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"Requirements for Smart rotors"

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Requirements for Smart Rotor Technology

Based on the Upwind 5MW reference wind turbine

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Abstract

This report summarizes the technical requirements imposed for all components, needed to achieve a functional and "smart rotor" version of the Upwind 5MW reference wind turbine. All requirements have been derived from simulations on the 5MW wind turbine or research on specific components. The study mainly refers to modified blades incorporating spanwise distributed aerodynamic control surfaces with local sensor inputs and dedicated controllers. No options like structurally tailored blades or hub-blade connections are considered. The operation of boundary layer control options can be treated as normal aerodynamic control surfaces. All important aspects are summarized: aerodynamic design, structural design, actuator design and sensors/controllers requirements.

1) Aerodynamics – aerodynamic control surfaces

From aeroelastic simulations it can be appreciated that the demand for control surfaces is stated as follows: The bigger the better. Larger control surfaces (chordwise and spanwise length) provide larger control authority, translated in the end as increased load reduction capabilities. Although the need for increased ΔCl is straight forward, the aerodynamic section design requirements can be more complicated.

- **Type of control surface – lift control capability**

The type of aerodynamic control surface has an impact on the load reduction performance. Previous studies have shown (see Troldborg 2005) that a flexible flap with a strong curvature is more effective in controlling aerodynamic loads that softly curved or a rigid one, especially at larger flap chordwise lengths (The "flap effectiveness" parameter $\Delta Cl/\Delta\delta$ / $\Delta Cl/\Delta\alpha$ is good for comparison). Further sensitivity studies have

shown that a small flap length (5% chord) strongly curved flap with flap deflections +-10deg. is capable of controlling most of the expected wind variations. If the slightly increased hinge moment is not so important design issue, a 10% chord flap with deflections +-5 degrees is more appropriate because of the increased ΔCl capability and the reduced drag penalty. These results hold for a given airfoil (Risø-B1-18). Concerning the airfoil for tip section the Upwind 5MW Reference Wind Turbine (NACA-64618) the same analysis and optimization should be conducted. (Univ. Stuttgart). Some results have already been presented, showing that the associated drag penalty with flap deflection or cambering is not considerable, but his was for a 20% chord flap.
Furthermore, the required flap deflection has to be defined by what range of disturbances need to be controlled. The +-10 degrees derived previously, referred to a 60m diameter rotor. A detailed investigation of the expected disturbances (so angles of attack) in the reference turbine has been performed, together with an analysis of what part of disturbances is important to control in terms of fatigue. This will determine the required flap angles and required control bandwidth. The analysis was performed by DUWIND (see Barlas 2008) and concluded that the in representative normal load cases the angle of attack ranges from -5.8 to 7.9 degrees at the tip sections. This is associated with a certain ΔCl that can be alleviated with 10%c (rigid) flap angles ranging from -12 to +12 degrees. A 5%c flap needs more than -15 to +15 degrees deflection angles for full control authority. So, a 10%c flap seems a promising solution. Only if the associated drag penalty is considered high, the smaller flap should be chosen, which will unfortunately reduce the load control capability. Regarding extreme load cases (extreme operating gusts and extreme direction change) the required 10%c flap angle is -15 to +15 degrees. Although the investigated changes in angle of attack are considered quite high for the tip section (comment by Risø), the highest limits have been taken including yaw misalignment cases, in order to cover all possible operating conditions.

- **Drag penalty**

In general, the drag penalty with the control surface deflection should be as low as possible. An optimization has to be made on the required ΔCl and the associated ΔCd as explained earlier. The resultant Cl/Cd ratio affects power performance as it will be discussed below.

- **Pitching moment**

From aeroelastic simulations at DUWIND and Risø (see Andersen 2006), but also from simple 2d models (see Buhl, Andersen, Barlas 2008) it has been shown that the activation of the flap for load control introduces a highly increased pitching moment (Cm), in some cases in the order of 300%. This affects the torsional degree of freedom with implications on the structural design, but also affects the local angle of attack from torsional deflections. It is essential to design a flapped airfoil where flap deflections don't cause dramatic changes in Cm. (Univ. Stuttgart). Otherwise, the torsional stiffness of the blade should be increased, as it will be discussed below.

