Upwind Work Package 1B3, deliverable 4:

"Inventory of control concepts"

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Inventory of control concepts

The main part of the Smart Rotor research is dedicated to the development of actuators that function in an aerodynamic and structural feasible way. However, in order to obtain feedback control also sensors and control algorithms are needed. In this task we will focus on the issues concerning the sensors. Issues are:

- what signal to measure?
- durability of the sensor. This topic comprises of issues like:
    - fatigue resistance
    - sensitivity to lightning strike
- powering of the sensor
- how to transmit the signal to the controller?

1. Control strategies and sensor signals

The goal of the control system is to provide the aerodynamic control device with such a signal that the fluctuations in the blades loading are mitigated. The fluctuation in loading lead to vibrations that can be detected as accelerations, displacements and strains along the blade. The aerodynamics are not only the means by which we want to control the blade's vibrations but also the main source of the disturbances because of fluctuations in the inflow; turbulence. Therefore, there are basically two types of control strategies:

1. Feed forward control by measuring the incoming flow (See the bottom part of Figure 1) or by mitigating known disturbances like tower shadow and wind shear.
2. Feedback control by measuring the response (pressure distribution, acceleration, displacement or strains. See the top figure of Figure 1.

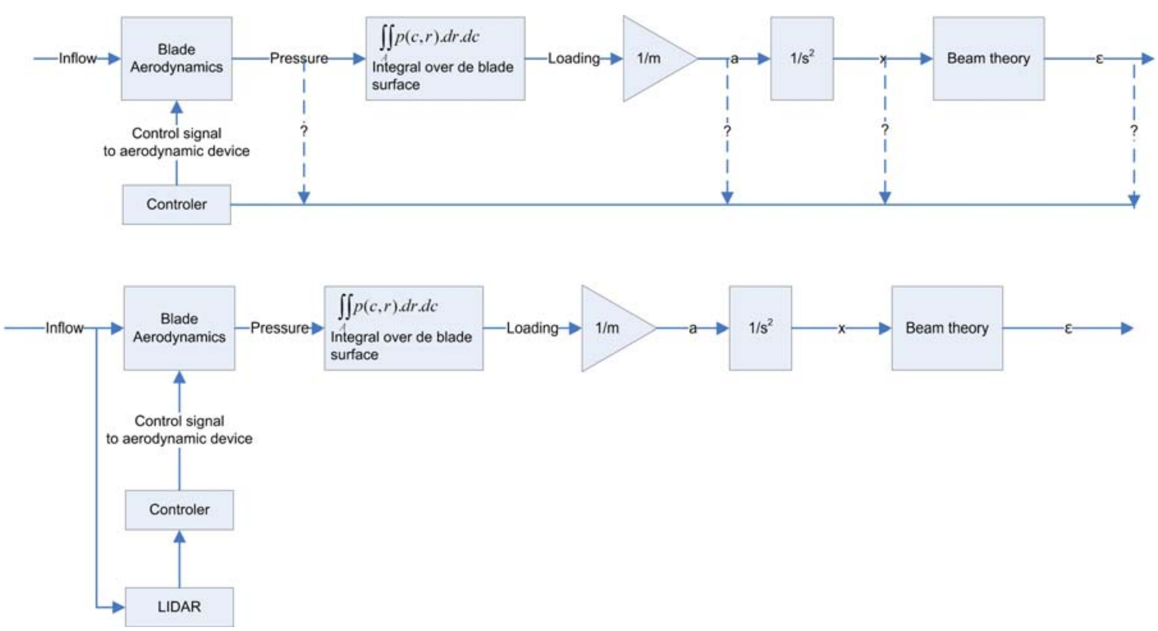

Figure 1: Control strategies based on feedback control (top) and measuring the inflow (bottom). m, a, x, and ε are the mass, acceleration, displacement and strains respectively.

Feed forward control based on known disturbances is discarded because only predictable changes in the aerodynamics like wind shear and tower shadow can be mitigated. Measuring the inflow is discarded because the technology required for this control strategy is not robust enough. LIDAR, the technique mentioned in Figure 1, requires enough aerosols in the inflow, but doesn't work in fog, rain or snow. So we will focus on feedback control. As can be seen in the top part of Figure 1, many types of signals can be used and for each signal different measurement techniques exist. Pressure can be measured with Pitot tubes, but these get blocked to easily. For measuring the (tip)displacement in a blade, a laser or a advanced position tracking system could be employed, but since the goal is to mitigate the fluctuations in loads (and thus stresses and strains), there will be a focus on the different means of measuring strains.

