accelerometer, temperature, humidity, and light sensors
- Single-channel external analog input to 16-bit ADC
- User-selectable sampling rates and anti-aliasing filters
- Customizable digital filters

Applications

- Structural health monitoring
- Asset management (shock, temperature, humidity)
- Seismic event detection
- Civil, mechanical and aerospace vibrational analysis

Model	Description
ISM400CA	Imote2 Structural Health Monitoring Board

ISM400

Developed as part of the Illinois Structural Health Monitoring Project, the ISM400 sensor board combined with the Imote2 platform provides, for the first time, the ability to collect synchronized, instrument-quality, vibration data using wireless sensors.

The sensor board provides three axes of acceleration as well as light, temperature and humidity measurements. The 4 channel analog to digital converter (ADC) can accommodate the addition of one external analog input signal. (e.g. strain measurement.) The ISM400 sensor board provides user-selectable anti-aliasing filters and sample rates that can meet a wide range of application demands.

This versatile sensor board is tailored to structural health monitoring (SHM) applications and is capable of providing the information required for comprehensive infrastructure monitoring.

Specifications

Three-axis Accelerometer

- ST Micro LIS344ALH
- Acceleration Range:
  - +/- 2g

Temperature and Humidity Sensor

- Sensirion SHT11, 2 Channels:
- First Channel, humidity (14-bit):
  - 20 to 80%RH @ +/-3%RH
  - 0 to100%RH @ +/-5%RH
- Second Channel, temperature (14-bit):
  - 0 to 40 °C @ +/-1 °C
  - -40 to 70 °C @ +/-2.5 °C

Light Sensor

TAOS TSL2651with I²C interface, 2 Channels:

- First Channel Sensitivity (16-bit):
  - Visible Light and IR
- Second Channel Sensitivity (16-bit):
  - IR only

General Purpose ADC

- Single channel analog (16-bit)
- Input signal range:
  - Analog 0 to 3V

Software Support

The board is supported by the ISHMP Services Toolsuite, which provides an open-source software library of customized services and examples of SHM applications utilizing wireless sensor networks (WSNs).
The ISHMP Services Toolsuite on the Imote2 employs TinyOS as the operating system.

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Figure 11-1: ISM400 data sheet.

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