State of the art and prospectives of smart rotor control for wind turbines

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Abstract.
The continued reduction in cost of energy of wind turbines, especially with the increasingly upscaling of the rotor, will require contribution from technology advances in many areas. Reducing loads on the rotor can offer great reduction to the total cost of wind turbines. With the increasing size of wind turbine blades, the need for more sophisticated load control techniques has induced the interest for locally distributed aerodynamic control systems with built-in intelligence on the blades. Such concepts are often named in popular terms "smart structures" or "smart rotor control". This paper focuses on research regarding active rotor control and smart structures for load reduction. It presents an overview of available knowledge and future concepts on the application of active aerodynamic control and smart structures for wind turbine applications. The goal of the paper is to provide a perspective on the current status and future directions of the specific area of research. It comprises a novel attempt to summarize and analyze possible advanced control systems for future wind turbines. The overview builds on existing research on helicopter rotors and expands similar concepts for wind turbine applications, based on ongoing research in the field. Research work has been analyzed through *UPWIND* project's work package on *Smart Rotor Blades and Rotor Control.* First, the specifications of unsteady loads, the state of the art of modern control for load reduction and the need for more advanced and detailed active aerodynamic control are analyzed. Also, overview of available knowledge in application of active aerodynamic control on rotating blades, from helicopter research, is provided. Concepts, methods, and achieved results are presented. Furthermore, R&D so far and up-to-date ongoing progress of similar applications for wind turbines are presented. Feasibility studies for wind turbine applications, preliminary performance evaluation and novel computational and experimental research approaches are reviewed, including DUWIND's recent achievement of applying feedback aerodynamic control on a wind tunnel model of a scaled blade for load reduction. The potential of load reduction using smart rotor control concepts is shown. This study provides a unique overview of advanced aerodynamic control methods utilizing smart structures for wind turbines, discusses feasibility of future implementation, and also quantifies key parameters and shows the challenges associated with such an approach.

Nomenclature

c	airfoil/blade chord, m
R	rotor radius, m
k	reduced frequency
Re	Reynolds number
C_l	lift coefficient
C_d	drag coefficient

C_m moment coefficient
C_f flap chord length
α angle of attack, deg
β angle of flap, deg
$2D$ two dimensional
$3D$ three dimensional
CFD computational fluid dynamics
f actuation frequency, Hz
PID Proportional Integral Derivative controller
LQR Linear Quadratic Regulator controller
T_L microtab location (% of chord from trailing edge)
T_H microtab height (% of chord from airfoil surface)
t airfoil thickness, m
BEM Blade Element Momentum theory

1. Introduction

The size of wind turbines has been steadily increasing over the past years. Rotors of 120m diameter are now a reality. The growth in blade length tends to make the blades a larger proportion of the total system cost. With the intention to lower the cost per kWh, new trends and technological improvements have been a primary target of research and development.

Such trends include increasing power performance, reducing weight, reducing design margins, designing for higher life cycles, improving materials, using new design tools, improving blade geometry and reducing loads. Reducing the cost of wind turbine blades has an effect on the costs of energy, but only a small percentage of the total. However, if an innovative blade design can result in decrease in loading, the general cost will decrease, as rotor loads affect the loading of other components, as the drive train and the tower [1].

Design loads on wind turbines are generally divided into ultimate (extreme) loads and fatigue loads. Fatigue loads are a key factor for the design of wind turbines. Reducing fatigue loads can result in a significant reduction in cost, affecting required materials, maintenance costs and system reliability.

The general aim of many research and development programs in this area is focusing on developing new technology capable of considerably reducing ultimate and fatigue loads on wind turbines. Many concepts exist and have been considered in the past. Principally, two methods exist: passive and active control. Passive load control is achieved when changes in wind speed are counteracted through the passively adapting (aero-)elastic response of the rotor blades. With active control, the blade loads are adapted, by adjusting the aerodynamic properties of the blades (change of angle of attack or lift coefficient) based on specific measurements. Both types of load control have been used in the past. Passive control solutions like tension-torsion coupling, bend-twist coupling and sweep-twist coupling are still under investigation [2]. Individual pitch control is the most advanced active control that is nowadays applied. Although passive control systems are usually chosen mainly for their simplicity, for wind turbine applications, such systems are not necessarily simple, and consequently reliable and easily maintainable. As all passive control systems for flow control phenomena, these are inherently open-loop and effective only over limited operating conditions, since the flow contains complex unsteady motions. On the other hand, in (closed-loop) active control, one utilizes measurements of the current state of the system along with a model to alter its response. In consequence, active control techniques offer significantly more flexibility, especially when dealing with unsteady changes in a flow state [3].

A further concept of active control is being investigated recently in various research programs. This concept is focusing on a much faster and detailed load control. Control should be possible for each blade at any azimuthal position and any spanwise station, by aerodynamic control

devices with embedded intelligence distributed along the span. This means the implementation of efficient, innovative actuators which drive certain aerodynamic surfaces, and through the combination of sensors and controllers, provide active "smart" control. By definition, a smart structure involves distributed actuators and sensors and one or more microprocessors that analyze the responses from the sensors and use integrated control theory to command the actuators to apply localized strains/displacements to alter system response [4].
The target of this control for wind turbine applications is mainly the reduction of fluctuating loads on the blades. The potential and the state of the art of such advanced controls for wind turbines are considered necessary to be analyzed and presented. Research is mainly initiated based on similar concepts from helicopter control and is recently investigated by various wind energy research institutes. A recent inventory of progress in research on these topics can be found in [2]. In the framework of the International Energy Agency an Expert Meeting was held on "The application of smart structures for large wind turbine rotors". The proceedings show a variety of topics, methods, solutions, which reflects the state-of-the-art: the research towards smart structure rotor technology has started and seems promising. Also, the progress and ongoing achievements of the UpWind project work package "Smart Rotor Blades and Rotor Control" were presented in [5].
In this study, the need for smart wind turbine control will be explained, achieved results from R&D so far will be presented and up-to-date ongoing research will be analyzed. This includes the recent wind tunnel experiments at DUWIND, regarding the application of feedback control on a variable geometry blade for load reduction. Some issues on analysis of smart control devices are also presented through the text as analyzed in [6].

2. Load reduction control systems

2.1. Defining unsteady environment and ways of influencing it

The loads action on a wind turbine during operation can be divided into aerodynamic loads and structural loads. These loads are related by the aeroelastic coupling. The aerodynamic forces on the rotor are affected by the relative velocities on the blade sections. These velocities show fluctuating values during wind turbine operation. Most of these fluctuations are of a periodic nature (appearing in multiples of the rotor frequency) but also stochastic components exist.
In general the following effects contribute to these fluctuations causing a asymmetrical inflow field:

- Horizontal or vertical wind shear
- Tower shadow
- Turbulence (and rotational sampling of eddies)
- Yaw and tilt misalignment

Furthermore, gravity forces on the rotor blades cause a periodic excitation of the rotor blade structural dynamics at the rotational frequency of the rotor. These can interact with structural modes of other components, e.g. tower and drive train.
To reduce fatigue loads during the operation of a wind turbine, control systems should be able to influence the structural loads [7]. In order to alleviate the described loads the control system of a wind turbine should be able to either reduce the fluctuations of the aerodynamic loads or add damping to the structural modes [8]. Many approaches for control for load reduction, only using the existing pitch system, have been proposed and will be summarized below.

2.2. Developments in wind turbine control systems for load reduction

Upscaling of the wind turbine rotors during the years has not led to significant changes in the blade structure. On the contrary, the blade loads control systems have evolved greatly

[9]. Until the nineties, the wind turbines making use of the "Danish Concept" combined constant rotor speed with stall of the flow around the rotor blades: increasing wind speeds automatically induce increasing drag forces that limit the absorbed power. All other control options were considered too complex. The simplicity of this concept has certainly contributed to the success of the "Danish concept", but evolution toward large rotor sizes appeared to be uneconomical. Nowadays, all large wind turbines run at variable rotational speed, combined with the adjustment of the collective pitch angle of the blades to optimize energy yield and to control the loads. This was a big step forward: the control of the blade pitch angle has not only led to power regulation, but also to a significantly lighter blade construction due to the lower load spectrum and a lighter gear box due to reduced torque peaks.