Sensors will require some specific characteristics that are proposed next:

- Lightweight: multiplexing capability
- Immunity to electromagnetic waves
- Minimum sensitivity to temperature
- Ease of integration in the structure: manufacturing facilities
- Robustness on a long term
- Minimum calibration requirements
- Precision of measurements. Adequate range and time response.
- Long term stability of measurements
- Reliable operation in harsh environment

2. Analysis of different types of sensors used in wind turbine blades

ELECTRICAL-TYPE STRAIN GAUGES

The majority of strain gauges are foil types. They consist of a pattern of resistive foil which is mounted on a backing material. They operate on the principle that as the foil is subjected to stress, the resistance of the foil changes in a defined way.

The strain gauge is connected into a Wheatstone Bridge circuit with a combination of four active gauges (full bridge) or two gauges (half bridge) or a single gauge (quarter bridge). In the half and quarter circuits, the bridge is completed with precision resistors.

The complete Wheatstone Bridge is excited with a stabilised DC supply and with additional conditioning electronics, can be zeroed at the null point of measurement. As stress is applied to the bonded strain gauge, a resistive changes takes place and unbalances the Wheatstone Bridge. This results in a signal output, related to the stress value. As the signal value is small, (typically a few millivolts) the signal conditioning electronics provides amplification to increase the signal level.

Typical strain gauge resistances range from 30 Ohms to 3 kOhms (unstressed). This resistance may change only a fraction of a percent for the full force range of the gauge, given the limitations imposed by the elastic limits of the gauge material. Thus, in order to use the gauge as a practical instrument, we must measure extremely small changes in resistance with high accuracy. Forces great enough to induce greater resistance changes would permanently deform the gauge conductors themselves, thus ruining the gauge as a measurement device.

Strain gauges provide one- or two-dimensional strain information. These sensors are sensitive to temperature fluctuations, and a compensating system is consequently required. Generally their main drawback is that their mounting process must be done with high care to assure long life time and high accuracy. Also, these sensors require accurate calibration, and sometimes recalibration during their operating life because of changes in their properties. None of these types of sensors can assure the number of stress cycles in the lifetime of a wind turbine. They are not robust enough on a long term.

The characteristics of these sensors in measurement range and time response seem to be appropriate to their use in rotor control. These types of sensors have been used traditionally to sense blades in order to obtain the strain in different parts of it, especially in the root. With these measurements, aerodynamic loads in the blade can be calculated. Strain gauges are mainly used in laboratory tests or in wind turbine prototypes, but not in serial production [1, 2, 3].

ACCELEROMETERS

An accelerometer is a device that measures the vibration, or acceleration of motion of a structure. The force caused by vibration or a change in motion (acceleration) causes the mass to squeeze the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration.

Accelerometers consist of two transducers. The primary transducer sense acceleration and responds to it by a displacement. This displacement is sensed by the secondary transducer which gives an electric signal as response. There are two types of primary transducers which are spring retained seismic mass and double cantilever beam. The secondary transducer can be of different types: Piezoelectric, Potentiometric, Reluctive, Servo, Strain gauge (Piezoresistive), Capacitive and Vibrating element.

Firstly, piezoelectric accelerometers are considered not suitable for rotor control because their lower frequency (typically 1Hz) is too high to measure the blade vibrations occurring at frequencies lower than 1Hz. That’s why passive accelerometers, which are able to measure accelerations down to zero frequency, have to be chosen. The differences between these types of sensors are their frequency range, their cost, and their frequency response. Costs are not very high. Indeed the widespread use of accelerometers in the automotive industry has pushed their cost down dramatically.

Important characteristics of accelerometers include dynamic range of acceleration, frequency response, transverse sensitivity (sensitivity to motion in a non-active direction), mounting errors, temperature and acoustic noise sensitivity and mass.