- **Airfoil design with control surface regarding power production**

The activation of the control surface for load reduction locally changes the Cl/Cd ratio according to the operating conditions. This means that deviations from optimal Cl/Cd ratio will occur that depending on the airfoil design can be larger than the ones for the baseline (no flap control) case. This has been shown by aeroelastic simulations of DUWIND and Risø where reductions in power in the order of 0.5-1% have been observed with active control of flaps for load reduction (see Andersen et al. 2008 and Lackner 2008). So a large ratio of L/D around the design Cl should be established by incorporating that as a requirement in the airfoil design (Univ. Stuttgart). Aeroelastic simulations shows that for the variable speed region a slight increase in power production can be accomplished when the controller targets optimum axial induction as opposed to direct load reductions (see Andersen et al. 2008). So, modifications for optimized power regulation can also be incorporated at the controller design instead of the airfoil design if needed.

- **Spanwise length of flaps and placement**

The general demand for flap spanwise length would be again: the larger the better. But this should be optimized again in order to reduced cost associated with installing more control device length, maintenance etc. An analysis by Risø using a 66m diameter rotor with constant rotational speed (See Andersen 2006) gives good insight. Considering one big flap placed near the tip, the additional reduction in fatigue loads is decreasing with increasing flap length, so an optimal big flap length can be established. Considering multiple flaps, additional fatigue load reduction can be achieved compared to the same spanwise length of one big flap because of damping of additional vibration mode shapes. Of course each flap should be activated by an individual signal (e.g. local acceleration) for that to happen. Further investigations concerning the Upwind 5MW Reference wind turbine should be made to establish these values for our case. (DUWIND, Risø). Different options for distributed control can be chosen depending on the available sensor signals and control hardware.

- **Importance of unsteady aerodynamic effects**

It is known from theory that the range of ΔCl of an airfoil pitching or flapping is reduced in an unsteady case, compared to the static (or very low frequency) one. This reduction can be up to 75% in very high frequencies and also phase delay effects are included in the response. At high frequencies also, this reduction is larger for the pitching case compared to the flapping case. This implies that the flap ability of changing lift decreases with increasing frequency (or better reduced frequency $k = \frac{\omega \cdot c}{2 \cdot V}$). This should be taken into account in the design of the required flap length and deflection, which is done in a static way. DUWIND has quantified the levels of unsteadiness found in the Upwind 5MW Reference Wind Turbine. It turns out that for the various investigated load cases, the motion frequency where unsteady aerodynamic phenomena start to appear varies between 0.24 and 0.89 Hz depending on the case. The motions considered include pitching, flap/edge bending and angle of attack/vertical gusts. Since the frequency range for unsteadiness is between the bandwidth of interest, unsteady aerodynamics should be considered in any analysis.

- **Noise generation**

Due to tightened noise regulations, noise reduction is one important issue for the design of next generation on-shore wind turbines. This issue has to be considered in the design of a smart rotor as well. Otherwise the promising potential of a smart rotor may not be tapped. For modern wind turbines the mechanical noise is reduced to such a level that the flow-induced noise dominates. To evaluate the importance of the aerodynamic noise for a smart rotor, the different noise portions have to be distinguished. The causes of the flow-induced noise are mainly divided into three groups: Low-frequency noise, inflow turbulence noise and airfoil self-noise. Low frequency noise originates from the changes of the wind speed experienced by the blades due to the presence of the tower and the wind shear. It is to be expected that this particular noise source can favorably be affected by means of an adequate adaptation of the rotor control surfaces. Another type of noise, denoted turbulent inflow noise, occurs when atmospheric turbulence encounters the blade surface. One member of the airfoil self-noise is turbulent boundary-layer trailing-edge interaction noise or just trailing-edge noise. According to field measurements performed within previous European research projects, this noise type is dominant at least for the terrains where the measured turbines are operated. This noise type arises due to an interaction of the turbulent pressure fluctuations underneath the boundary-layer with the blade trailing-edge and is thus determined by the state of the boundary-layer in the vicinity of the trailing edge. A flap deflection, in principle, can increase the trailing edge noise. The reason is that the deflection of the flap distorts the pressure distribution. This increases the loading of the boundary layer and can even cause flow separation. Due to the associated increase of the turbulence production, finally, the trailing edge noise increases. The aspect of trailing edge noise, therefore, has to be considered in the design of the smart rotor blade sections at least as a limiting constraint (Univ. Stuttgart).

2) Structures

The realization of smart rotor and rotor control will possible lead to the redesign of blades because the load spectrum is reduced. On the other hand, to realize a smart rotor, redesigning the layout of a blade might be necessary. In both cases there are several structural demands and considerations which should be taken into account. These are:

- **Stiffness**

To define the stiffness requirements, we can distinguish two different considerations: the global and local stiffness. The first is related to tip deflection and aeroelastic stability and the second to panel buckling and aerodynamic shape stability. As a guideline for global stiffness it could be stated that the bending stiffness EI and torsional stiffness GI should remain constant, or possibly increase with redesign. Alternatively, tip deflection and torsional displacement under a given load case could be taken as a demand. For local stiffness, in current blade design, sandwich structures are employed. Any other concept or reducing the sandwich thickness should lead to the same shape stability. From the aerodynamic requirements it has also been shown that the blade torsional stiffness will probably have to be increased to compensate for the increased pitching moment due to flap deflection. This has to be modified unless the airfoil will be modified for reduced pitching moment variations.

