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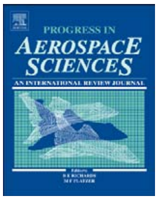

Review of state of the art in smart rotor control research for wind turbines

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ABSTRACT

This article presents a review of the state of the art and present status of active aeroelastic rotor control research for wind turbines. Using advanced control concepts to reduce 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 build-in intelligence on the blades. Such concepts are often named in popular terms 'smart structures' or 'smart rotor control'. The review covers the full span of the subject, starting from the need for more advanced control systems emerging from the operating conditions of modern wind turbines and current load reduction control capabilities. An overview of available knowledge and up-to date progress in application of active aerodynamic control is provided, starting from concepts, methods and achieved results in aerospace and helicopter research. Moreover, a thorough analysis on different concepts for smart rotor control applications for wind turbines is performed, evaluating available options for aerodynamic control surfaces, actuators (including smart materials), sensors and control techniques. Next, feasibility studies for wind turbine applications, preliminary performance evaluation and novel computational and experimental research approaches are reviewed. The potential of load reduction using smart rotor control concepts is shown and key issues are discussed. Finally, existing knowledge and future requirements on modeling issues of smart wind turbine rotors are discussed. This study provides an overview of smart rotor control for wind turbines, discusses feasibility of future implementation, quantifies key parameters and shows the challenges associated with such an approach.

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1. Introduction

The size of wind turbines has been steadily increasing over the past years. Rotors of more than 120 m diameter are already in prototype stage. With the intention to lower the cost per kWh, new trends and technological improvements have been a primary target of research and development. Reducing the cost of wind turbine blades has an effect on the cost 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 turbine blades. 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 technologies capable of considerably reducing ultimate and fatigue loads on wind turbines. Many concepts for load reduction 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 appropriate sensor inputs. individual pitch control is the most advanced active control that is applied nowadays. The traditional passive control solution based on aerodynamics is stall control, used for power regulation. Other passive control solutions based on aeroelastic tailoring, like tension–torsion coupling, bend–twist coupling and sweep–twist coupling are still under investigation [34,2,3]. Although such systems are usually chosen mainly for their simplicity (compared to the use of additional components for active control), for wind turbine applications, such systems are not necessarily reliable and easily maintainable. From the controls point of view, active control techniques offer significantly more flexibility, especially when dealing with unsteady changes in a flow state [4].

A more advanced concept of active control is being investigated recently in various research programs. This concept is focusing on a much faster and detailed load control. Ideally, control should be possible for each blade at any azimuthal position and any span-wise station, by aerodynamic control devices with embedded intelligence distributed along the span. This implies the implementation of efficient, innovative actuators which drive local aerodynamic surfaces, and through the combination of sensors and controllers, provide (feedback) load control. Such concepts are generally referred to as ‘smart rotor control’, a term used in rotorcraft research. 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 [5].

The target of this control for wind turbine applications is the reduction of fluctuating loads on the blades in a more detailed way than modern blade pitch control. 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 being investigated by various wind energy research institutes. The work package ‘Smart rotor blades and rotor control’ in the *Upwind* European Union framework program, the project ‘Smart dynamic control of large offshore wind turbines’ sponsored by the the Dutch Technology Foundation STW and the Danish project ‘ADAPWING’, all deal with the subject of smart rotor control. In the framework of the International Energy Agency two Expert Meetings were held on ‘The application of smart structures for large wind turbine rotors’, by DUWIND (Delft University Wind Energy Research Institute) and Sandia (Sandia National Labs), respectively. The proceedings show a variety of topics, methods and solutions, which reflects the ongoing research [34,35]. Existing knowledge and research on the subject has been recently reviewed in the framework of the Upwind project and preliminary presented in [36], where this article builds on.

In Section 2, the unsteady loads on modern wind turbine rotors are analyzed together with existing solutions for load control. In Section 3, a general overview of knowledge in aerospace and rotorcraft fields is presented regarding the investigated subject. In Section 4, different proposed concepts for smart rotor control components and strategies are discussed, including basic sets of requirements for future implementation. In Section 5, the overview and analysis of up-to-date research for wind turbine application is presented. A discussion on modeling issues is contained in Section 6. Finally, general conclusions and discussion is presented in Section 7.

2. Unsteady loads and control for load reduction

2.1. Defining unsteady environment and ways of influencing it

The loads acting on a wind turbine during operation can be divided into aerodynamic and gravity loads (external), and structural loads (internal). 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 are important. The rotational sampling of the incoming turbulent field is also indicated by 1p (once per revolution) and higher harmonic frequencies superimposed on the turbulence spectrum in the frame of reference of a rotating blade section. In general the following effects contribute to the total fluctuations comprising an 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 [38]. 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 [39]. Many approaches for load reduction control, using the existing full-span blade pitch system, have been proposed and will be summarized below.

2.2. Evolution of wind turbine control systems for power regulation and 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 [37]. 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. It is believed that further upscaling of wind turbine rotors will require more advanced load control systems for load reduction (see [61,81]).

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. Focusing only on periodic loads, control strategies from helicopter research have been investigated. Cyclic Pitch Control (1p cyclic change in pitch, see [39,40]) and higher harmonic control (pitch actions with multiples of rotor frequency, np, see [41,42]) have shown some potential of load reduction. Although the wind field 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 by superimposing a cyclic variation of the pitch angle per blade, because of the dominance of stochastic variations due to turbulence and variation of wind shear and upflow according to environmental conditions [43]. More advanced approaches of using the blade pitch mechanism for load reduction control purposes have been proposed, based on real feedback control loops. Power regulation is always achieved through the collective pitch angle. Bossanyi [43–45] 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. van Engelen and van der Hooft at ECN (the Energy research Center of the Netherlands) [46] suggest a parametrization of feedback loops for individual pitch control around 1,2,3p frequencies for load reduction, making use of the multi-rotational (or Coleman) transformation, while the same method is investigated for stability analysis by Bir [47]. In a different approach, Larsen et al. [48], 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 usually 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 [49] suggest the estimation of incoming wind speed based on energy balance and Hand et al. [50] propose the use of a LIDAR (light detection and ranging) system to directly measure the upwind incoming flow field and react with the pitch system. The individual pitch control approach has been further explored incorporating advanced control techniques for further load reduction. In [51], a multivariable H_2[1] individual pitch controller with feed-forward wind disturbance rejection technique is utilized and it is shown that better load reduction capabilities can be achieved. An H_∞[2] multivariable controller is used in [52], where active tower damping is included. Load reduction comparable to simple PI (proportional integral) controller with a first order low pass filter was achieved and robustness to uncertainty in aerodynamic coefficients has been shown. Similar work with multivariable controls including tower mode active damping is shown in [53] where reduction in fatigue loads is presented compared to a normal PI controller. Hand and Balas [54] have also shown the efficiency of a disturbance accommodating controller, which incorporates properties of coherent turbulence inflow structures, in achieving load reduction compared to a normal PI controller.

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[1] H_2 is a modern control theory method for linear-quadratic optimization problems, where external disturbances are assumed to be Gaussian white noise.

[2] H_∞ is a modern control theory method for linear-quadratic optimization problems, when the external disturbances are taken to be worst-case disturbances.

Individual pitch control can provide further load reduction and is still under research investigation. Nevertheless, some issues that keep load reduction control up to certain limits have been identified. The large multi-MW blades can limit the speed of the pitch actuator needed for load reduction control. Also, the excessive use will lead to wear of the pitch bearings and actuator. The results from the previous research efforts show that the demanded pitch angles and rates are relatively high especially when trying to reduce fluctuations caused by turbulence. In [55] the dynamics and stability of a hydraulic pitch actuator are simulated, and it can be seen that the behavior the actuator can limit the fast reaction time needed for load control. Furthermore, more distributed control is required in order to achieve considerable load reduction of the fluctuations in the asymmetric inflow field of large rotors. Active control based on real-time measured quantities (being loads, accelerations or inflow states) 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. Small, low inertia aerodynamic surfaces can both result in fast control reaction time and distributed control over the asymmetric incoming wind field. 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 [56] and results are presented here after the review of existing research in aerospace.

3. Relevant research in aerospace

3.1. Aircraft applications

The problem of actively controlling aeroelastic responses has been a major concern through the history of aerospace. Controlling structural responses using aerodynamic means can have various beneficial results like flutter suppression, fatigue load alleviation, gust alleviation, noise reduction or increased ride quality. Thus, long-term research programs have been investigating various applications in aircraft wings. The historical perspective of the subject has been well documented by Mukhopadhyay [6]. Programs like the Active Flexible Wing (AFW) [7], the Benchmark Active Control Technology (BACT) [8], the Smart Wing [9] and the Active Aeroelastic Wing program [10] have demonstrated the ability of active control systems to deal with aeroelastic instabilities, reduce loads or improve performance. In these campaigns, important issues have been analyzed, like unsteady aerodynamics, control surface design, actuator dynamics, controller design for load reduction and flutter suppression, and aeroservoelastic modeling, simulation and wind tunnel testing of actively controlled wings.