2.3. Advanced pitch control

The next step in blade load control was Individual Pitch Control: pitch angle adjustment per blade instead of collective. This further alleviates the rotor loads, specially due to periodic effects (wind shear, tower shadow, upflow and shaft tilt). Not only do the blades benefit from this reduction, but also the drive train and nacelle structure. Although these effects cause a systematic azimuth-dependent variation in the aerodynamic conditions at a point on the blade, in practice, it is very difficult to achieve any real gains in this way because of the dominance of stochastic variations due to turbulence and variation of wind shear and upflow according to environmental conditions [10]. More advanced approaches of using the blade pitch mechanism for load reduction control purposes have been proposed. Focusing only on periodic loads, control strategies from helicopter research have also been investigated. Cyclic pitch control (1P cyclic change in pitch, see [8],[11]) and Higher Harmonic Control (pitch actions with multiples of nP, see [12],[13]) have shown some potential of load reduction. Furthermore, Bossanyi [10],[14],[15] has proposed the use of additional load sensors on the blades (strain gauges, accelerometers) to superimpose an additional (individual) pitch demand to the collective pitch. T. van Engelen and E. van der Hooft at ECN [16] suggest a parametriztion of feedback loops for Individual Pitch Control around 1,2,3P frequencies for load reduction. In a different approach, Larsen et al [17], demonstrated significant load reductions by using Individual Pitch Control, based on local blade flow measurements (angle of attack and relative velocity). The reductions are in the order of 9-31% for various wind turbine components. Results are compared with the Cyclic Pitch control concept and appear more promising. All the above approaches show reductions of 10-20%, although large and fast pitch changes are required, which will lead to excessive wear of the pitch actuators. Also, control is based on a measuring and reaction principle of quantities on the rotor. A recent, different approach is investigated, based on the concept of feed forward control of incoming wind field. Van der Hooft and van Engelen [18] suggest the estimation of incoming wind speed based on energy balance and Hand et al [19] propose the use of a LIDAR system to directly measure the upwind incoming flow field and react with the pitch system.
Active control based on real-time measured quantities can deal with fast changes in aerodynamic loads. This is the target of smart rotor control, that is analyzed through this paper. By smart rotor control, the active aerodynamic load control by using distributed devices with built-in intelligence is meant. More detailed and fast aerodynamic control can contribute to the challenges associated with unsteady phenomena and deal with stochastic components. The advances in materials and control technology have contributed to the development of such systems. The inventory and analysis of concepts for wind turbine smart control have been analyzed in [6].

3. Rotorcraft experience

The concept of active control on rotor blades by using smart structures (actuators, sensors, controllers) has been thoroughly studied in the field of helicopter technology. The interest for

smart rotor control in helicopter rises mainly because of the importance of vibration and noise reduction at the rotor. In this literature field a lot of topics have been studied, including control surface concepts, smart materials, smart actuators, design options, control strategies, modelling and experimental testing. For general issues on active control and adaptive wings, mainly focusing on aircraft applications, one should refer to the articles of Breitbach [20] or Stanewsky [21]. Generally, some differences exist between helicopter and wind turbine applications. These mainly include different operating conditions, maintenance requirements and size and weight of blades. Although the unsteady environment is similar to a certain extent [22], wind turbines are subjected to some other complicated effects like wind shear, turbulence, tower shadow and wakes of other turbines, and, on the other hand, airloads acting on helicopter blades (mostly in forward flight) are highly periodic due to the high variances in both the local angle of attack and the relative velocities seen by the blade sections during one revolution.
Summary reports have been published over the years overviewing existing research studies, aerodynamic control device concepts, actuators selection, smart materials and feasibility for rotor control. Famous reports are the ones of Straub [23] and Chopra [4] where all available concepts are analyzed. More specifically, for control concepts, pitch control, twist control, camber control and moveable control surfaces (trailing edge flaps or servo tabs actuated by smart materials) are proposed. Also, smart materials for actuation purposes are reviewed (piezoelectric, electrostrictive, magnetostrictive, shape memory alloys (SMA) and electrorheological fluids) and actuator configurations are analyzed. Smart materials are favorable for actuation purposes due to several reasons: compact size, large actuation displacements with low energy requirements and fast frequency broadband response. A lot of experience in smart control for helicopter applications has been gained through the last decade, resulting in various successful applications. Some representative examples are summarized in [4]: Koratkar and Chopra built 1.83 m diameter scaled rotor models with trailing edge flaps actuated by piezo-bimorphs. Froude-scaled models were built and tested in a vacuum chamber and on a hover tower and finally Mach-scaled rotor models in closed-loop testing in the wind tunnel. Using a neural network controller, with a flap deflection of ± 5 degrees, individual blade control resulted in over 80% reduction in vibratory hub loads. Moreover, Lee and Chopra built a model of a blade section of 30 cm length with trailing edge flaps actuated with piezo-stacks, using a double lever (L-L) amplification mechanism. The expected increased performance of flaps at different operating conditions was shown (e.g. ± 10 degrees at 36 m/s). Bernhard and Chopra built a 1.83 m diameter Mach-scaled smart active-tip rotor actuated with piezo induced bending-torsion coupled composite beam. The achieved tip pitch deflections were 1.7 to 2.9 degrees. Chen and Chopra built a 1.83 m diameter Froude-scaled rotor model with controllable twist blades actuated by embedded multilayered piezoceramic elements. The results showed the potential partial load vibration suppression. Also, Roger and Hagoon, Derham and Hagood and Cesnic and Shin developed Mach-scaled models with controllable twist, utilizing embedded active fiber composites. The results showed enormous potential for full scale rotor applications. Regarding SMA actuators, Chopra investigated the application by developing a blade section model with tab actuated by SMA wires. The performance in terms of deflection was very good.
The most recent research in active rotor control using smart devices is that in ADASYS project (a joint task between Eurocopter, EADS CRC, Daimler Chrysler Research Labs and DLR) [24],[25]. A full scale rotor was developed based on a BK117/EC145, utilizing actively controlled piezoelectric actuated trailing edge flaps (Fig. 1,2). The system was tested during flight and showed excellent performance in reduction of vibratory loads (50-90% reduction).

By studying the various attempts for smart rotor control in helicopters some conclusions can be drawn. Because of the strong periodic nature of airloads in helicopter blades some investigations have focused on applying high frequency periodic aerodynamic control to reduce these fluctuations, instead of feedback control based on measured quantities (e.g. Higher

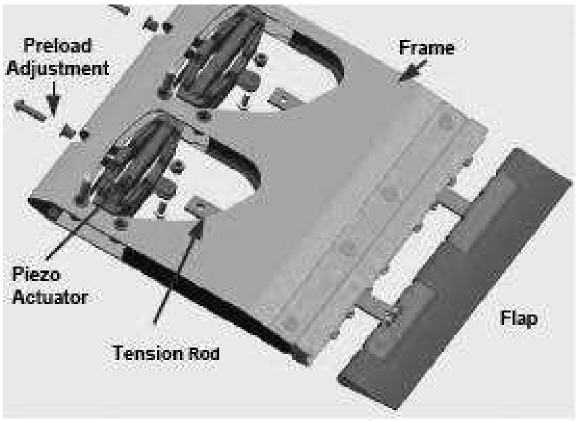

Figure 1. Layout of the piezoelectric actuated flaps developed in ADASYS [24].

Figure 2. Actively controlled piezoelectric actuated flaps on the BK117 blade [25].

Harmonic Pitch control). The use of aerodynamic control surfaces (trailing edge flaps, tabs, moving tips) on the blades give the advantage of faster control with smaller deflections (due to the large leverage near the blade tip) for reduction of blade root moments, without using full blade pitching which is inefficient due to the use of the swashplate [1] and the larger inertia. Also, because of the small size and thickness of the helicopter blades, the use of smart actuating devices was identified early. So, a large part of this field's research is focusing on the use of so called "smart materials" that provide high energy density with small size and low power consumption. Because of the large centrifugal forces and generally large loads on the sections (compared to their size) the maximum aerodynamic effect of the control surface is a big issue. The maximum achieved deflections of the control surfaces by using smart actuators is the most important control parameter for such applications. Various amplification mechanism have been generally used in order to increase the displacement of the control surfaces by using mechanical amplification. Furthermore, a significant attempt was made to use embedded actuation on the blades which results in shape morphing (camber control) or twisting (active twist). Unique methods utilizing active fiber composites showed shape control capability, although generally the use of small deflection surfaces is preferred due to simplicity, reduced weight and power consumption. From the control objective point of view smart rotor application approaches in helicopters have managed to develop efficient systems, which with the use of advanced control algorithms achieve significant results concerning vibration and noise reduction.