- **Strength**

When redesigning a blade, it could be stated that the value of the employed strength criterion (e.g. Tsai-Hill or Tsai-Wu) should remain the same. The same holds for the critical buckling load.

- **Fatigue**

A redesigned blade should allow for the same amount of fatigue cycles. This is dependent on the design and the material's (S,N)-curve. Another issue that should be taken into account is the residual strength of the material: after a number of fatigue cycle, the material should be able to withstand the same peak load.

- **Stability**

Stability (e.g. flutter) is a matter of stiffness and mass distribution. In principle, the same flutter boundary should be held: if the blade becomes lighter, it can be designed less stiff or vice versa.

- **Combination**

It should be noted that when increasing properties for one load case, the others should also be assessed. For instance, if a blade can be dimensioned smaller because of a reduction in fatigue loads, the stiffness of the redesign should be evaluated for tower clearance issues.

- **Structural lay-out or material systems**

For this, the same as above holds. Moreover, when redesigning the lay-out of the blade, the redesign should allow for the same or required aerodynamic shape. Other considerations are: the price of the materials and production method and the productibility of the design (large, MW-sized machines).

- **Risk of actuator failure.**

One other thing that should be assessed is the failure of the "smartness" of the rotor. The design should take into account some contingency. The chance that a "smart" feature outlives the blade is not big and its lifetime is hard to predict. Therefore it is important that the blade will be able to function, to some extent, without the control feature. By "functioning" it is meant that the turbine should at least be stopped without blade failure. This might sound logical, but a full stop is one of the most severe design load cases for a turbine blade. Others include gusts and tip deflection.

3) Actuators

- **Actuator delay and controllability**

The actuator should influence the flow in a smooth and predictable manner. This might not always mean linear control is possible, but at least it must be analyzed how controlling the aerodynamic loading with the device is possible.

- **Durability**

The lifetime of the actuator must be in the same order of magnitude of the rotor blade, or a self-healing or self maintaining system should be in place. Issues that limit the lifetime of the actuator are:

- Fatigue. As explained above, one of the goals of the smart rotor research is to reduce fatigue. Including a device which is very sensitive to cyclic motions and deformations is therefore not feasible, even if the device itself reduces fatigue loads in the blade.
- Lightning strike. Most actuator concepts are electrically driven. Devices that involve high voltage applications are more susceptible.
- Oxidation. MW-sized turbines are increasingly placed off shore, which makes oxidation of (new) parts an important issue.
- Degradation or change of actuator performance in time. Both SMA and piezo electric materials are known to show a change in performance over time. This must be taken into account.

- **Required bandwidth**

The required bandwidth for actuators is derived from frequencies of disturbances in the blades (spectrum of angles of attack) and blade motions. Also a compromise has to be made in up to what frequencies is important to control, regarding fatigue reduction. This analysis has been performed by DUWIND (Barlas 2008) for relevant operating conditions. The required bandwidth of interest varies from 0 to 6Hz. Very low frequencies should be considered, since contain large amplitudes of oscillations. High frequencies are also very important as it has been shown, because they contribute to fatigue loads as much as low frequencies.
The bandwidth of the actuator should be at least twice the frequency of the disturbances that are to be controlled. In the case of complete damping of the aerodynamic disturbances this implies actuating at least 12Hz or when damping structural vibrations it leads to actuating at twice the eigenfrequency of the mode that is to be damped (e.g. 1.4 Hz for first flapwise bending damping).

- **Required deflection (when operating as aerodynamic control surfaces) or displacement (when moving aerodynamic surfaces)**

The required deflection of actuators embedded directly as control devices (piezoelectric flaps, SMA deformable trailing edge) is derived by the aerodynamic requirements. The ranges of +-12degrees or >+-15degrees are the most relevant for a 10%c or a 5%c rigid flap respectively (or equivalent flexible camber). This concerns fatigue load reduction. For extreme load reduction ++-15 degrees or >+-20 degrees are the most relevant for a 10%c or a 5%c rigid flap respectively (or equivalent flexible camber).
When the actuator is operating indirectly and drives the control surface, its motions can be determined by geometrical parameters of the layout, in order to correspond to the same control surface deflection as mentioned above.