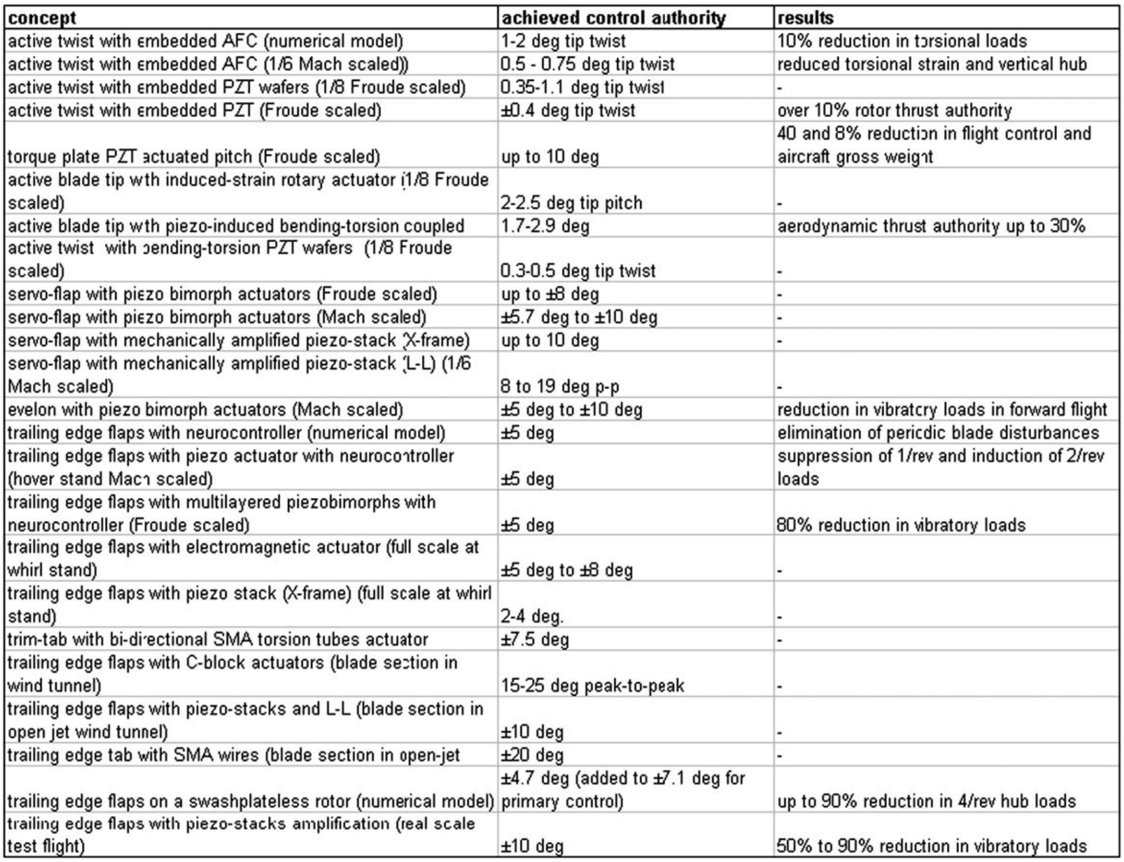
Moreover, various research activities in aerospace have been oriented in the use of adaptive materials and integrated system for aeroelastic control. The use of smart material actuators has been considered as an effective solution for control surface actuation. Also, the concept of morphing airfoils as aerodynamic control surfaces has been explored (an idea not so new, since it was used by the Wright brothers in their first successful flight in 1903). An interesting overview of early aerospace research programs about controlled aeroelastic response using such concepts is documented in [11]. Research on the topic is ongoing with numerous recent publications on controlling aeroelastic response with trailing edge flap devices for gust alleviation or flutter suppression (see [12–14]).

3.2. Helicopter applications

Although investigations of controlling aeroelastic responses in typical airfoil sections or wings offers the basis for every attempt of aeroelastic control, the concept of applying this idea to wind turbine rotor blades can be approached more realistically considering similar applications in rotorcraft research. The concept of active control on rotor blades, especially 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, modeling and experimental testing.

However, some differences exist between helicopter and wind turbine applications. Firstly, some operating parameters are different: Helicopter blades experience higher rotational speeds, frequencies, centrifugal and aerodynamic forces (compared to their size). Moreover, the high amounts of scheduled maintenance required for helicopters are a given fact, whereas, wind turbine blades have low maintenance requirements, and considering the limited maintainability of offshore wind turbines, the use of devices that raise additional requirements is not easily justified. On the other hand, wind turbine blades are of much higher size scale, very much cost-driven and reliable, but not so limited by weight (compared to helicopter blades used for flight). This leads to some restrictions but also advantages, concerning active control applications. Also, the aerodynamics of a wind turbine are in many ways parallel to the ones found in helicopter rotors. Same problems include the challenges in understanding and predicting the unsteady blade airloads and performance, as well as predicting the dynamic stresses and aeroelastic response of the blades [15]. On the other hand, wind turbines are subjected to some other complicated effects like wind shear, turbulence, tower shadow and wakes of other turbines. Airloads acting on helicopter blades (mostly at forward flight) are highly periodic due to the common variations in both the local angle of attack and the relative velocities seen by the blade sections during one revolution.

Major research programs have been running over the years evaluating previous research studies, aerodynamic control device concepts, actuators selection, smart materials and feasibility for rotor control. Review articles like the ones of Straub [23] and Chopra [5], analyze available concepts. 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 20 years resulting in various successful applications. Some representative examples are well summarized in [5]. Research achievements from the long term smart rotor program at the University of Maryland are mainly presented. Investigations focused on closed-loop wind tunnel testing of Mach-scaled or Froude-scaled models, incorporating smart material actuated control devices. Discrete and embedded piezoceramic actuators as well as SMAs have been utilized. The concepts of trailing edge flaps, active tips and active full-blade twist have been explored. The potential for load reduction has been demonstrated. Recently, Roget and Chopra [16] performed



concept	achieved control authority	results
active twist with embedded AFC (numerical model)	1-2 deg tip twist	10% reduction in torsional loads
active twist with embedded AFC (1/6 Mach scaled))	0.5 - 0.75 deg tip twist	reduced torsional strain and vertical hub
active twist with embedded PZT wafers (1/8 Froude scaled)	0.35-1.1 deg tip twist	-
active twist with embedded PZT (Froude scaled)	±0.4 deg tip twist	over 10% rotor thrust authority
torque plate PZT actuated pitch (Froude scaled)	up to 10 deg	40 and 8% reduction in flight control and aircraft gross weight
active blade tip with induced-strain rotary actuator (1/8 Froude scaled)	2-2.5 deg tip pitch	-
active blade tip with piezo-induced bending-torsion coupled	1.7-2.9 deg	aerodynamic thrust authority up to 30%
active twist with bending-torsion PZT wafers (1/8 Froude scaled)	0.3-0.5 deg tip twist	-
servo-flap with piezo bimorph actuators (Froude scaled)	up to ±8 deg	-
servo-flap with piezo bimorph actuators (Mach scaled)	±5.7 deg to ±10 deg	-
servo-flap with mechanically amplified piezo-stack (X-frame)	up to 10 deg	-
servo-flap with mechanically amplified piezo-stack (L-L) (1/6 Mach scaled)	8 to 19 deg p-p	-
evelon with piezo bimorph actuators (Mach scaled)	±5 deg to ±10 deg	reduction in vibratory loads in forward flight
trailing edge flaps with neurocontroller (numerical model)	±5 deg	elimination of periodic blade disturbances
trailing edge flaps with piezo actuator with neurocontroller (hover stand Mach scaled)	±5 deg	suppression of 1/rev and induction of 2/rev loads
trailing edge flaps with multilayered piezobimorphs with neurocontroller (Froude scaled)	±5 deg	80% reduction in vibratory loads
trailing edge flaps with electromagnetic actuator (full scale at whirl stand)	±5 deg to ±8 deg	-
trailing edge flaps with piezo stack (X-frame) (full scale at whirl stand)	2-4 deg.	-
trim-tab with bi-directional SMA torsion tubes actuator	±7.5 deg	-
trailing edge flaps with C-block actuators (blade section in wind tunnel)	15-25 deg peak-to-peak	-
trailing edge flaps with piezo-stacks and L-L (blade section in open jet wind tunnel)	±10 deg	-
trailing edge tab with SMA wires (blade section in open-jet	±20 deg	-
trailing edge flaps on a swashplateless rotor (numerical model)	±4.7 deg (added to ±7.1 deg for primary control)	up to 90% reduction in 4/rev hub loads
trailing edge flaps with piezo-stacks amplification (real scale test flight)	±10 deg	50% to 90% reduction in vibratory loads

Fig. 1. Developed concepts and achieved results in smart structures concepts for helicopters.

closed loop control wind tunnel tests on a four bladed Mach scaled rotor with individually controlled trailing edge flaps. The actuation was based on piezoelectric bender actuators. System identification was used for controller design. Simultaneous reduction of 1 and 4/rev components of fixed-frame loads is demonstrated (43% reduction). All known smart-material solutions for aeroelastic and vibration control have also been summarized by Giurgiutiu [22]. Active blade twist and active flaps concepts are reviewed, together with variety of smart material actuation concepts.

The subject of aeroservoelasticity has gained significant interest in rotorcraft research during the last decade. Especially the concept of actively controlled flaps has been greatly explored. The general perspective of the topic has been summarized very well in [17–19]. More recent work focuses on optimization of active flap control for vibration reduction and performance enhancement [20,21].

The most successful recent research in active rotor control using smart devices is the one in the ADASYS project (a joint task between Eurocopter, EADS CRC, Daimler Chrysler Research Labs and DLR) [24–27]. After long term experience in higher harmonic and individual blade control techniques, the active flap concept for vibration reduction was pursued. A full scale rotor is developed based on a BK117/EC145. Actively controlled piezoelectric actuated trailing edge flaps are used on each blade. The system is tested during flight, in open-loop and closed-loop configuration and shows excellent performance in reduction of vibratory loads (50–90% reduction).