It is possible to sense vibrations in two or three orthogonal dimensions instead of just one. This is done by using two or three-axis accelerometer sensors along with appropriate processing circuitry [4].

In wind turbine applications, accelerometers are mainly used in maintenance for vibration analysis: bearing, generator and gearbox monitoring but they are not very extended in blade sensing.

ACOUSTIC EMISSION MONITORING

The phenomenon of Acoustic Emission (AE) occurs due to stress waves generated when a material suffers a small displacement of its surface. Materials subjected to stress or strain emit sounds waves as a result of a sudden very small structural changes. It is a non-destructive technique.

Acoustic sensors are attached to the material in order to detect these waves. They listen to the component. The most common variety of transducers for AE monitoring are piezoelectric sensors that convert the accelerations at the surface into an electrical signal:

Broadband piezoelectric transducers: respond to all frequencies of the stress wave
Resonant piezoelectric transducers: for detecting stress wave emission in large structures, these sensors are more common as they can detect events much further away

Stress wave propagation in polymer composites depends on the frequency. The high frequencies are attenuated more quickly than the lower ones which travel much further. However the range of low frequencies is dominated by “noise” sources. A sensor resonant at 150kHz is a good compromise between sensor spacing (2m) and noise rejection. A sensor resonant at 60kHz will allow a much wider spacing but will respond strongly to unwanted “noise” signals. A sensor resonant at 300kHz might never respond to “noise” signals but will respond only to AE from failures that occur a matter centimetres from the sensor location [5].

The piezoelectric sensors can be susceptible to electrical interference and are relatively voluminous. Another option for AE transducers is the use of fibre optic sensors. They don’t have these problems, but results from tests which have been carried out aren’t very promising.

Wind turbine blades made of composites have sudden audible AEs during damage growth. So, it makes them suitable to be monitored with AE equipment. The principal application in this field is damage detection and location. AE monitoring has been used mainly in static testing, proof testing, fatigue testing and certification tests more than for loading measurements. Several examples of these functionalities are available [5, 6, 7].

Using an array of sensors is possible to determine at what location the blade starts to fail. This information can be used to improve blade design and manufacturing. The problem is that to detect and locate damages in a big structure, a high number of sensors are needed and signal processing is complicated.

Specific software is needed to detect different kind of damages like fatigue crack, or fiber breakage in a composite material among material failure processes.

FIBRE OPTIC: BRAGG GRATINGS

There are different technologies of fibre optic to measure strain. The type of fibre optic sensor which tends to dominate is the fibre Bragg gratings sensor. Bragg gratings are made by illuminating the core of a suitable optical fibre with a spatially varying pattern of intense UV laser light. This modified fibre serves as a selective mirror: light travelling down the fibre is partially reflected at each of the tiny index variations, but these reflections interfere destructively at most wavelengths and the light continues to propagate down the fibre uninterrupted. However, at one particular narrow range of wavelength, constructive interference occurs and light is returned down the fibre. Maximum reflectivity occurs at the so-called Bragg wavelength (λ_B) given by:

$$\lambda_B = 2n_{eff}\,\Lambda$$

where n_{eff} is the effective refractive index and Λ is FBG period [8].

When the composite changes its strain, n_{eff} and Λ parameters are altered. When there is a variation in the temperature, n_{eff} also changes.

We can deduce that a change in the reflected wavelength is due to a change in the fibre deformation and /or a change in the temperature. So Fibre Bragg Gratings are sensors capable of measure deformation and temperature.

Certain characteristics are deduced from the behaviour of the FBG:

The information is transmitted in variations of the wavelength of the reflected wave. The advantage over systems based on changes of intensity is that the precision is not affected by losses in the system [9], nor by variations in the intensity source.
The fibre has the same size and the same resistance as the original fibre. The fibre can be embedded in the material structure without altering its integrity. In addition it is flexible, lasting and has small size.
An important advantage is the possibility of multiplexing several sensors in a same fibre. So, optical elements can be shared and then the price per sensor is more competitive. In addition, the weight of the wiring is reduced and the connectivity is simplified.
The double sensitivity to temperature and strain is the main drawback to be solved before the generalized use of these sensors [10]. Several techniques have been proposed to solve this problem. Most of the solutions use a double FBG, one of them isolated from deformations (joined to a rigid element). With both measurement, an analysis must compensate for possible temperature fluctuation during strain measurements. Also, these sensors require accurate calibration.