4. Smart rotor research for wind turbines

As the reasons concerning the need for application of smart control concepts for wind turbines have been analyzed and an overview of helicopter research in the field has been presented, various attempts of applying similar concepts for wind turbine load control will be reviewed. The target of this paper is not to fully cover research related to active aerodynamic control for load reduction, but to provide a perspective on the current status and future directions of the specific area of research, analyzing key issues. Although some preliminary investigations for active control using devices on the blades had been made during the 90's, research regarding smart control for wind turbines is a new, innovative and ongoing part of research at various wind energy research institutes. Concepts, methods and achieved results in potential for load

[1] The swashplate is the set of discs and pitch links on the helicopter rotor shaft, which controls the collective and cyclic pitch of the blades.

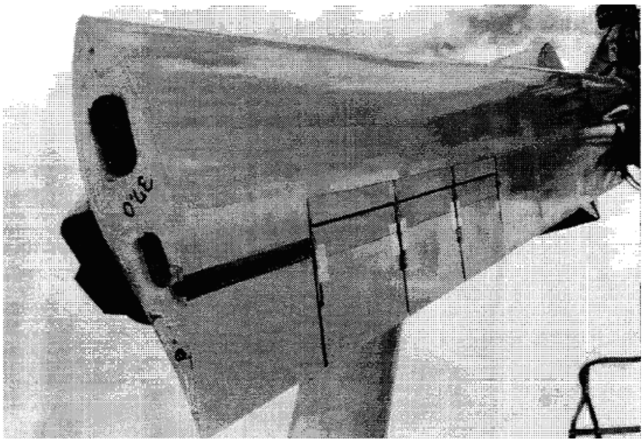

Figure 3. The "CER" turbine blade equipped with ailerons [28].

reduction, through simulations and experimental approaches are presented, focusing on up-to-date research.

4.1. Early investigations

Preliminary investigations of alternative control devices distributed on wind turbine blades had been performed by the National Renewable Energy Laboratory (NREL) during the 90's in the USA. These devices (mainly ailerons) have been analyzed to be used for power regulation purposes and aerodynamic braking. Series of wind tunnel experiments have been performed examining different configurations [26],[27], simulations quantifying the devices performance and also field tests [28] (Fig. 3). Although the aileron devices were investigate in fixed positions (no active control), important 3D effects associated with variable span-wise deployment of the control devices were identified during operation.
In later investigations regarding actively controlled devices for load reduction, simulations were performed. In [29] a PI closed-loop controller was used in the aeroelastic code FAST (with the AeroDyn module). The controller was designed based on system identification with the objective of controlling ailerons (on the outer 30% blade span) for power regulation. Look-up tables were used for the aerodynamics of the ailerons. The response of the system to specific wind input conditions (gust, smooth turbulence) with and without control was investigated. The controlled ailerons could reduce the response time to a step-gust wind input and yielded reasonable performance for a range of wind speeds and input conditions. In [30] a different approach for the design of the controller was used. The FAST code was used, in conjunction with system identification tools, to generate a wind turbine dynamic model for use in active aileron control design. The load reduction in fluctuations (gust or smooth turbulence) for the aileron controlled cases is only quantified in time series plots of root flap bending moment in the references.

4.2. Feasibility studies

The renewed interest in aerodynamic control devices on the blades for active load reduction purposes has induced the investigation of the feasibility of such concepts.
A preliminary investigation in smart rotor control for wind turbines has been conducted by Marrant, van Holten and Kuik for the project "Smart Dynamic Rotor Control for Large Offshore Wind Turbines" funded by the (Dutch Technology Foundation STW). Some preliminary results of the study are summarized in [7]. Research deals with the inventory of rotor design options,

possible load reductions, aerodynamic control devices, actuators and smart materials. Basic directions for relevant research have been suggested.
A more recent and up to date feasibility inventory was made by Barlas [6] for the UPWIND work package "Smart Rotor Blades and Rotor Control". State of the art in smart rotor knowledge is overviewed and analysis of different concepts is performed regarding aerodynamic control devices, actuators, sensors and controllers. Inventory analysis results show preliminary feasibility of concepts and directions for ongoing and future research. Aerodynamic control devices affecting the local angle of attack or lift coefficient for a certain angle of attack are analyzed. More promising options seem the use of trailing edge flap devices (rigid or flexible), variable camber airfoils and microtabs. Also, options for actuators (especially based on smart materials), sensors and controllers are presented together with a requirement survey of design issues and modelling.

4.3. Control surfaces investigations

In order to investigate the possibility to control fluctuating loads on the blades, research programs have focused on analyzing the aerodynamic efficiency of certain devices (surfaces). Simulations and wind tunnel test quantify important parameters which are important for the control purposes. Of course, there is a lot of knowledge regarding aerodynamics of control surfaces, but only the ones investigating the use as load reduction devices for wind turbines will be analyzed.
Trailing edge flap devices have been thoroughly investigated by Risø. Especially, attention has been drawn on the concept of variable geometry trailing edge, since the option of smoothly deforming the aft part of an airfoil using smart materials is possible with modern technology advances, and the potential of using such an approach is of great interest. In [31] a CFD study was carried out to determine the effect of the size and shape of the variable trailing edge geometry on the aerodynamic characteristics. Three different shapes of trailing edge geometry were analyzed: rigid, soft curved and strongly curved. From the static simulations it was concluded that soft curved flaps with flap chord to section chord ratios ranging from $c_f/c = 0.05 - 0.10$ would be optimal because of the great influence in lift with insignificant drag penalty. From the dynamic measurements, it was concluded that the amplitude of the lift generated on an oscillating airfoil could be reduced by the counteracting movement of the flap for a wide range of reduced frequencies [2] (k=0.09 - 0.36). Some comparison results are shown here (Fig. 4,5).

In [32] a 2D aeroelastic model was developed, based on a panel code and a spring-damper system for an airfoil with deformable trailing edge. For control, a simple PD control algorithm is used, with a target control strategy to minimize the tip deflection variation of the blade. The results show the potential of such a control. The standard deviation of the airfoil displacements has been reduced to 25% of the value corresponding to no control, during the 2 sec. simulations. In all the other simulations (100s turbulence, gust) the decrease in the displacement amplitudes was evident.

In [33] Gaunaa describes a potential flow analytical method for the unsteady 2D force distribution on a variable geometry thin airfoil undergoing arbitrary motion. In addition to already developed potential flow analytical expressions for unsteady aerodynamics of thin airfoils, usually described as thin plates with the addition of flat control surfaces (see Theodorsen[34] and Leishman[35]), this method adds the option for a smooth deflection of the airfoil shape by superposition of chordwise deflection mode shapes.
This analytical model was used by Buhl et al [36],[37], coupled with a linear spring/damper model for the elastic deformation of the airfoil. An optimal control strategy was used to minimize the fluctuations on the airfoil normal force. The analysis showed that when the airfoil experienced

[2] The reduced frequency k is defined as $k = \omega.c/2V$, where ω is the angular frequency of the unsteadiness, c is the blade's chord and V is the velocity of the blade.

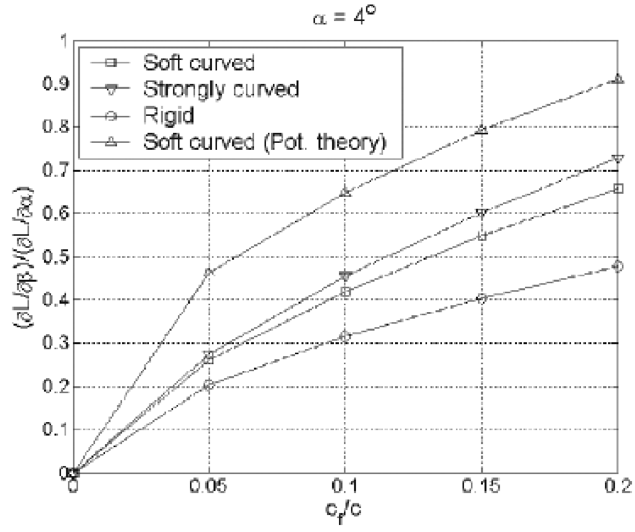

Figure 4. Flap effectiveness at $\alpha = 4^o$ for different flap lengths and flap types. Flap effectiveness in defined as the ratio of change in lift produced by the flap angle over that produced by a change in angle of attack. 2D CFD calculations [31].