Although the field of smart rotor research for helicopters is vast, and it is not the purpose of this article to fully cover it, based on the most important research and development effort, different concepts can be compared. Based on literature (especially Refs. [5,16–22] provide a large amount of information) a table of most important achievements in this field has been compiled (Fig. 1). The different implemented aerodynamic devices and actuators can be seen, together with details on the implementation (model, wind tunnel testing, scaling) and capabilities (control authority, loads reduction). Also in Fig. 2, a schematic of most important concepts is presented. The general layout of various actuation options for each case is also illustrated. By analyzing the various achievements, some conclusions can be drawn. Firstly, it is clear that maximum control authority can be achieved by using trailing edge flaps in combination with mechanically amplified smart material actuation. This has also been proven in real scale applications. Active twist concepts with embedded smart material features has proven interesting, but limited control authority can be provided. Also, the blade structure is changed considerably, affecting weight and stiffness properties. Also limited variability in the control authority is possible (and no variable spanwise control). On the other hand, discrete hinged devices, although offering great performance in loads reduction as appearing from the mentioned investigations, can require a complicated internal structure with pitch links, rods, etc. All these results are of great interest for wind turbine smart rotor applications, and should be taken into account as lessons learned from the helicopter research.

By studying further the various attempts for smart rotor control in helicopters some conclusions can be drawn also from the design point of view. Because of the strong periodic nature of airloads in helicopter blades some investigations have focused on applying high frequency aerodynamic control to reduce these fluctuations, instead of real feedback control based on measured

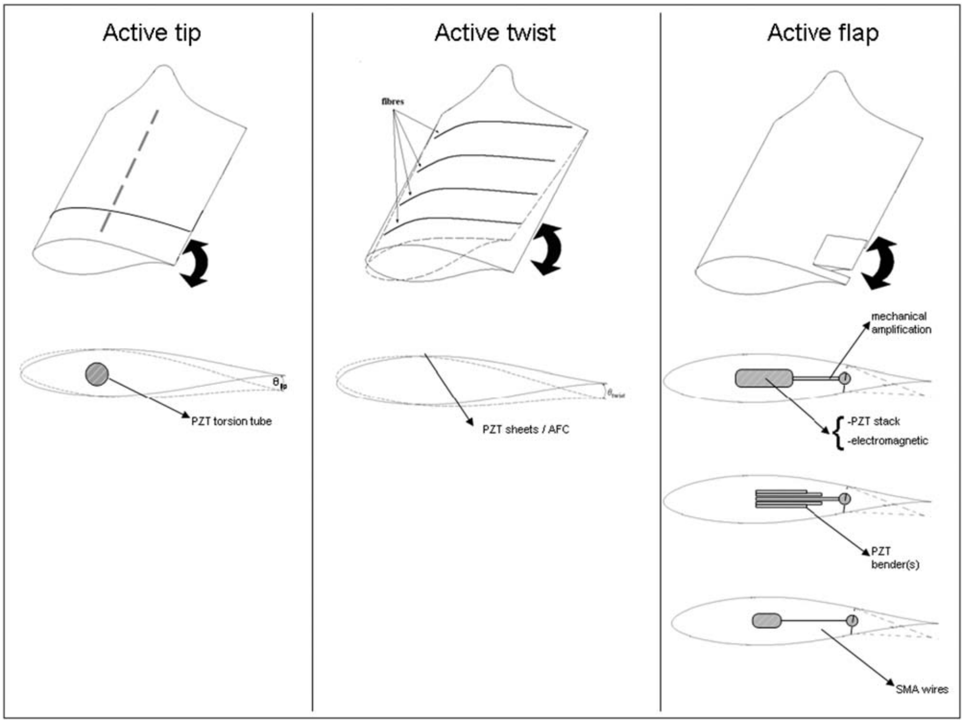


Fig. 2. Schematics of smart structures concepts for helicopters.

quantities (e.g. Higher Harmonic Pitch control). The use of aerodynamic control surfaces (trailing edge flaps, tabs, moving tips) on the blades gives the advantage of faster control with smaller deflections (due to the large moment arm near the blade tip) for reduction of blade root moments, without using full blade pitching that is inefficient due to the use of the swashplate and the larger inertia. Also, because of the small size and thickness of the helicopter blades, the potential of smart actuating devices was identified early. Smart materials can 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 parameter for such applications. Various amplification mechanisms have been generally used in order to achieve bigger displacements. Most smart materials exhibit low strains and moderate forces for large scale applications. In order to make them applicable as discrete actuator devices, mechanical amplifiers are used to increase the strain where force and strain capabilities of the material are interchanged. Several configurations have been proposed. Usually, this kind of mechanical amplification systems use parts as rods, arms, frames, etc. to deliver amplified displacement or power to specific control devices from the actuators. Always a trade-off between force and displacement is taking place. 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. Analysis of concepts

In this section, the different concepts of application of smart rotor control for wind turbines are presented and analyzed. Concepts regarding aerodynamic control devices, actuators and smart materials, sensors and controllers are overviewed. Extensive analysis has been performed through UPWIND project's work package 'Smart Rotor Blades and Rotor Control' [56]. A conceptual layout of the various components realized on a wind turbine blade can be seen in Fig. 3. Details on the comparison of various concepts are presented here, where a general prospective of future implementation is discussed. Details on research work using some of these concepts are presented in Section 5.

4.1. *Aerodynamic control surfaces*

Aerodynamic control surfaces or devices act as the input on the smart control objective, changing the local aerodynamic characteristics on the blades and providing the necessary control actions.

In order to apply active control, aerodynamic devices on the blades should be able to either change the characteristic $C_l - \alpha$ curve over specific sections or directly change the angle of attack. In order to control the fluctuating structural loads on the blade root (and consequently on other components) the devices should be placed near the blade tip, because of the larger moment arm achieved in this way. Moreover the simplicity, the aerodynamic efficiency, the linearity and achieved bandwidth of the control devices are crucial parameters. Furthermore, a lot of design restrictions make the application of such devices challenging. Increase in weight, complexity, moving parts, increased maintenance and increased danger of lightning strikes should be avoided at much as possible. The modern wind turbine blades are considered very reliable and require only limited maintenance at the blade pitch bearing. Additional aerodynamic devices should

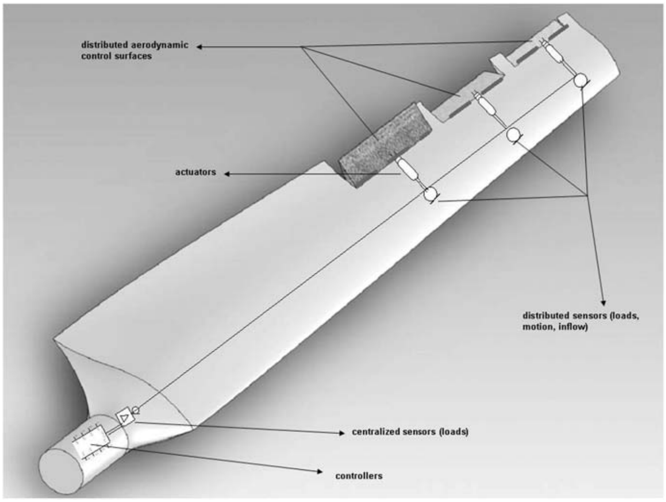


Fig. 3. Conceptual layout of a smart wind turbine rotor blade.

justify their contribution in increase in total cost or decrease in reliability, by providing efficient load reduction capability. The required aerodynamic performance of such devices strongly depends on the operating conditions and the wind turbine characteristics, but also parameters like the aerofoil type. Some general estimation for what range of aerodynamic loads these devices will have to alleviate can be made. For example Troldborg [58] calculated a representative change in the inflow angle at a section near the tip of a 30 m long blade induced by a turbulent wind field, wind shear and tower shadow effects. The standard deviation in the inflow angle was 1.6°. Aerodynamic control devices will have to be able to produce changes in angle of attack (or required lift for the same angle of attack) that can compensate for the incoming changes. Consequently, these devices (surfaces) can be firstly compared according to the changes in lift or angle of attack that they can achieve and their bandwidth. Barlas [99] analyzed the changes in inflow and predicted the theoretically required flap angles and actuation frequencies needed for full control of all fluctuations in aerodynamic (and structurally induced aerodynamic) loads on the tip sections of the 5 MW reference wind turbine used in the Upwind project. Representative IEC operating cases were simulated, including all wind disturbances and also various cases of yaw misalignment. The results show that 10% chord length trailing edge flaps located near the tips can alleviate all aerodynamic load fluctuations with a range in flap deflections between $+12^{\circ}$ and -12° in normal power production cases, and with a range of $+15$ to -15 in extreme load cases. Also, considering the blades, the load spectrum with considerable energy content, in these cases, extends virtually from 0 to 6 Hz. This means that the bandwidth of the actuators 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 12 Hz 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). The mentioned requirements comprise the theoretical upper limit of load reduction. In reality, the actuators and aerodynamic devices will not reach this performance, and design issues (e.g. power consumption) will determine the actual limits of load reduction performance. Also aerodynamic unsteadiness should be considered, which in dynamic operation will limit the performance of the aerodynamic devices compared to the quasi-steady analysis. For the above-mentioned reference wind turbine it has been predicted that unsteady aerodynamic effects will appear at typical inflow and blade motion frequencies during normal operation.