- **Cost**

For actuator costs two things are important: the price of the materials, components and fabrication involved and the operational costs, which are mainly related to power consumption. As a guideline it could be argued that the power consumption should be not more than 1‰ (a fraction of 0.001) of the power production. For a 5MW turbine this implies 5kW. The total cost of the devices in the end (including O&M) should be much less than the gain from the load reduction. This will have to be estimated as soon as a detailed design is established. Another guideline that can be used is that the total power loss (including power consumption of actuator and power loss of the turbine due to actuator operation) should be less than 1% (so 50kW for the reference turbine).

- **Structural integration**

The impact that the actuator has on the structure must be assessed carefully, mainly from a weight point of view. A fully integrated adaptive rotor will probably involve a lot of “dissolved” actuators whereas “add-on” devices such as micro-tabs might need local mounting points and reinforcements. It must therefore be assessed carefully whether the benefits of the specific actuator surpass possibly added weight or loss of structurally loadable parts. In addition, the structural demands that were formulated for the blade (e.g. stiffness, strength, stability, contingency of loss of actuator power), apply to the actuator itself too.

4) Sensors

- **Required type of sensor signal**

The required signal for *feedback load control* should be one of the following:
-Bending strains at the blade root.
-Local accelerations or deflections at the sections with control devices.
The second option can be used in the case of multiple flaps controlled individually.

The required signal for *feed-forward load control* should be one of the following:
-Local angle of attack at sections with flaps.
-Local dynamic pressure at sections with flaps.
-Local wind speed at sections with flaps (or at a distance in front of them).
A Pitot tube type of device or a Lidar type of device can be used in order to acquire signals for feed-forward control. In this way, the control devices will be activated based on incoming disturbances and not on effects of incoming disturbances as in the previous case. Duwind and Risø are working on both options.

Most controllers require a voltage signal as input. The sensor signal should therefore preferably be a voltage, or must be convertable to a voltage without to much effort. For electrical signals such as a current or a charge this is relatively simple, but the information given by a FBG must be converted from an optical to an electric signal. The power supply for this converter must be taken into account.

- **Sensor placement**

Sensors must be placed at such a position that the measured property is excited maximally at that position, or that at least a sensible sensor signal is obtained. The sensors should ideally identify direct and cross couplings between aerodynamic, gravitational and inertial loads. Sensors for estimating the controller performance should also be included in the design. Many options for sensing quantities are considered as discussed above. Most feasible will be investigated (DUWIND, Risø).

- **Signal delay**

This is also related to the quality and type of the signal: when measuring a deflection, a change in inflow, pressure distribution and acceleration have already occurred. So even if the signal shows no delay, it might still be "too late". Of course, this also involves the processing and transmitting of the signal.
Generally: As small as possible. Upper limit should be established.

- **Signal noise**

As small as possible. Upper limit should be established.

Input needed here, mainly from control algorithm and control hardware requirements.

- **Signal amplification and filtering**

Some sensor signals need additional processing through amplifiers and filters before they can be transmitted and/or used by the controller. If this is done on site, the application of additional hardware, including power supply for it, must be taken into account.

- **Robustness and durability**

The sensors inside the blade, even more than with actuators, must be durable and robust. The same issues hold for sensors as for actuators, but the demands for sensors are probably even more severe because actuators are possible designed to be replaceable, whereas sensors will be embedded in the base-structure of the blade.

- **Price**

As with actuators, the price of placing sensors, both in terms of power consumption and costs, must be taken into account. This cost can be included in the total additional cost as described at the actuators section.

5) Controllers

- **Control algorithms**

Any control algorithm is feasible as long as it leads to stable control of the wind turbine and fully exploits the potential of the sensor/actuator combination. Although until now, simple PID algorithms have been used in individual control loops, the combination with other control objectives has to be established. Possibly control with multiple in- and outputs (MIMO) has to be used for that reason. It is not decided if more advanced control algorithms (non-linear control) should be used. The utilization of distributed control that is stable and achieved high load reduction performance without compromising power production will possibly need a more advanced control strategy. (WP 5)

- **Control strategy**

‘Control strategy’ can be defined as a combination of sensor and actuator types and placement in combination with the algorithm. Therefore the demands on the control strategy are the sum of the demands on its components. But as with sensors and the control algorithm, the strategy should be aimed at exploiting the full potential of the hardware for maximal load reduction in a cheap, durable manner.
Many options for control strategies are open: different sensors, feed-forward, feedback, individual control loops at every control device based on local signals, MIMO control based on global signals, model predictive controllers implementing constraints etc. All options will be investigated. (Risø, DUWIND)

- **Combination/interference of all controllers**

The aim should be one controller with possibly multiple input and outputs. So combination with existing generator and yaw control. If this is not possible, a good assessment of the possible interference or cooperation between controllers should be made. The important issue will be the combination of fatigue load reduction ‘smart’ control and existing collective pitch control for power regulation. Some choices exist there and are already investigated at DUWIND. (WP 5)

- **Control hardware:**

  - **Type of control hardware**. Depending on the control strategy several distributed controllers (1) or a central control (2) will be used.
    1) For the first option, an embedded hardware control designed for this purpose would be the most suitable solution.
    2) For the second option a PC with software or PLC would be suffice. Prototypes could be made on a PC easy access, possibility of fast changes, debugging capability and scalability.