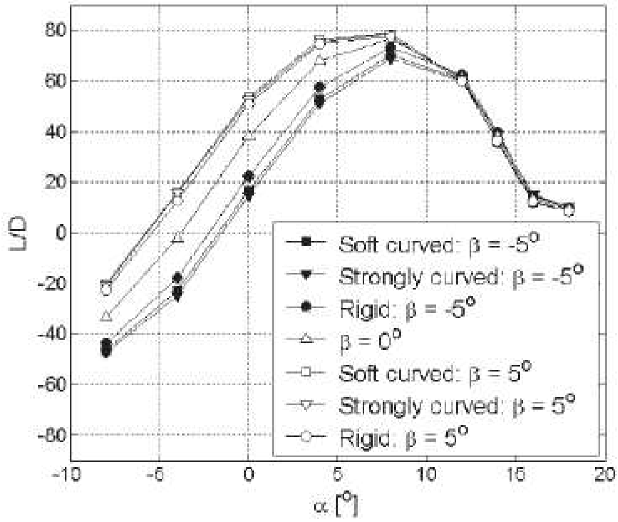

Figure 5. Lift to drag ratio for different types of flaps at different deployment angles ($c_f/c = 0.10$). 2D CFD calculations [31].

a wind step from 10 to 12 m/s the standard deviation of the normal force could be reduced by up to 85% when the flap was controlled by the reading of the airfoil flapwise position and velocity, while reductions of up to 95% could be obtained when the flap was controlled by the reading of the angle of attack. When the airfoil experienced a turbulent wind field, the standard deviation of the normal force could be reduced by 81% for control based on measured angle of attack. The maximum reduction using a combination of flapwise position and velocity was 75%. Calculations showed that the effect of a time lag in the actuators and sensors significantly reduces the efficiency of the control algorithm. Likewise, the effect of a low maximum actuation velocity reduces the efficiency of the control algorithm. Representative results are shown (Fig. 6, 7).

The investigation of variable trailing edge geometry was further extended at Risø by building a prototype and performing wind tunnel tests [38]. A profile section of 2m was fitted with 36 piezoelectric actuators ("THUNDER"© actuators from FACE©, Fig. 8) at 10% of chord length. The thin curved actuators were directly glued to the trailing edge of the profile. Static and dynamic tests were performed. The step and sinusoidal responses of the lift due to the flap deflection were modelled with an indicial function formulation. The flaps were actuated in order to reduce the lift force fluctuations generated by pitching the profile. A reduction of 82% was measured in a prescribed pitch and flap motion (with a phase shift of 40 degrees).

A different kind of aerodynamic device suggested for active control is the one of "microtabs". The use of microtabs as aerodynamic devices for load control on wind turbine blades has been proposed and extensively investigated by van Dam [39],[40],[41],[42]. The microtab concept has been derived from an earlier concept of Gurney flaps. Micro tabs are small (deployment height in the order of the boundary layer thickness) translational devices placed near the trailing edge of an airfoil (Fig. 9). The deployment (normal to the surface) of such tabs changes the trailing edge flow development (Kutta condition), so the effective camber of the airfoil, providing changes in lift. Lift enhancement is achieved by deploying the tab on the lower (pressure) side

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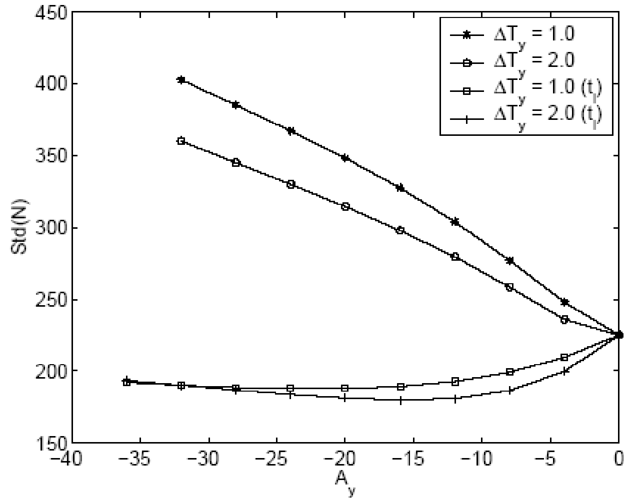

Figure 6. Wind step: Normal force standard deviation as a function of control parameter A_y (airfoil deflection in flapwise direction) for different time integration windows (ΔT_y) with and without time lag (T_l) [36].

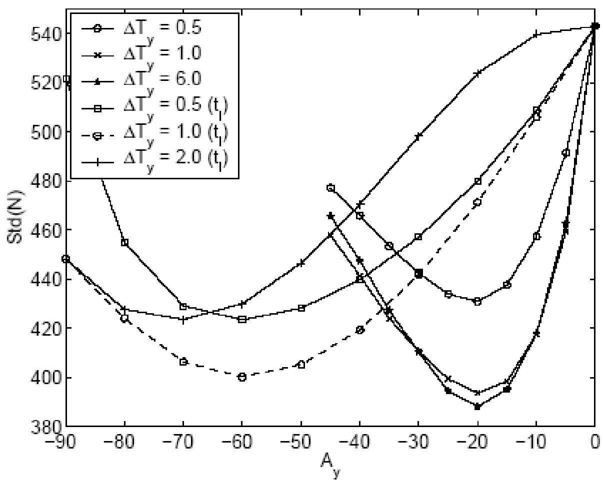

Figure 7. Turbulent wind: Normal force standard deviation as a function of control parameter A_y (airfoil deflection in flapwise direction) for different time integration windows (ΔT_y) with and without time lag (T_l)[36].

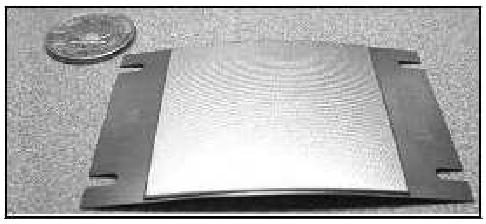

Figure 8. The "THUNDER©" (THinUNiformDrivER) piezoelectric actuator.

of the aerofoil, while lift mitigation is achieved by deploying the tab on the upper (suction) side of the aerofoil. Their function is mainly on-off, since they change the effective camber of the airfoil by changing the trailing edge point, so no proportional change in lift can be achieved as e.g. in the case of trailing edge flaps. Variable change in lift can be achieved by spanwise deployment of microtabs. These tabs are mainly mentioned as MEM tabs (Micro Electrical Mechanical tabs), as they are based on the concept of microjoinery (dovetail slider joints), actuated/controlled by small integrated electronic circuits. Their effect on lift has been shown as powerful as conventional control surfaces such as flaps. The minute size of these devices allows for faster response times and, by the use of smart feedback control, can result in the overall reduction of system complexity, weight and cost. The effect of varying tab location, height and width has been simulated by van Dam using CFD. Results show an increase of 50% for Cl in the linear range of the lift curve. Also, data showed that a 1% of chord tab placed at 5% of chord from the trailing edge provided the best compromise for lift, drag and volume constraints in the trailing edge. Regarding increase in drag, from the experimental work of van Dam it can be seen that a increase ΔC_d of up to 0.025 can be noticed at the case of a deployed microtab (20% increase compared to the baseline airfoil with C_d of 0.01). For a change in lift coefficient of $\Delta C_l = 0.2$, the drag penalty is 0.002 in a representative case of a deployed

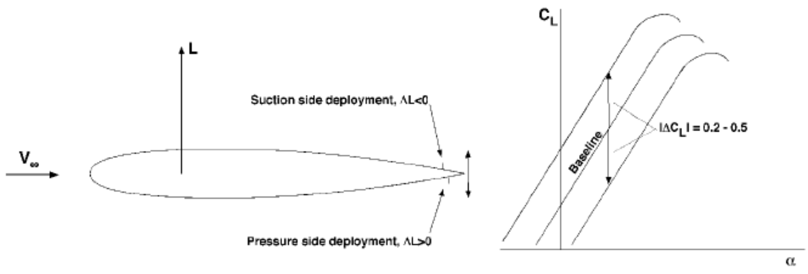

Figure 9. Microtab-based aerodynamic control concept[41].

microtab. On the other hand, For a change in lift coefficient of $\Delta C_l = 0.2$, the drag penalty is 0.001 in a representative case of a deployed trailing edge flap [31]. Although the increase in drag strongly depends on the angle of attack surface deployment and chosen airfoil, in the case of microtabs it seems to be slightly increased. Also, noise issues are believed to be connected with the deployment of microtabs. On the work of Oerlemans [43] it was shown that microtabs produce a high level of trailing edge noise but only an increase in broadband noise when in gapped configurations.