4.1.1. Flaps

Inspired by existing technology in aircraft and rotorcraft applications, the general concept of a small movable control surface to directly control lift on a blade seems promising for active load control. By increasing (deployment on the pressure side) or decreasing (deployment on the suction side) the camber of the airfoil, trailing edge flaps generate substantial change in the lift coefficient of the airfoil (change in maximum lift, lift curve slope and zero-lift angle of attack [100]), by altering the pressure distribution along the chord. Such devices can achieve significant change in lift over a blade using small surface deflections, have intrinsically better structural and safety features than single shaft mechanism that should operate a tip control surface and have substantial smaller power requirements than full or part span pitch control. Also, high frequency control is possible (due to low inertia of surfaces) and such devices seem attractive to be used in combination with smart materials for actuation. Trailing edge flaps can be employed in two manners: either as discrete flaps or as continuous deformable trailing edge (Fig. 4). Discrete flaps (or ailerons) are mounted on the blade (hinged) and require a moment over the hinge to achieve the required position. These kinds of flaps are generally promising, but pose certain disadvantages. They do not comprise an integrated design solution, all the necessary mounting components are subject to wear and corrosion and the aerodynamic performance (mainly lift to drag ratio) is reduced due to the sharp change in the camber. Furthermore, surface discontinuity triggers stall and poses noise issues. Continuous deformable trailing edge (the word flap does not probably apply to this situation—variable trailing edge geometry is more applicable) shows a smooth change in shape, which increases its effectiveness (flap effectiveness in lift change and lift to drag ratio [100]), is an interesting integrated solution for an aerodynamic control device and is composed of very simple and uniform parts. To be actuated, a bending moment must be exerted on the trailing edge. On the other hand, this kind of control has to work against the structural rigidity of the trailing edge (depending on the material) and its skin will probably be subject to fatigue. This concept is based on a combination of the ideas of aileron-flap and camber control based on skin deformation, utilizing small part of the blade. Actuating solutions range from conventional motors to smart material actuators, which will be analyzed later.

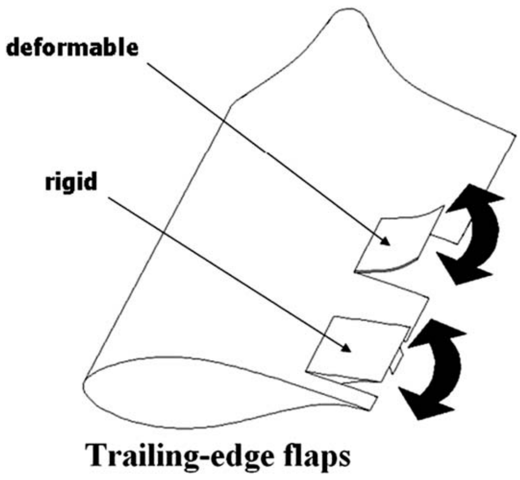


Fig. 4. Trailing edge flaps concept.

Fig. 5. Microtab concept.

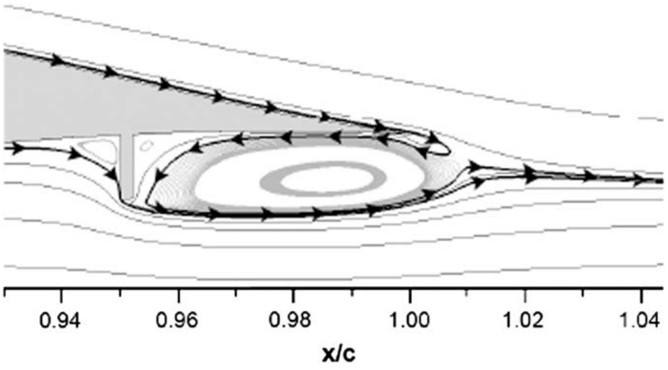


Fig. 6. Microtab induced flow in airfoil trailing-edge region [71].

4.1.2. *Microtabs*

The use of 'microtabs' as aerodynamic devices for load control on wind turbine blades has been proposed and extensively investigated by van Dam [66–69]. The microtab concept has been derived from an earlier concept of Gurney flaps. Microtabs are small (deployment height in the order of the boundary layer thickness) translational devices placed near the trailing edge of an airfoil (Fig. 5). The deployment of such tabs changes the trailing edge flow development (Kutta condition), so the effective camber of the airfoil, providing changes in lift (Fig. 6). The microtab deploys approximately normal to the surface and has a maximum translation in the order of the boundary layer thickness, 1–2% of the chord. Lift enhancement is achieved by deploying the tab on the lower (pressure) side of the aerofoil, while lift mitigation is achieved by deploying the tab on the upper (suction) side of the aerofoil. Another possibility to reduce the lift is to locate the tab near the onset of pressure recovery in order to induce flow separation. 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, though, can be achieved by spanwise deployment of microtabs (Fig. 6).

These tabs are usually 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. When the upper and lower tab are both installed near the trailing-edge, typical increases in lift coefficient which have been found in literature are $\Delta C_l = 0.3$ for a tab height-to-chord ratio $T_h/c = 1\%$ with maximum increases of $\Delta C_l = +0.4$ for a $T_h/c = 2\%$ and when the upper tab is located at the onset of pressure recovery even values of $\Delta C_l = -0.55$ can been seen. The lift over drag ratios of airfoils with microtabs decrease with respect to the base airfoil for lift coefficients up to the base airfoil maximum lift coefficient. Above this maximum lift coefficient it may exceed the lift over drag ratios of the base airfoil. Because of the minute size of these devices, much faster response times can be achieved than other control concepts. For large scale wind turbine applications, such devices will not probably be in the microscale and will be actuated in a different way. They can be actuated using classic electro-actuators or smart material actuators based on piezoelectric materials.

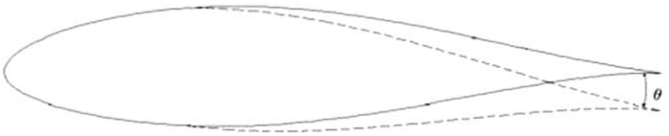


Fig. 7. Camber control concept.

4.1.3. *Camber control (morphing)*

Camber control is another effective way of controlling the aerodynamic forces by directly changing the shape of the airfoil. This action has direct effects on the force distribution on the blade, so it can be used for active load alleviation purposes (Fig. 7). This can be achieved generally by implementing smart materials inside the blade skin, or some kind of internal deformable structure. Such actuation process has to overcome all applied aerodynamic, dynamic and structural forces and deform the inner structure of the airfoil. Various concepts have been proposed for actuation, ranging from deformable construction for the center part of the chord to bending the aft section (or just the trailing edge). The former concept can be actuated by an internal framework which can be deformed by discrete actuators, or smart materials. This kind of framework is used to provide load carrying paths and it is often referred to as a 'compliant mechanism'. In [91] the development of an adaptive trailing edge airfoil concept is described, based on distributed compliance. The concept achieves significant deflection, bandwidth and structural integrity. For the latter type of concepts, solutions similar to the continuous deformable trailing-edge flap can be introduced, as mentioned above. The challenge associated with this concept is that it requires very large strains in the skin. Partially weaker skin sections will have to be used for camber control. This is feasible probably only for small variable geometry surfaces (as mentioned in the trailing edge flap section), in order not to compromise the integrity of the blade structure. Overview of adaptive wings, mainly focusing on aircraft applications, is summarized in papers of Breitbach et al. [92] and Stanewsky [93]. Some issues have also been discussed by [23] for helicopter applications.

4.1.4. *Active twist*

Another approach, the active twist concept, focuses on actively twisting the whole blade (or just an outboard part) over its complete span. The twist change results in change in local angle of attack. The change in pitch is largest at the tip, which is effective for aerodynamic control. Of course, with this concept, no (spanwise) distributed control is possible. The concept is based on the actively controlled bending-torsion or tension–torsion coupling. For this, an actuator is integrated within the blade that is made of anisotropic fiber composite material (Fig. 8). Research in this concept for helicopter applications has shown good results in providing aerodynamic control, but still some disadvantages are evident, especially for the large scale application for wind turbine blades. First of all the response times for such a control concept will not be fast enough for active control purposes due to relatively large inertia. Also, the strains and control forces needed to twist the whole blade are estimated to be very high. Krakers [94] showed that with current materials for a blade of length 0.5 m and aspect ratio of 6.6 a piezoelectric induced twist could be achieved of around 1° when the aerodynamic and structural forces

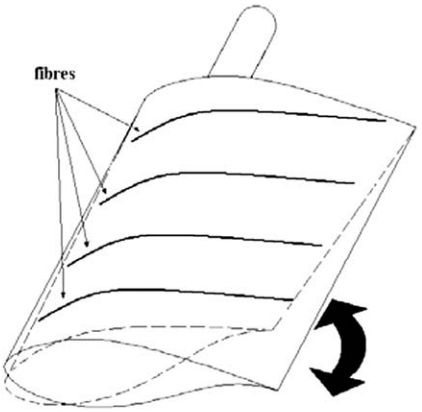


Fig. 8. Active twist concept.

are not taken into account. The strain required to obtain a twist of 4° at the tip has been determined to be in the order of 800μ for a wind turbine blade of 60 m with a mean chord of 3.4 m and a t/c ratio of 28%. For actuation purposes, smart materials are attached under the skin in fiber form or in the blade spar. In this way, small twist deflections can be achieved. This concept requires a torsional weak design of the blade, which may also be critical with respect to flutter. The largest problem with respect to the use of an active twist rotor would be the large scale integration of smart materials in the torsion box or complete rotor blade structure. Especially the use of piezoelectric fiber composites would lead to a very heavy and expensive structure. A clear advantage of this concept is that a smooth rotor blade is obtained which does not change the aerodynamic behavior of the original blade design. In [91] it is predicted that by using a compliant mechanism framework a linear twist of up to 1° per foot can be obtained, although it is not clear if this concept is directly upscalable. Some results about active twist concepts on helicopter blades have been summarized by Chopra [5].