From a sensing point of view, the merits of the optical fibre technology are numerous:

- Very light
- Small in diameter
- Resistant to corrosion and fatigue
- Capable of wide bandwidth operation
- Immune to electrical interference

- Mechanically flexible, diverse geometry possible
- No protection required against lightning
- Extreme sensitivity
- Do not generate heat or electromagnetic interference
- Low attenuation of signals
- Possibility for detecting health status of the structure

3. Smart Structures

Inventory of sensors

Analysis of sensors used in wind turbine blades described above and piezoelectric materials used as sensors are taking into account. Lightweight construction and flexibility as sensors and actuators in a large variety of applications makes these piezoelectric materials feasible for aerodynamic control in wind turbines.

Investigation and collection of information to obtain the best choice of sensors and the way to integrate these elements into the smart blade. This task is under way.

Feasibility of the use of wireless transmission with the selected sensors and auto-feeding capabilities.

There is a need of a wireless sensor system specifically designed for blade monitoring. The location of the wind turbine rotor restricts the possibilities of a wireless design. The following necessities are required for this kind of sensor systems:
Power supply: two alternatives are suitable to power a wireless system in the blade of a wind turbine: auto-feeding or battery. Any alternative imposes the characteristic of a VERY LOW CONSUMPTION for the whole system.
Distance between sensors: the rotor diameter in the multimegawatt machines is expected to be around 125m.
Continuous monitoring: it is important to have monitoring information in a continuous way to be able to detect fatigues and material degradations constantly

Taking into account the necessities and restrictions above mentioned concerning a blade monitoring, the only reasonable solution is ZigBee standard. This solution allows simple, low-cost wireless networks. This standard is typically used for monitoring and control purposes and require low power, which means they can run a log time on inexpensive batteries.

ZigBee solution is based on IEEE 802.15.4 standard. It operates in the ISM (Industrial, Scientific and Medical) radio band with worldwide coverage for 2,4GHz frequency band. The Zigbee standard is an emergent technology, but in this moment different products are available in the market. Sensor system architecture. The block diagram for a ZigBee sensor application is represented:

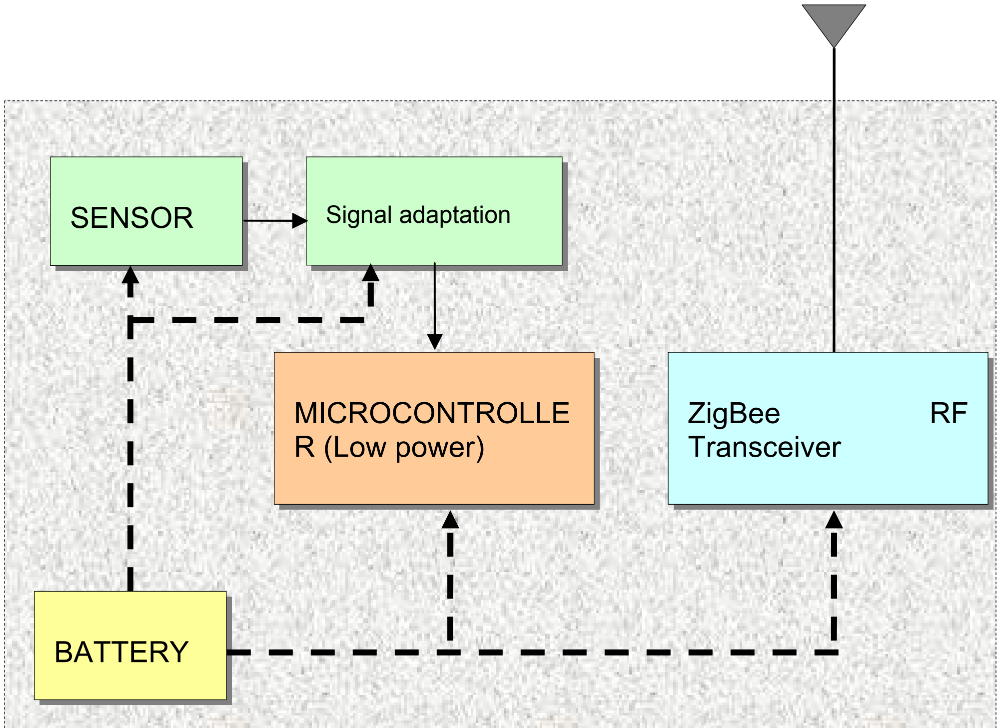

Figure 2: block diagram for a ZigBee sensor application

<u>Sensor</u>

Different electrical sensors can be embedded in the system.