3D CFD simulations were also conducted in order to investigate the effect of gaps or serrations in the tabs (because solid tabs suffer from vortex shedding). The relationship between tab solidity ratio and change in lift was found to be highly linear, which is important for control purposes. So microtabs show distinct relationships between tab-gap sizing and the resulting level of load control. Also, 2D experiments in the UC Davis Wind Tunnel were performed in order to calculate the aerodynamic performance of fixed and actively controlled MEM tabs. The experiments were conducted at $Re = 1x10^6$ for the two blade sections (fixed tabs and remotely controlled integrated tabs) for different locations and heights (for the fixed tab) and compared to CFD calculations. Results show good aerodynamic performance. Furthermore, in [42] unsteady CFD simulations of deploying microtabs were performed. Results for the static cases were validated with the previous experimental ones. The unsteady studies show the unsteady aerodynamic behavior of the microtabs during deployment. It was concluded that, in general, the global temporal response is independent of the aerodynamic device. Compared to trailing edge flaps, the temporal response of flaps depends highly on the size and deployment angle.

4.4. Investigations in wind turbine control for load reduction

In literature one can find research investigations of aerodynamic control surfaces satisfying different targets (e.g. flutter suppression, gust alleviation etc). In the previous section, results concerning aerodynamic control devices (surfaces) designed for wind turbine blades for active load reduction purposes were shown. Here, results from more global active load control investigations on wind turbine rotor models are presented.

At DUWIND a comparison of different concepts for smart rotor control of wind turbines was carried out by Marrant [44]. Four different smart rotor blade concepts were compared based on their potential to reduce fatigue loads for particular dimensions, their aerodynamic efficiency, bandwidth and complexity. The fatigue load case during normal power production (including turbulence and wind shear effects) was examined, comparing load calculations for the conventional blade and the "smart" blade. The benchmark wind turbine was the DOWEC (Dutch Offshore Wind Energy Converter) concept 6MW turbine. A time-marching BEM model with no dynamics included was used. The maximum load alleviation capacity of the smart structures has been used in the analysis, where it has been assumed that the smart rotor blade

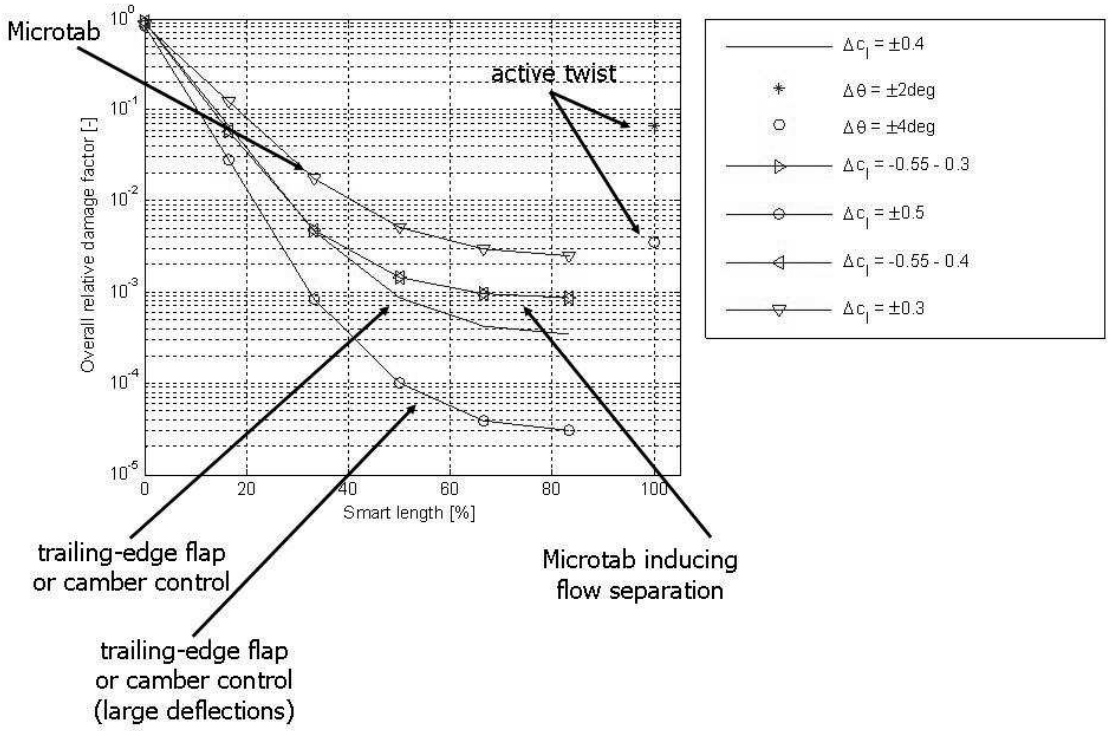

Figure 10. Comparison of smart rotor blade concepts with infinite bandwidth [44].

has full knowledge of the wind field at every time step, moreover as a first approximation the smart blade is assumed to react instantaneously to the load change. So, no controller was designed. The four smart blade concepts compared were: trailing edge flaps, microtabs, camber control (which change the $C_l - \alpha$ curve) and active twist (which change the angle of attack). The variations in blade flap root bending moment were calculated for the baseline blade and the smart blade incorporating different spanwise lengths of smart devices (no edgewise or torsional degrees of freedom were included in the model). The limited bandwidth of the devices was also taken into account by cutting off the maximum frequency of the Fast Fourier Transform (FFT) of the blade root flap bending moment. Rainflow counting and Miner's law were used after that for determining the fatigue damage in order to compare the different concepts. The comparison parameter was the ratio of the total fatigue damage of each smart concept over the conventional blade (overall relative damage ratio).

The actuation of the concepts was theoretically based on piezoelectric actuators. The camber control concept was supposed to be actuated by an inflatable structure concept. The values of ΔC_l or $\Delta\alpha$ and maximum bandwidth were taken from literature. The results for unlimited and limited bandwidth can be seen in Fig. 10 and 11. From the preceding analysis it can be seen that active trailing-edge flap control/active camber control ($c_l = 0.4$) is about twice as effective as microtab control ($c_l = 0.3$). Only microtabs with a larger tab at the lower surface ($c_l = -0.55 \pm 0.3, f_{max} = 2Hz$) can keep up with the active trailing-edge flap/active camber control concept up to 15% smart structure length. For active trailing-edge flaps, active camber control and microtabs, smart structure lengths of 30% are most efficient for the reduction of

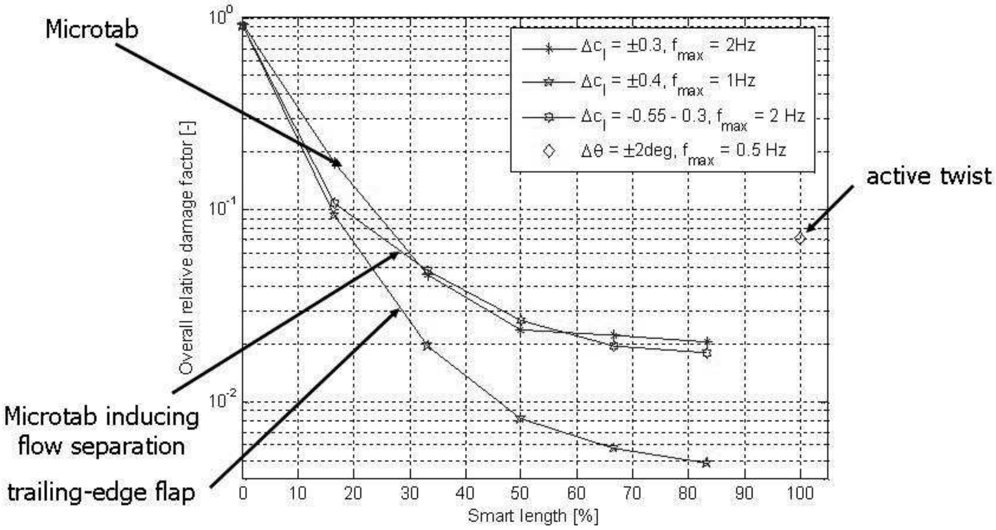

Figure 11. Comparison of smart rotor blade concepts with limited bandwidth [44].

fatigue loads. Although active twist control is feasible, it is expensive, results in heavier blades and is a very inefficient way to reduce fatigue loads.