4.1.5. *Boundary layer control*

Using a different approach, boundary layer control methods have been proposed for load control on wind turbine blades. These methods consist of techniques able to influence the flow close to the surface of the airfoil achieving change in the overall characteristics of the flow around it, so influencing the aerodynamics characteristics of the airfoil. Most known methods are boundary layer suction/blowing, synthetic jets, (active) vortex generators and plasma actuators. Traditionally all these methods are used as a boundary layer manipulation concept. Then, these devices are located on the airfoil surface and used for separation control at moderate or large angles of attack, thereby altering the airfoil pressure distribution largely. Besides boundary layer separation control, boundary layer control devices can also be used for camber control at lower angles of attack. Although this 'virtual aeroshaping' is a much more immature research area than separation control, high expectations exist. In [102], the effects of circulation control on a wind turbine blade performance and loads are studied. Gurney flaps and trailing edge blowing are compared. Their potential in increasing torque but also thrust forces is shown.

The boundary layer suction method, consists in operating a powered system to suck boundary layer flow from closely spaced vertical slots. Suction control on airfoils is an old concept originating from Prandtl's experiments in 1904. Some notes on the theoretical background can be found in [101]. The technology evolved during the last century and numerous experimental aircraft applications have been explored. The development of a boundary layer suction system is quite complicated, since it involves considerations on optimum slot placement, structural modifications, power system, amount of suction, etc. This concept's main interest is the prevention of flow separation and the reduction of drag, but by using actively controlled suction, the virtual shape of the airfoil can be changed, so control in lift can be achieved theoretically.

Synthetic jets are zero-net mass flux jets created by employing an oscillatory surface within a cavity. The jet is formed by alternating momentary ejection and suction of fluid across an orifice and is entirely created from the fluid that is being controlled, so no fluid ducting is necessary. Net momentum addition and a change of direction are obtained, because low momentum flow is removed from the boundary layer during the suction phase and high momentum flow is blown out perpendicular to the surface. It is shown that these jets can be used to modify the flow field on length scales that are one to two orders of magnitude larger than the characteristic jet length scale [74]. The commonly used actuators are piezoelectric diaphragms exited in a periodic manner, but other options of smart material actuators are also under consideration. Virtual shape control near the leading edge has been shown by Vadillo et al. [95]. Also, because the trailing edge is a more effective location for camber control this position might be used for effective lift changes. It is proposed to use synthetic jets analogous to the microtabs. The drag penalty is highly reduced for a continuous jet in comparison with a small Gurney flap [96]. Synthetic jets might be even more effective at a lower momentum coefficient and allow for a simpler construction, since no continuous pumping is needed.

Vortex generators are aerodynamic surfaces, consisting of small vanes that create a vortex. The generators mix the free stream with the stagnant air to get it moving again. This process is typically referred to as re-energizing of the boundary layer. Vortex generators increase drag but delay separation and stall effects. They can also be used to improve the effectiveness of control surfaces. Passive (fixed) vortex generators have been investigated in the past for use on wind turbine blades for flow separation control. Active (oscillating) vortex generators have been proposed to be used for active flow control purposes [103], utilizing the 'virtual aeroshaping concept'. Again, this research investigation is more immature than boundary layer separation control.

Plasma actuators are another concept of boundary layer control, recently proposed for wind turbine blades [77]. Plasma actuators consist of thin electrodes separated by a dielectric insulator. A high voltage ac potential is supplied to the electrodes. When the ac amplitude is large enough, the air ionizes in the region of the largest electric potential. The ionized air (plasma) in the presence of the electric field produced by the electrodes results in a body force on the ambient air. Details of the physics and mechanism of the plasma actuator are provided by [75,76]. It has been shown that locating plasma actuators close to the trailing edge can delay separation and stall at high angles of attack and also affect lift at low angles of attack.

4.1.6. *Concept comparison*

From the concepts analysis and existing research work some conclusions can be drawn. Trailing edge flap control seems to be one of the most efficient of the proposed aerodynamic control surfaces. The change in lift and drag characteristics as well as the linearity, the bandwidth and the simplicity of this concepts makes it attractive from the control point of view. Especially the use of deformable trailing edge on the blades provides better aerodynamic efficiency, as soon as the structural feasibility and actuation requirements can be met. Microtabs are considered attractive due

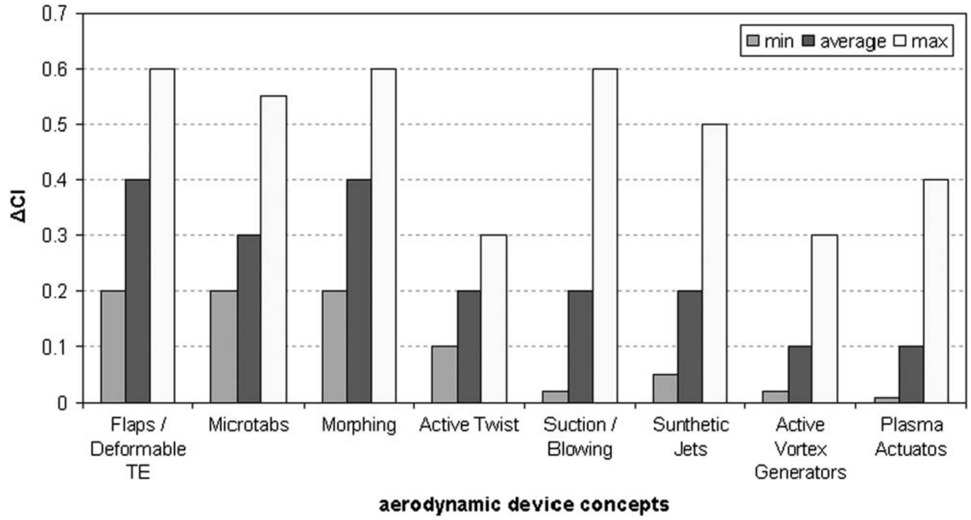


Fig. 9. Comparison of aerodynamic device concepts in terms of lift control capability.

to the simplicity, bandwidth and small actuating power needed. The on–off characteristic makes them less efficient for detailed load control, but more advanced use of them can be achieved by controlling an arrayed operation of microtabs, although further research investigations should be made. Camber control is highly efficient due to aerodynamic characteristics but structural restrictions need to be considered. Compliant small surfaces are feasible and should be considered. Although active twist control is feasible, it is expensive, results in heavier blades, requires high power consumption and consequently, results in a quite inefficient way to reduce fatigue loads. Moreover, boundary layer control methods show high potential and appear attractive due to minute size, but need to be further investigated in terms of their potential to control lift in normal operating ranges of angles of attack. Although high control over lift variations has been shown in high angles of attack [73] or in artificial induced separation [77], the control authority in normal operating conditions (i.e. moderate angles of attack) seems limited or non-existent [77,73]. A comparison graph of aerodynamic performance (lift control capability) of all concepts is presented here (Fig. 9). Ranges of ΔC_l values are extracted from available literature data for wind turbine specific investigations. It can be seen that trailing edge flaps (or deformable trailing edges), camber control and microtabs have very good average and maximum lift control capability. It should be noted that the highest ΔC_l capability of microtabs appears only in lift reduction due to tab inducing flow separation at the airfoil suction side. The range of this performance depends on the angle of attack, the type of the flap, the flap to chord ratio and the airfoil. Data are complied from wind tunnel measurements, CFD and potential flow model simulations appearing in literature, and presented here in an averaged way. The results for the active twist concept are based on $2-4^\circ$ twist at tip section airfoils. For all the boundary layer control options, it is common that the maximum performance appears in very high angles of attack, where with their actuation, stall is avoided. At lower angles of attack, the ΔC_l capability is limited, except in the case of circulation control by using blowing jets at the trailing edge.

4.2. *Actuators-smart materials*

Actuators comprise one of the most important parts of active control. The requirements associated with different types of actuators for smart rotor control and actuation based on smart materials will be analyzed in this section.

The main categories of actuator types are embedded and discrete. Requirements depend strongly on the specific type of actuator and the control surface concept. The main requirement concerns the required deflection (or extension) necessary for the aerodynamic surface. Some ranges for rigid flaps have been already identified as discussed previously. Concerning weight, the actuators should not increase scientifically the weight of the blades. Although weight requirements for wind turbines are less strict than in helicopter applications, there must be taken into account (especially for stability reasons, if it affects the position of the blade center of gravity with respect to the aerodynamic center and the elastic axis). Concerning broadband response, depending on the control strategy, the actuator must be dynamically responsive at the frequency range of interest. The wind turbine size pursued in the control investigations will affect the control frequency. For a reference 5 MW wind turbine discussed previously, a bandwidth of 12 Hz is considered necessary for response to the full load spectrum. This bandwidth can be in the order of 2 Hz if, for example, only the first flapping mode is to be controlled. Also, margins should be added for time lags and delays. Other design requirements include the linear actuation behavior, high resistance to fatigue loads, insensitive to oxidation and lightning strikes, and limited degradation or reduced performance.