  - **Power consumption.**
    1) A low power consumption should be a target for the design. 3W could be a normal number for this parameter in each distributed control. This doesn’t seem to be high comparing to other parts in the wind turbine.
    2) A PC or PLC is also used for the other controls (pitch and yaw), so there is no extra consumption for this new control.

  - **Robustness and durability.**
    1) As the placement has difficult accessibility, it is important that control hardware is durable and robust.
    2) This issue is not so important.

  - **Hardware placement.**
    1) The location for the control boards is nearby the sensors and actuators. These boards have to be replaceable, because even if the hardware design is

robust, there's no guaranty that the control hardware breaks down before the blade.

2) The placement is the nacelle.

- **Price.**
  1) As with actuators and sensors, the price of placing this specific hardware control, both in terms of power consumption and costs, must be taken into account. This cost can be included in the total additional cost as described at the actuators section.
  2) There is no extra price for this new control.

- **Functionality.**
  1) Different functions are embedded in this architecture: sensor adaptation and A/D converter, DSP (Digital Signal Processor) and Bus interface to exchange data with the nacelle.
  2) Only the control functionality is included in the central control. The rest of the functionality that the distributed control implements in its board needs to be integrated in a "distributed adaptation board". This board has to keep the same requirements that have been described above for the distributed control board.

6) Interfaces

At this point, different modules are going to be considered in order to specify the interfaces among them.

<u>Sensor module</u>: consist of the sensor itself, its adaptation and an analog to digital converter.
If the sensor was FBG (Fiber Bragg Gratings), this module would be different. The sensor will be apart from its adaptation and the A/D converter.

<u>Actuator module</u>: consist of the actuator itself and its adaptation.

<u>Control Hardware module</u>: consist of a powerful processor to implement the load reduction control algorithms. This control could be distributed or centralized.

- **Distributed control**

  - **Interface between the sensor modules and the control hardware**. The output of the sensor module is a digital signal proportional to the measured parameter. The sensor adaptation and control hardware are in the same electronic board. The interfaces are simple tracks in this board. The signals are digital ones (0 to 5 Volts).

- **Interface between the actuator modules and the control hardware.** The input of the actuator module is a digital signal proportional to the required deflection. Each actuator is controlled by a hardware control. Both are nearby. A serial bus interface is needed with the following requirements
  i. Length of the bus: 1m approximately
  ii. Point to point serial connection
- **Interface between the distributed control (DC) and the central PLC**. Some parameters have to be exchanged between the distributed control and the central PLC which controls the pitch and the yaw angle.
  i. Inputs to the DC: wind speed, angle of attack, pitch angle, yaw angle… Input needed here, mainly from control strategy requirements
  ii. Inputs to the PLC: blade load, alarm events from sensor measurements … Input needed here, mainly from control strategy requirements

  A serial bus interface is needed (in fact 3, 1 per blade) and has to be compliant with the following requirements:
  i. Length of the bus: 80m at the most.
  ii. Multipoint serial connection
  iii. Immune to noisy environmental

- **Central control**

Load reduction, pitch and yaw control are implemented in this central control. The hardware could be a PLC or a PC inside the nacelle.

- **Interface between the sensor modules and the control hardware**. The output of the sensor module is a digital signal proportional to the measured parameter. The control hardware has to receive all the sensor measurements that have to travel along the blade. A serial bus interface is needed (in fact 3, 1 per blade) and has to be compliant with the following requirements:
  i. Length of the bus: 80m at the most.
  ii. Multipoint serial connection
  iii. Immune to noisy environmental

  This part is not applicable if FBG are selected as sensors.
- **Interface between the actuator modules and the control hardware.** The input of the actuator module is a digital signal proportional to the required deflection. The control hardware has to send all the actuator signals. A serial bus interface is needed and its requirements are the same as the ones for the sensors.

- **Power lines**

A relatively high power supply is needed at each flap for the actuators to deflect the flaps. So, power cables have to be carried along the blade. (Volts?)