At DUWIND a preliminary investigation of using trailing edge flaps for power regulation and load control instead of full-pitch control had been carried out [45]. Although steady cases were simulated using BEM and flap aerodynamic parameters were based on look-up tables, results provide interesting first order design guidelines. Different flap configurations were investigated. When compared to the full span pitch control system on a representative 3 bladed 5.5MW upwind rotor design, it was found that the fixed pitch/trailing edge flap concept is able to yield on average 2% more power below rated wind speed because of aerodynamic improvements made in the inboard root section (5-20%R). To regulate power output above the rated wind speed, it was found that tip flaps of spanwise lengths of 25%R and chordwise lengths of 20%c where sufficient to regulate power output with flap deflections of less than -5 degrees.

A more recent attempt by NREL [47] was the investigation of microtab aerodynamic devices for load control. The aeroelastic code MSC-ADAMS (with the AeroDyn aerodynamic module) was used with a LQR controller. The aerodynamic effects of the microtab devices were incorporated only in form of adjustment in static lift and drag based on the experimental and computational results of van Dam [39],[40],[41]. A control strategy based on a LQR state space controller was developed, which includes individual blade pitch control and controls the turbine operation differently into distinct operation regions. A step change in logarithmic wind shear exponent was simulated and control response for traditional PI for (collective) blade pitch, Individual Pitch and microtab control were compared in reduction of blade tip deflection. Also

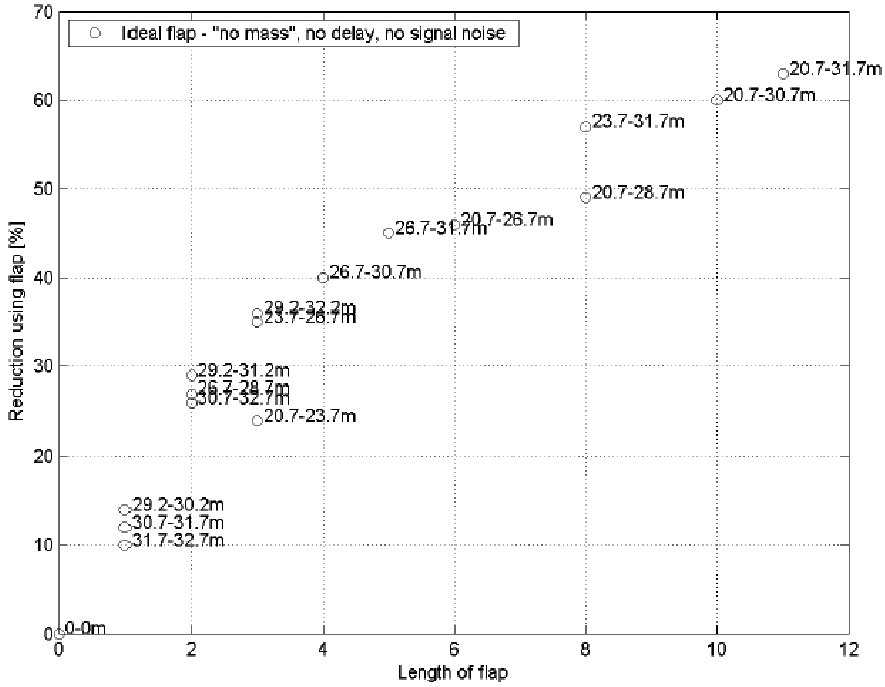

Figure 12. Reduction in equivalent flapwise root bending moment for different spanwise length of flaps and different spanwise positions. 3D extended BEM simulations [46].

peak and fatigue loads were calculated based on IEC load cases. The variations in tip deflection were quickly reduced with the MEM tabs. With small control actions, the microtabs showed significant load reduction potential. Different extreme loads were reduced up to 9% and fatigue loads up to 25% with the microtab control. The example for the case of a step change in wind shear was presented. We see that Individual Pitch Control slowly adapts to the change and reduces the tip deflections, but using large and quite fast pitch actions. Microtab control adapts faster to the change and reduces tip deflections faster.

In [46] the research work at Risø on the 3D modelling of a wind turbine rotor with actively controlled, deformable trailing edge geometry is presented. A modified version of unsteady BEM is used. The unsteady flap aerodynamics and camberline dynamics are the same as described in [36],[37],[33]. The blade is modelled as a cantilever beam using modal expansion. The turbine in this case is using a 33 meter long blade. A PID controller using input signals from local flapwise deflections or accelerations was implemented. Effects of system time lag, flap power consumption and signal noise were included. Rainflow counting and Wöhler curves were used to determine the equivalent loads, which are minimized by a simplex-type optimization scheme, finding the optimal control for the considered case. The numerical investigations showed a huge load reduction potential very dependent on time delay. The computational tests showed fatigue load reduction potential of up to 64%. Equivalent flapwise root bending moments were reduced, although with reduced potential (40%) when signal noise, actuator time lag, flap mass and maximum power consumption were added. Moreover, optimal placement and dimensions of flaps was investigated (Fig. 12). It can be seen that a 11 meter flap gives equivalent load reduction of more than 60%. Also, split flaps of different lengths were investigated. With this way it is possible to more effectively damp out energy from more vibrational mode shapes if the

Figure 13. "Smart Blade" at the TU Delft LSLT wind tunnel test section.

flapping sections are divided.

4.5. Applied feedback control (DUWIND's "smart blade" experiment)
Although the potential of load reduction using smart control concepts for wind turbine blades has been shown in various computational investigations, the necessity for small scale experimental setups proving the idea, taking all dynamics into account and providing first order design solutions rises. In DUWIND a prototype of a scaled wind turbine blade was designed with embedded load reduction control devices and feedback control was applied in wind tunnel experiments. An experimental wind tunnel setup was prepared. The design of the setup as well as some of the first results are shown in [48]. Here, only the description, main results and findings are presented. The reader should refer to future publications to appear, for an extensive analysis of the experimental work. The ultimate goal of the approach was to show that vibrations in scaled down blade due to unexpectedly varying aerodynamic loads can be significantly reduced using trailing edge devices with an active control system. The 90cm long blade model with a 12 cm constant chord, constant thickness and no twist along the span was attached to the (specially designed) pitch system at the TU Delft Low Speed Low Turbulence Wind Tunnel roof and it was free to deflect over a table at the free end (Fig. 13). The table ensured that no tip effects would occur that add uncertainties to measurement data. The pitch system could change the angle of attack at the blade with high speed and precision.

The glass-epoxy composite blade was designed to be representative of the dynamics of a large scale wind turbine blade. The scaling parameter used was the reduced frequency k. It was used to scale the wind field disturbance (the multiples of angular frequency 1P and 3P were considered important) as well as the first flapping natural frequency on the blade (since the devices will try to reduce the vibrations in the blade flapping direction). The first flapping natural frequency was tailored during the structural design of the blade (by tuning the stiffness). The aerodynamic excitation was simulated by the pitch excitation system. The scaled 1P, 3P and first flapping natural frequency of the blade were 3.5, 10.5 and 12.5 Hz respectively. The aerodynamic control devices used were based on the concept of deformable trailing edge (or partial camber control).

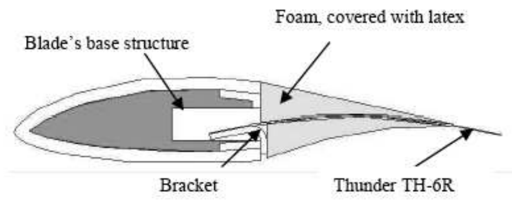

Figure 14. Design and mounting of the actuators.

Four Thunder© TH-6R piezoelectric bender actuators were used, forming two different flaps of 50% chord length size placed near the tip. The thin actuators were covered with soft foam, in order to keep the trailing edge aerodynamic shape, and a latex skin, which can expand under the actuator deflection, providing a smooth aerodynamic surface (Fig. 14). A piezoceramic patch was used in the blade root in order to measure the change in flapping bending strains and an accelerometer at the blade tip to measure the change in acceleration of the deflecting tip. Because the interest was in the vibration reduction control, no direct aerodynamic measurements were carried out, so aerodynamic phenomena cannot be quantified. Control was applied using a dSpace© system linked to the Control Desk GUI in Matlab Simulink©. The main tests that have been carried out concern feed forward (open loop) and feedback (closed loop) control cases. For the feed forward cases, sinusoidal motions of the pitch and the counter-acting (both) flaps for different amplitudes and frequencies were carried out. Furthermore, measurements at different mean angles of attack of interest were performed, also at stall conditions. The sensitivity of the phase angle between the two motions was examined. In this way the maximum reduction in the fluctuating loads for prescribed (known) motions of excitation and actuation was shown. The maximum reduction ranges were up to 90%, especially near the natural frequency of the blade, were vibrations are amplified. A representative result is shown in Fig. 15. For the feedback control tests, the transfer function of the dynamics of the system was constructed using the subspace system identification method, based on step and noise signals for the pitch actuator and the (both) flaps respectively. From that, a loop-shaped controller was designed, tuned and applied in dSpace. The input excitation cases were a sinusoidal, a step and a random signal, for different amplitudes and frequencies of interest, simulating various aerodynamic excitations like gusts and turbulence. The controller performance was great, reducing the fluctuations in root bending stresses for all cases (maximum reduction of root strains 95% for a sinusoidal disturbance, significant damping of the first eigenfrequency of the blade with a step disturbance). Representative results are shown in Fig. 16,17. For the random signal (representative noise signal) mimicking turbulence with 1P and 2P excitations, although the signal is completely unknown for the controller, it showed very good performance, leading to reductions of 60% in the scaled 1P frequency and 80% in the scaled 3P frequency. The Power Spectral Density (PSD) of the measured strains with and without controller is shown in Fig. 18.