4.2.1. *Conventional actuators*

Hydraulic, pneumatic and electrical actuators are the most common types of actuators used in various engineering applications and in existing wind turbines for traditional control purposes (blade pitch control, yaw control). For large loads and large strokes, hydraulic actuators are often used. Although, the necessary frequency ranges for pitch control and the required forces and strokes are no problem for these actuators, detailed requirements for using them for active smart control purposes must be studied. The main disadvantages regarding hydraulic actuators are considered fluid leakage problems, regular maintenance, space needed for actuators and fluid containment and delays in actuation. Pneumatic actuators provide weight reduction compared to other kinds of traditional actuators but have certain important drawbacks regarding their use in active smart control applications. These systems suffer usually from leakage problems, require regular maintenance, have reduced frequency range and exhibit certain instabilities. Electro-mechanical actuators are used in most of the modern wind turbines for full-span pitch control. Maintenance requirements are lower compared to other actuation solutions. DC motors are commonly used because of their simplicity and easy-to-control capability. For large control surface actuation purposes (full-span pitch control) electrical motors are not able to achieve fast speeds for active control of fluctuating loads. For small on-the-blade control surface actuation purposes (e.g. flap control), electrical motors can be used, but practical issues like weight, maintenance and power requirements should be taken into account.

4.2.2. *Smart material actuators*

The concept of smart rotor blade control imposes strict requirements for the installed equipment on the wind turbine blades, especially when considering a scenario for offshore wind turbines. Traditional actuators probably do not meet minimum requirements for such concepts. Furthermore, proposed concepts of aerodynamic control surfaces (distributed along the blade span) require fast actuation without complex mechanical systems and large energy to weight ratios. Promising solution for this purpose is the use of smart material actuator systems. By definition, smart materials are materials which posses the capability to sense and actuate in a controlled way in response to variable ambient stimuli. Generally known types of smart materials are ferroelectric materials (piezoelectric, electrostrictive, magnetostrictive), variable rheology materials (electrorheological, magnetorheological) and shape memory alloys. Piezoelectric materials and shape memory alloys are generally the most famous smart materials used in actuators in various applications. The development of their technology has reached a quite high level and commercial solutions are available and widely used.

4.2.3. *Piezoelectric*

Piezoelectric actuators convert electrical energy to mechanical energy. For actuation purposes, two widely used piezoelectric materials are piezoceramics (mostly used: lead zirconate titanate—PZT) and piezopolymers (mostly used: polyvinylidene fluoride—PVDF). Also, single crystal PZN-x%PT and Langazsite are promising piezo materials (because of their low density and high piezo strain coefficients) but have not been used for actuation purposes yet [94]. Good overviews of piezoelectric materials and actuators and relevant applications can be found in [104,105,109,94]. PZT costs about 60$ per 50 cm^2, 0.2 mm thick sheets. PZN-x%PT and Langasite are single crystals, which are much more expensive to produce. They cost about 1000$ per 50 cm^2, 0.25 mm thick sheets. The specific density of piezos is quite low (1770 $\text{kg}\,\text{m}^3$ for PVDFs). The power consumption of PZTs is also quite low since they require high electrical fields but with low amplitudes. PZTs are commonly used for actuation purposes as shape control applications, as they exhibit significant deformations, while PVDFs are used as sensors, since they have a significant weaker electromechanical coupling coefficient than PZTs. Piezoelectric materials exhibit nearly linear field–strain relations for small electric fields, which is of great interest when employing them in control systems. At higher electric fields these materials exhibit significant hysteresis and strain-based nonlinearities. Moreover, they have low saturation strains (0.08%), moderate forces and fast response (up to 100 Hz bandwidth) with low power requirements. Lightweight construction and flexibility as sensors and actuators in a large variety of applications makes these smart materials feasible for aerodynamic control in wind turbines, but specific combinations of actuator forms and control surface concepts should be studied for more detailed design of such ideas. Displacements and forces attainable with PZTs depend greatly on the method of actuator/structure integration. Common piezoelectric basic structures are sheets, uniform benders, bimorph benders, stacks, tubes and piezoelectric fibre composites. Single sheets can be energized to produce motion in the thickness, length, and width directions. They may be stretched or compressed to generate electrical output. Uniform actuators are bending actuators and consist of a piezo sheet and a substrate. Thin two-layer elements (bimorphs) are the most versatile configuration of all. They may be used like single sheets (made up of two layers), they can be used to bend, or they can be used to extend. 'Benders' achieve large deflections relative to other piezo transducers. 'Extenders', being much stiffer, produce smaller deflections but higher forces. Multilayered piezo stacks can deliver and support high force loads with minimal compliance, but they deliver small motions. Piezoelectric fiber composite actuators consist of fibers of PZT, instead of layers, embedded in a polymer. These fibers make the actuator more flexible. An actuator tube is a composite tube with imbedded, attached or included piezoelectric materials. Other types of configurations using PZT are considered very feasible for actuation purposes, since they deliver large displacements (usually taking advantage of a kind of precompression between their components). Most well known actuator layouts are the RAINBOW, the THUNDER© and the LiPCA actuators, which have been extensively studied for adaptive aerostructure applications [106–108]. For specific design configurations the requirements for displacements and forces should be met. Most smart materials exhibit low strains and moderate forces for large scale applications. In order to make them applicable as discrete actuator devices, mechanical amplifiers should be used to increase the strain where force and strain capabilities of the material are interchanged. Several configurations have been proposed (especially in the helicopter literature). Usually, this kind of mechanical amplification systems use parts as rods, arms, frames, etc. to deliver amplified displacement or power to specific control devices from the actuators. Always a trade-off between force and displacement is taking place. For wind turbine applications, the need for very high forces or displacements are not so strict compared to helicopter blades, since aerodynamic forces (per blade area) and centrifugal forces are smaller. Moreover, maintenance requirements restrict the use of complex devices (moving mechanical parts) on the blades. Piezoelectric material actuators can be used as discrete actuators to move aerodynamic control surfaces on the blades (flaps, microtabs, synthetic jet diaphragms) or as embedded actuators on the blade material to deflect the blade geometry (active twist, camber control). Further details on piezoelectric material properties, frequency response, and modelling techniques can be found in [5].

4.2.4. *Shape memory alloys*

Another well-known and with high potential category of smart materials is the one of shape memory alloys (SMA). SMAs are able to sustain and recover relative large strains (up to 10%) without undergoing plastic deformation. Most popular SMAs are Ni–Ti ('Nitinol'—mostly used), Cu–Zn–Al and Cu–Zn–Al–Mn. Fundamental to shape memory alloys is the so-called shape memory effect. Once deformed at low temperature, SMAs can return to their original shape after heating above the transition temperature. This is of course a reversible process. The process followed is: austenite → cooling → martensite → heat recovery → austenite. Unfortunately, the process of heat cooling and heat recovery gives the SMAs low response times and bandwidth. Heat sink devices can be used for improving the cooling procedure (e.g. Peltier elements). Also, other non-linear effects (hysteresis, creep) comprise a disadvantage for control use. A review of this effects and modeling techniques is provided in [5]. It is believed that better dynamic models are needed to describe their behavior. SMAs are drown into barstock, rod, wire, tubing, sheets and foils, and can be imbedded, attached, or included in a composite tube.

Discrete coil springs when large forces and small displacements are required, are used. With such custom forms SMAs are a promising solution for embedded actuation for shape control of blades. SMA wires can be implemented inside the blade to pull on the skin for deformation purposes [110]. Efficient solutions for the heating and cooling procedures should be adapted for that. Considering the different concept of embedded actuators for deformable blades (camber control, flexible flaps, active twist), different sets of requirements are involved. As it has been mentioned in the aerodynamic control concept section, for deformable surface actuation, a torsional weak design should be employed in order to use smart actuators. The current design of wind turbine blades uses the torsion box in order to carry the global loads, and the blade skin carries only the local pressure loads. To apply full blade (chord-wise camber control or active twist) deformations different blade structural properties or load carrying layouts (e.g. ribs) should be considered. Sheets of piezo materials, piezo fibers or SMAs can be used (integrated in the structure, or under the skin) for shape control. Existing knowledge shows that small deflections can be achieved in that way by using existing smart material properties, but this concept (full blade twist) is not considered feasible for now [94]. Still, large layers of smart materials must be used which add weight and cost to the blade. A feasible concept is the use of integrated or under-the skin smart actuators to deform small surfaces as trailing edge flaps. Still the flexibility of the skin should be considered.

Other categories of smart materials are electrorheological fluids or gels, magnetorheological fluids or gels, electrostrictive materials and magnetostrictive materials. Most of these materials exhibit relatively large strains and forces, but most important disadvantages concern strong non-linearities, hysteresis, strong temperature dependency and low response times (see [38,5]).