One option is using strain gauges to get strain measurement related to the joint. The system will have relevant information about the status of the union.

Another option is using a 3-axis accelerometer with low power consumption to detect flapwise, edgewise and spanwise acceleration.

In both cases, it is important to take into consideration that it is necessary to switch off the power supply of the sensor while the rest of the system (microcontroller and ZigBee RF transceiver) is in stand-by mode. It is possible to do it using digital switches controlled by microcontroller device.

<u>Signal adaptation</u>

A simple adaptation is required to prepare the signal from the sensor to the AD converter embedded in microcontroller.

Microcontroller

A microcontroller is needed to convert the signal coming from the sensor to digital format. So an embedded ADC is required.

In addition to this conversion, the microcontroller is in charge of all data processing required for the application:

- Software adaptation for the sensor conversion.
- Basic algorithms applied to sensor information to detect problems in the joint.
- Communication processing: basic protocol to prepare resulting information to be sent to the hub processor.

In this part lies the intelligence of the system.

The main characteristic of the microcontroller is that it has to be *Low Power Consumption*. There are special devices with low power property, but they are not very complex and not very fast. So the idea of developing complicated algorithms in this microcontroller in real time must be removed.

ZigBee RF transceiver

This is the part in charge of wireless communication, transmission and reception. It has to be compliant with ZigBee and IEEE 802.15.4 standards.

An antenna has to be connected to this part in order to reach specified communication distances. Depending of its size, different distances could be reached.

There are products in the market that integrate both microcontroller and transceiver.

Battery

A typical 3V commercial battery can be used. We can think of a capacity of 1500mAh to do some approximation about life time.

The limitations of a system based on ZigBee standard are:

Low amount of data and low duty cycle of the sensor: in order to have a low power consumption, the system has to work in a “standby mode” more than 99,9% of the time, while it is doing its proper functions (measurement, processing, transmission) in the left time. It is an extremely low duty cycle (<0,1%). In addition to it, the maximum bandwidth for the ZigBee standard is 250kbs.
Location of the sensors: although theoretical transmission length could reach 100m, this can be done in ideal conditions, with the antenna of the system outdoor, always in front of the other antenna. Assuming that the location of the system (electronic and antenna) will be inside the blade, transmission length will be reduced notably.

Wireless communications behave in a very different way depending on the blade material. Carbon fibre presents some problems of resonance because of the conductive characteristic of this material. The feasibility of wireless communications in this kind of blades is not guaranteed. Glass fibre doesn't present any problem.

Different solutions to power the different blade embedded sensor are the following:

Radiofrequency power transmission: electrical power can be transmitted through free space using electromagnetic waves. The electric-electromagnetic conversion efficiency usually is quite high around 90%. The main causes of power losses in a electromagnetic link are due to the presence of metallic or dielectric obstacles that can reflect or absorb the electromagnetic energy. As an example, a system that has a unidirectional antenna fixed to wind power tower located in the blade rotating axis will be considered. The distance between this system and any receiver located in the blades does not depend on the blade position. As the sensors are embedded inside the blade mechanical structure, they introduce additional power losses, specially for carbon fibre blades.

Vibration energy harvesting is based on a simple idea: the conversion of the mechanical vibration of machinery into an electrical signal. This is a very powerful idea because almost any motor, generator or moving industrial equipment produces a significant vibration, so this kind of power generator devices can be used in the industry. Then the main challenge to use this technology in wind power generator blade resides in characterization of its vibration frequency range and acceleration, that will be mainly dependent on rotational speed and wind conditions.

Solar power modules: new photovoltaic modules are quite strong and flexible to be adapted to any surface shape, including the wind power blades. Those modules have been widely used in architectural solutions proving their robustness.

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