Measurements with the distributed control concept, i.e. utilizing both flaps with autonomous controlled motions to reduce vibrations for two different mode shapes of bending, have not yet been carried out. The table used for the quasi 2D purposes was discarded and additional measurements were also performed. Further investigations will be made in order to quantify unsteady aerodynamic phenomena associated with the control actions (using Particle Image Velocimetry (PIV) techniques) and make comparisons with developed aeroelastic models. This wind tunnel experiment of DUWIND is a novel achievement of application of feedback aerodynamic control for load reduction focusing on wind turbine blades cases.

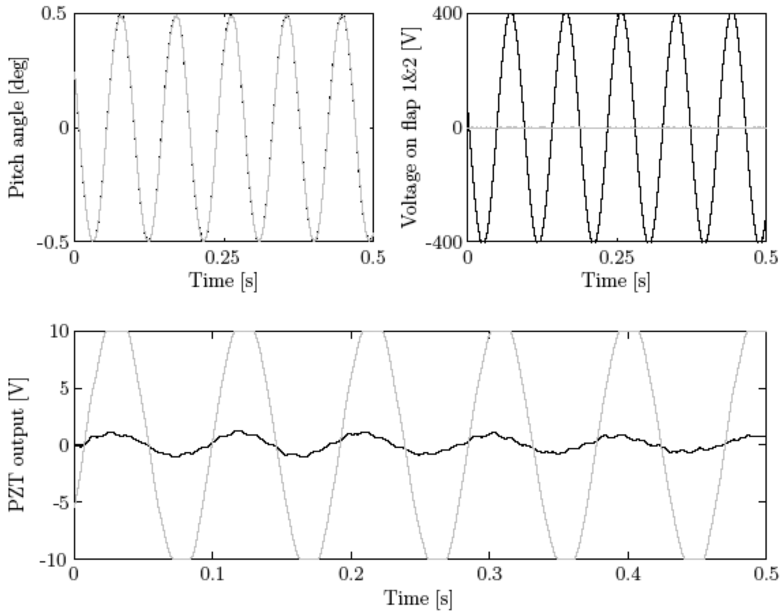

Figure 15. Reduction in root strain fluctuations in the case of a sinusoidal pitch excitation of 12.5 Hz with 0.5 degrees amplitude around angle of attack of 5 degrees at 45 m/s with prescribed counter-acting flaps motion (feed forward control) (1V=21.3μ strain). Grey line: without flaps, Black line: feed forward control of flaps. Experimental results.

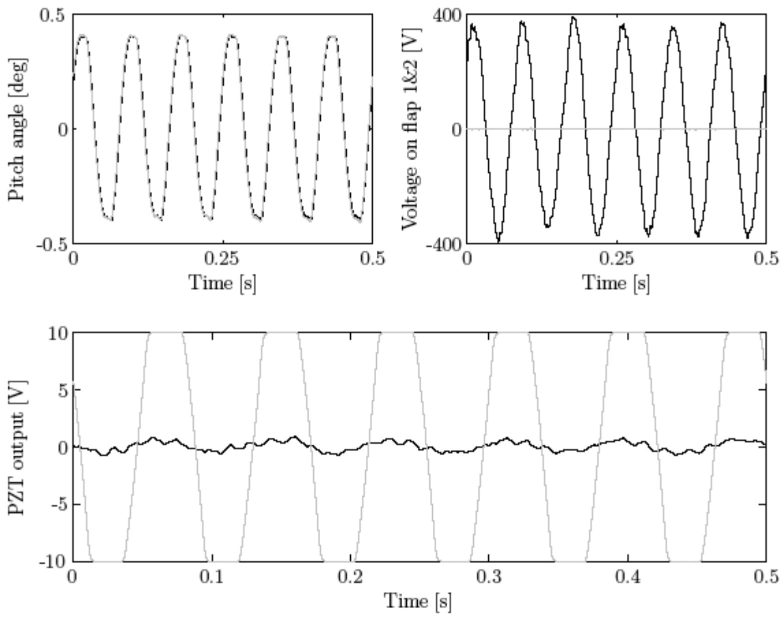

Figure 16. Reduction in root strain fluctuations in the case of a sinusoidal pitch excitation of 12.5 Hz with 0.5 degrees amplitude around angle of attack of 5 degrees at 45 m/s with feedback controlled flaps motion (1V=21.3μ strain). Grey line: without flaps, Black line: feedback control of flaps. Experimental results.

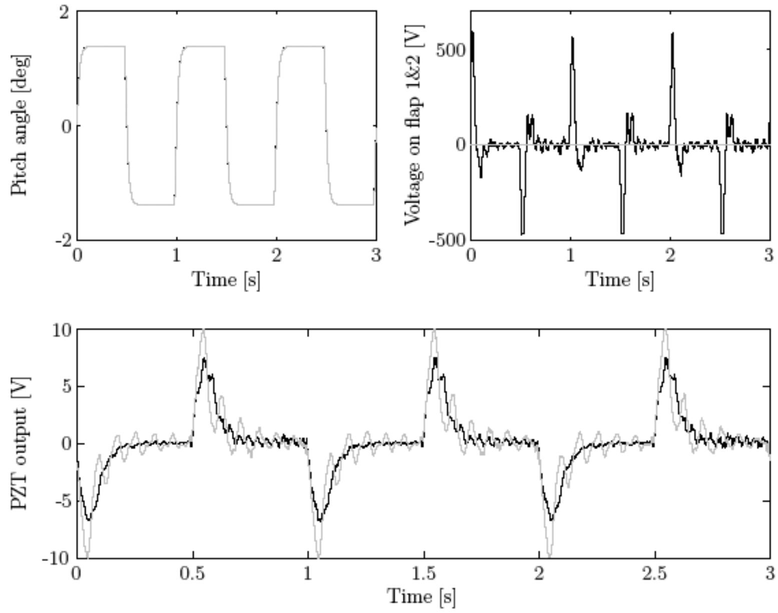

Figure 17. Reduction in root strain fluctuations in the case of a step pitch disturbance at angle of attack of 5 degrees at 45 m/s with feedback controlled flaps motion (1V=21.3μ strain). Grey line: without flaps, Black line: feedback control of flaps. Experimental results.

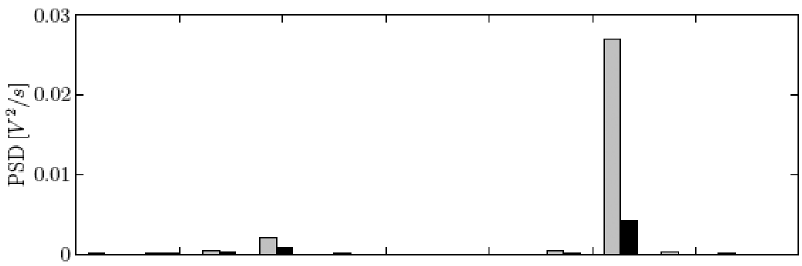

Figure 18. PSD of measured strains with (black line) and without (grey line) feedback control for the case of a representative noise signal. Experimental results.