4.3. Sensors

In the concept of smart blades for rotor control, a point of high importance is the sensing systems. The aerodynamic loads acting on the blades, or their effects, should be determined and used as inputs in the controller. Also the direct or indirect effect of gravitational and inertial loads should be sensed. 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. From the controls prospective, important states of the dynamic system should be sensed (or estimated) from the control signals. The choice of sensor placement and kind also strongly depends on the control strategy. Fig. 10 provides a conceptual process tree based on the physical background of the whole process of inflow, loads and blade response. It can be seen that various choices of physical states exist, which can be used as sensor signals for aeroelastic control: inflow velocities, pressures, accelerations, deflections, strains. Depending on the control strategy but also on practical issues and capabilities of measurement equipment, different choices can be made. It is important to understand that if the target is control of aeroelastic responses (which is the main focus of this article), always a kind of response on the structure is needed, even though flow measurements are utilized.

Sensors for wind turbine blades will require some specific characteristics that are proposed next. Some of them are common to actuators requirements.

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

Main sensor types are: electrical, piezoelectric and optical strain sensors, accelerometers and inflow measurement sensors. Strain sensors are mainly of electrical or optical type.

4.3.1. Strain sensors

The different types of electrical-type strain gauges are resistance strain gauges, capacitance strain gauges, photoelectric strain gauges and semiconductor strain gauges. These types of sensors have been used traditionally on blades in order to obtain the strains in different parts of them, especially in the root. Strain gauges are mainly used in laboratory tests or in wind turbine prototypes for load measurements but not in serial production. The characteristics of these sensors in measurement range and time response seem to be appropriate to their use in rotor control, even if they only provide 1D or 2D strain information. These sensors are sensitive to temperature fluctuations, and a compensating system is consequently required. Generally their main drawback is that their mounting process must be done with high care to assure long life time and high accuracy. Also, these sensors require accurate calibration, and sometimes recalibration during their operating life because of changes in their properties. Comparing to resistance strain gauges, capacitance strain gauges can be more rugged, but their mounting process is still complex. Semiconductor strain gauge shows higher sensitivity, and lower sizes than its counterparts. Probably, none of these types of sensors can assure the number of stress cycles in the lifetime of a wind turbine and provide a robust solution.

The strain measurement instruments based on optical methods are photoelastic strain gauges, moire interferometry strain gauges, holographic interferometry strain gauges and fiber optic strain gauges. The first three kinds of sensors are mainly considered not suitable to be used in a wind turbine rotor, because of their complexity. Only fiber optics strain gauges show good promises and are already used in wind turbine blade monitoring. From a sensing point of view, the merits of the optical fiber technology are numerous mainly due to their size, weight, electrical interference, sensitivity and reliability. Optical fiber sensors permit measurements that are either impractical or uneconomic with conventional measurement technology, such as foil strain gauges. The price of this technology, even if it is still high, begins to decrease thanks to the wide use of fiber optics in telecommunication. Another advantage over conventional technology is the ability to use a single strand of optical fiber to replace hundreds of wires required for measuring a given strain field using foil strain gauges, which entails economy and gain in space. The main drawback of fiber optic sensors is their temperature sensitivity. The kind of fiber optic sensor which tends to dominate is the fiber bragg gratings (FBG) sensor. FBG technology is already used in blade monitoring. Another fiber optic technology that has been used in wind turbine blades to detect failures, although it is not as extended as FBG systems, is the microbend strain sensor. Optical fiber based sensor systems for wind turbine blades have been investigated extensively for health monitoring purposes and a lot of knowledge has been gained [111,112].

Piezoelectric elements are also considered as a good choice for sensors (especially PZT [113]), but also some more advanced sensors are investigated e.g. based on surface embedded piezo fibers [97].

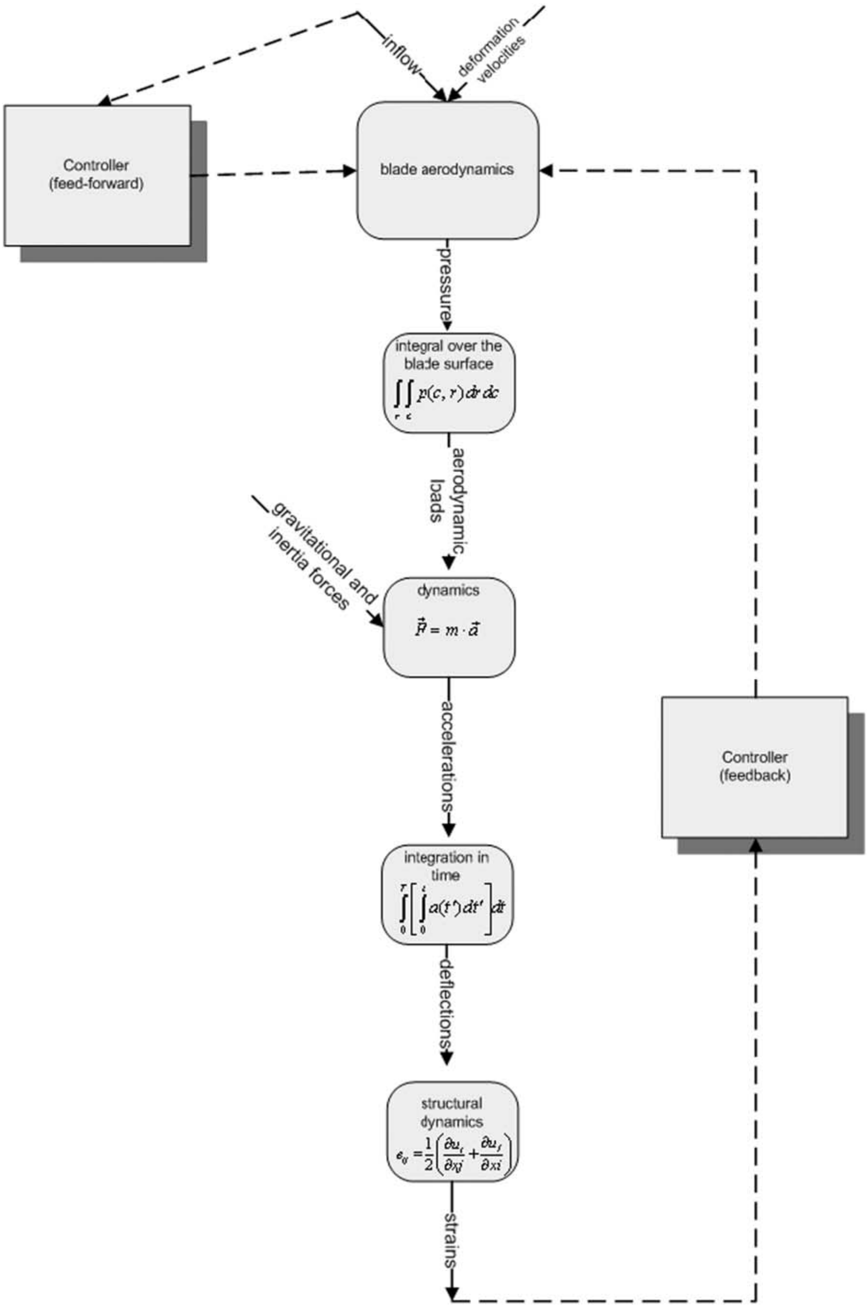


Fig. 10. Sensor signal options based on physical processes.

4.3.2. *Accelerometers*

Accelerometers sense acceleration and 'transform' it into an electric signal thanks to two transducers. The primary transducer sense acceleration and responds to it by a displacement. This displacement is sensed by the secondary transducer which gives an electric signal as response. There are two types of primary transducers which are either spring retained seismic mass or double cantilever beam. The secondary transducer can be of different types: piezoelectric, potentiometric, reluctive, servo strain gauge, capacitive or vibrating element. Piezoelectric accelerometers are considered not suitable for rotor control because their lower frequency (typically 1 Hz) is too high to measure the blade vibrations occurring at frequencies lower than 1 Hz. That is why passive accelerometers, which are able to measure accelerations down to zero frequency, have to be chosen. The differences between these types of sensors are their frequency range, their cost, and their frequency response. In wind turbine applications, accelerometers are mainly used in maintenance for vibration analysis: bearing, generator and gearbox monitoring, but they are not very extended in blade sensing.

4.3.3. *Inflow measurements*

As it has been discussed in Section 2.3, for a feed forward control concept for load reduction, sensors able to measure the incoming wind field should be considered. Relevant work utilizing individual pitch has been already mentioned [48,50]. Relevant work utilizing inflow signals for distributed flaps control (e.g. [82]) is also analyzed in the next section of this article. Inflow measurements can be achieved using various devices. A proposed option is the use of Pitot tubes on the blades. In this way the local dynamic pressure (and thus the velocity) can be measured by sensing the total and the static pressure on the tube. The local inflow angle can also be estimated in this way [115]. A different concept, the one of laser anemometry (lidar), offers a method of remote wind speed measurement. The technique was first demonstrated in the 1970s and has since been used in a number of research applications. Widespread deployment of the technique has so far been hampered by the expense and complexity of lidar systems. However, the recent development of lidar systems based on optical fiber and components from the telecommunications industry promises large improvements in cost, compactness, and reliability. One efficient technique is the use of coherent laser radar (CLR), also referred to as lidar, ladar, and CDL (coherent Doppler lidar) for the remote measurement of wind speed in the atmosphere. Lidar involves the emission of a coherent light beam and detection of the weak return reflected or scattered from a distant target. The technique provides a means to measure the line-of-sight component of wind speed via detection of the Doppler shift for light backscattered from natural aerosols (particles of dust, pollen, droplets, etc.) in the atmosphere. A basic underlying assumption that the scatterers accurately follow the flow is usually very reliable except in precipitation [50]. Lidar systems have already been investigated for wind turbine control applications [114].