5. Prospectives

The potential for load reduction by using smart control concepts for wind turbines has been proven with various approaches. Helicopter experience also has shown promising results both in simulations, scale experiments [4] and full scale applications [24],[25]. On the other hand, the application of such advanced control concepts on wind turbines will have to face great challenges, in order to come from research stage to product stage. More research investigations will have to be made in order to identify design parameters for aerodynamic control devices with full wind turbine simulations and more advanced tools will have to be used. The gained knowledge of the wind energy research community in unsteady aerodynamics, advanced dynamics and control will contribute to that. Also, whether all design restrictions are met will be critical for future applications. This means that current reliability and safety of wind turbine blades (and control)

should not be compromised and technology should not be too far off manufactures experience. This will probably be the main design driver for such systems. Already, in the very near future, scaled prototypes and scaled experimental setups will be prepared. After successful application, the next stage will be full scale prototypes, and in the future, field testing of such concepts. Research concerning smart rotor concepts for wind turbines is ongoing. Big research projects deal with this subject as has been already mentioned.
To sum up, the subject of smart rotor control for wind turbines is an innovative research area, preparing possible solutions for next generation of large (and offshore) wind turbines. Parallel research activities will have to be combined in the end, in order to establish necessary advanced technology to bring wind energy to the next stage of development "outsmarting" the scaling laws.

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[1] Veers P S et al. Trends in the design, manufacture and evaluation of wind turbine blades. *Wind Energy*, 6, 2003.
[2] Proceedings. In *IEA Topical Expert Meeting on The Application of Smart Structures For Large Wind Turbine Rotor Blades*, 2006.
[3] Collis S S, Joslin R D, Seifert A, and Theofilis V. Issues in active flow control: theory, control, simulation and experiment. *Progress in Aerospace Sciences*, 40, 2004.
[4] Chopra I. Review of state of art of smart structures and integrated systems. *AIAA Journal (USA)*, 40, 2002.
[5] Bersee H. Smart rotor blades and rotor control. In *EWEC 2007 - Upwind Workshop Track*, 2007.
[6] Barlas T K. Smart rotor blades and rotor control - state of the art - knowledge base report for upwind project wp 1b3. Technical report, UpWind WP 1B3, 2007.
[7] Marrant B A H and van Holten T. Smart dynamic control of large offshore wind turbines. In *OWEMES 2003*, 2003.
[8] Geyler M. Advanced pitch control for wind turbines. Technical Report 2001.001, Delft University of Technology - DUWIND, January 2001.
[9] van Kuik G A M. Introductory note. In *IEA Topical Expert Meeting on The Application of Smart Structures For Large Wind Turbine Rotor Blades*, 2006.
[10] Bossanyi E A. The design of closed loop controllers for wind turbines. *Wind Energy*, 3, 2000.
[11] Kuik W and Wegerif R C. Ultieme bladhoek regeling. Technical Report R052.01/01.09.98, Stentec Heeg, September 1998.
[12] Hammond C E. Wind tunnel results showing rotor vibratory loads reduction using higher harmonic pitch. *Journal of the American Helicopter Society*, 28, 1983.
[13] Chopra I and Gessow A. Recent progress on the development of a smart rotor system. In *26th European Rotorcraft Forum*, 2000.
[14] Bossanyi E A. Wind turbine control for load reduction. *Wind Energy*, 6, 2003.
[15] Bossanyi E A. Further load reductions with individual pitch control. *Wind Energy*, 8, 2005.
[16] van Engelen T G and van der Hooft E L. Individual pitch control inventory. Technical Report ECN-C-03-138, ECN, June 2005.
[17] Larsen T J, Madsen H A, and Thomsen K. Active load reduction using individual pitch, based on local inflow measurements. *Wind Energy*, 8, 2005.
[18] van der Hooft E L and van Engelen T G. Feed forward control of estimated wind speed. Technical Report ECN-C-03-137, ECN, December 2003.
[19] Hand M M, Wright A D, Fingersh L J, and Harris M. Advanced wind turbine controllers attenuate loads when upwind velocity measurements are inputs. In *44th AIAA/ASME*, 2007.
[20] Breitbach E J, Anhalt C, and Monner H P. Overview of adaptronics in aeronautical applications. *Air and Space Europe*, 3, 2001.
[21] Stanewsky E. Adaptive wing and flow control technology. *Progress in Aerospace Science*, 37, 2001.
[22] Leishman J G. Challenges in modelling the unsteady aerodynamics of wind turbines. *Wind Energy*, 5, 2002.

[23] Straub F K. A feasibility study of using smart materials for rotor control. *Smart Materials and Structures*, 5, 1996.
[24] Enenkl B, Klopper V, and Preibler D. Full scale rotor with piezoelectric actuated blade flaps. In *28th European Rotorcraft Forum*, 2002.
[25] Roth D, Enenkl B, and Dieterich O. Active rotor control by flaps for vibration reduction - full scale demonstrator and first flight test results. In *32nd European Rotorcraft Forum*, 2006.
[26] Migliore P G, Quandt G A, and Miller L S. Wind turbine trailing edge aerodynamic brakes. Technical Report NREL/TP-441-7805, NREL, April 1995.
[27] Miller L S. Experimental investigation of aerodynamic devices for wind turbine rotational speed control. Technical Report NREL/TP-441-6913, NREL, February 1995.
[28] Miller L S, Quandt G A, and Huang S. Atmospheric tests of trailing edge aerodynamic devices. Technical Report NREL/SR-500-22350, NREL, January 1998.
[29] Stuart J, Wright A, and Butterfield C. Considerations for an integrated wind turbine controls capability at the national wind technology center: An aileron control case study for power regulation and load mitigation. Technical Report NREL/TP-440-21335, NREL, June 1996.
[30] Stuart J, Wright A, and Butterfield C. Wind turbine control systems: Dynamic model development using system identification and the fast structural dynamics code. In *35th AIAA/ASME*, 1997.
[31] Troldborg N. Computational study of the risøb1-18 airfoil with a hinged flap providing variable trailing edge geometry. *Wind Engineering*, 29, 2005.
[32] Basualdo S. Load alleviation on wind turbine blades using variable airfoil geometry. *Wind Engineering*, 29, 2005.
[33] Gaunaa M. Unsteady 2d potential-flow forces on a thin variable geometry airfoil undergoing arbitrary motion. Technical Report Risø-R-1478(EN), Risø, July 2006.
[34] Theodorsen T. General theory of aerodynamic instability and the mechamism of flutter. Technical Report NACA Report 497, NACA, July 1935.
[35] Leishman J G. Unsteady lift of a flapped airfoil by indicial concepts. *Journal of Aircraft*, 31, 1994.
[36] Buhl T, Gaunaa M, and Bak C. Load reduction potential using airfoils with variable trailing edge geometry. In *43th AIAA/ASME*, 2005.
[37] Buhl T, Gaunaa M, and Bak C. Potential load reduction using airfoils with variable trailing edge geometry. *Solar Energy Engineering*, 127, 2005.
[38] Bak C et al. Wind tunnel test on wind turbine airfoil with adaptive trailing edge geometry. In *45th AIAA/ASME*, 2007.
[39] Yen D T, van Dam C P, Smith R L, and Collins S D. Active load control for wind turbine blades using MEM translational tabs. In *39th AIAA/ASME*, 2001.
[40] Nakafuji D T Y, van Dam C P, Michel J, and Morrison P. Load control for wind turbines - a non-traditional microtab approach. In *40th AIAA/ASME*, 2002.
[41] Baker J P, Standish K J, and van Dam C P. Two-dimensional wind tunnel and computational investigation of a microtab modified s809 airfoil. In *43th AIAA/ASME*, 2005.
[42] Chow R and van Dam C P. Computational investigations of deploying load control microtabs on a wind turbine airfoil. In *45th AIAA/ASME*, 2007.
[43] Oerlemans S. Wind tunnel aeroacoustic tests of six airfoils for use on small wind turbines. Technical Report NREL/SR-500-35339, NREL, March 2007.
[44] Marrant B A H and van Holten T. Concept study of smart rotor blades for large offshore wind turbines. In *OWEMES 2006*, 2006.
[45] Joncas S, Bergsma O, and Beukers A. Power regulation and optimization of offshore wind turbines through trailing edge flap control. In *43th AIAA/ASME*, 2005.
[46] Andersen P B, Gaunaa M, Bak C, and Buhl T. Load alleviation on wind turbine blades using variable airfoil geometry. In *2006 European Wind Energy Conference and Exhibition*, 2006.
[47] Mc Coy T and Griffin D A. Active control of rotor aerodynamics and geometry: Status, methods and preliminary results. In *44th AIAA/ASME*, 2006.
[48] Hulskamp A W, Beukers A, Bersee H, van Wingerden J W, and Barlas T K. Design of a wind tunnel scale model of an adaptive wind turbine blade for active aerodynamic load control experiments. In *16th ICCM*, 2007.