4.4. Controllers

For all active systems, the controller is the component that combines everything in a working system. The control loop combines an actuator, sensor, and a (feedback) controller. The design of the controller for active control applications is very critical for the performance and stability of the system. Many approaches for control have been proposed ranging from classical control theory (simple feedback control—PID) to advanced control techniques ($LQR, LQG, H_2, H_\infty, DAC$). Some theoretical remarks on controller choices for active flow control are well summarized in [4].

Some general remarks can be made on the use of controllers for smart rotor applications [98]:

- Essential is to have an accurate model of the dynamic behavior of the rotor. This can be built on first principles (for example by linearizing the full wind turbine dynamic model [119,120]), but also experimentally using system identification [116–118]. With the second approach, given input–output data, a mathematical model can be reconstructed. This method is fast and accurate, but captures only the most dominant dynamics. It is expected that this is sufficient for the load control purpose. The option of on-line system identification [125] is also very interesting, since it allows the direct re-construction of the transfer function of the system during closed loop operation, providing a robust model for the controller.
- In most of the cases (considering spanwise distributed control and multiple control objectives) the controller should be MIMO: multiple input, multiple output, and robust.
- The phase delay from sensor to controller to actuator should be extremely small. Every added delay affects strongly the performance and stability of the load reduction system.

Advanced control approaches for wind turbine load reduction control have already been summarized in Section 2.3. Generally, the use of additional sensors for individual pitch control, feed forward control of measured or estimated wind speed and multi-variable control are the most interesting options, but not necessarily directly applicable for distributed control using smart devices. The type of the controller depends on the concept of application of the aerodynamic devices and sensors (see Fig. 11). Independent (decoupled) single input single output (SISO) controllers based on local measurements can be utilized along the span (decentralized control scheme) or one central controller can activate all distributed devices based on global signals (e.g. tip acceleration, blade root moments) or distributed signals via a MIMO controller (centralized control). The concept of using more advanced distributed control concepts has also been proposed [121]. In any case, the stability and robustness of the controller at all operating conditions should be guaranteed.

Considering control algorithms, classical control theory for SISO systems can be used (PID feedback) or optimal control theory (LQR, LQG, H_2, H_∞). Usually the formulation of the aeroservoelastic model in the state-space domain facilitates the use of these kind of methods developed for MIMO systems [18]. Some other proposed advanced options for controllers for load reduction are repetitive learning control and positive position feedback control [56]. These controllers can efficiently deal with periodic disturbances and resonance vibrations and are also of low order and not based on any model assumptions.

4.5. General design issues

The realization of a smart wind turbine rotor requires implementation of aerodynamic control surfaces, actuators, sensors and

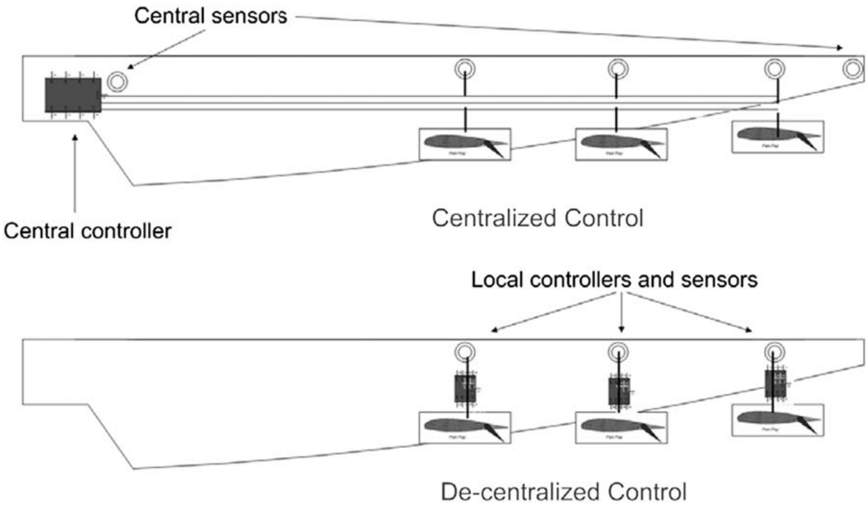


Fig. 11. Control concepts utilizing aerodynamic surfaces along the blade span.

control systems on the blades. Such implementations impose significant changes in the existing design of blades. Although research in smart rotor concepts is still in an advancing stage, design considerations must be made and restrictions and limitations must be taken into account before proceeding further. Such design requirements may be serious design drivers, sometimes with more significant effect than performance and load reduction results. Most important design issues are the reliability of control systems, size, weight, power consumption and other like sensitivity to lightning strikes. Size, weight and power consumption restrictions can be met as it can be seen from the preliminary analysis for the most favorable concepts. All these parameters are already taken into account in the first choice of smart control concepts. Reliability of all of the control systems (control surfaces, actuators, sensors, controllers) should be taken into account when designing large scale systems for wind turbine blades and has not been investigated in small and medium scale experiments, although in similar helicopter applications strict tests have shown that requirements can be met.

5. Smart wind turbine rotor research

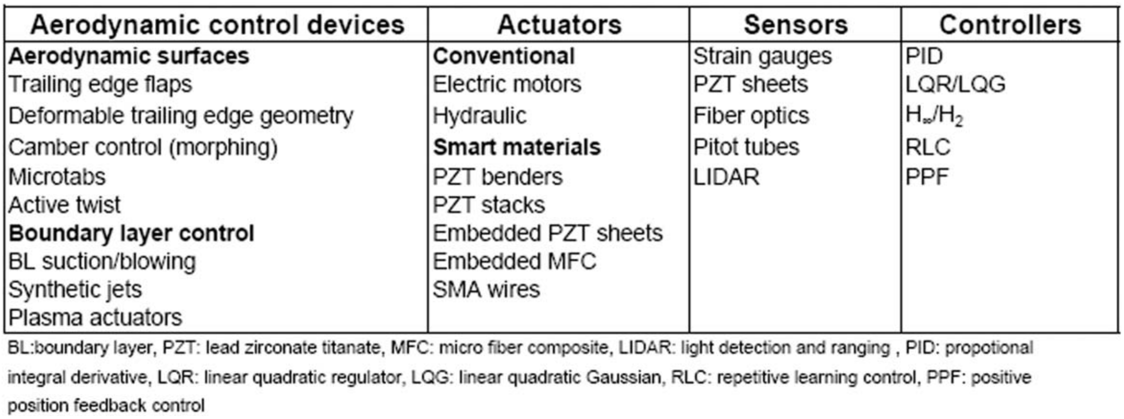
Although some preliminary investigations for active control using devices on the blades had been made during the 1990s, research regarding smart rotor control for wind turbines is a relatively new, innovative and ongoing part of research at various wind energy research institutes. Interest in the subject has increased during the past years, in connection with general research in evaluation of advanced controls for load reduction on modern large wind turbines. Various research investigations of applying smart rotor control concepts on wind turbines are reviewed, focusing on active control solutions. Concepts, methods and achieved results in potential for load reduction, through simulations and experimental approaches are presented.

5.1. Early investigations

Preliminary investigations of aerodynamic control devices on wind turbine blades have been performed by the National Renewable Energy Laboratory (NREL) during the 1990s in the USA. These aileron-type of devices have been analyzed to be used for power regulation purposes and aerodynamic braking. Series of wind tunnel experiments have been performed examining different configurations, simulations quantifying the devices performance and also field tests. In [28] five trailing edge devices are investigated to determine their use as wind turbine aerodynamic brakes. These devices are compared mainly according to the achieved lift to drag ratio reduction and drag increase. The spoiler-flap concept is considered the best choice. In [29] extensive 2D wind tunnel tests of these devices are conducted, analyzing various aerodynamic parameters for a range of angles of attack, control configurations and sizes. The control devices are evaluated also numerically during rotating operation using a BEM (blade element momentum theory) code. The overall performance of a wind turbine with such aerodynamic control devices is predicted, running simulations for various configurations (parametric fixed device configurations). In [30], field experiments using a 20 kW horizontal-axis wind turbine that incorporates variable-span, trailing edge aerodynamic control devices are presented. The target of these rotational, atmospheric tests is the quantification of the influence of span-wise 3D effects, by comparing aerodynamic parameters with the 2D experimental data from the previous research work. Although during the tests, only fixed configurations of three trailing edge devices are used, so not active control concepts are tested, this research work is of great importance, since it comprises a realistic investigation of the aerodynamic parameters associated with control devices used in variable span-wise length and the 3D flow effects associated with their performance. Specifically, a ‘softening’ of the stall behavior (ΔC_l around stall) is observed, compared with the infinite span (2D) results. Also, it is stated that the 2D experiments underpredicted the effective reduction in lift for short span devices near the tip. The reason is suggested to be connected with the effect of strong vorticity being shed due to the device uploading, which reduces the lift in the inboard section, thus enhancing the performance of the device in terms of power regulation. Such effects are considered of great importance when designing variable span-length aerodynamic control devices for rotational applications, based on 2D measurements and modeling.

5.2. Feasibility studies

The concept of active control of wind turbine aeroelastic responses using local aerodynamic devices on the blades, although receiving great interest, has not been fully treated as a whole, studying the feasibility of implementation in modern systems and analyzing all design parameters. Some recent works try summarizing available knowledge and future steps [57], but focus mostly on evaluation of certain actuation mechanisms. In Delft University of Technology this preliminary evaluation and knowledge base has been compiled during past years. Firstly, research work, concerning feasibility studies on smart rotor control for wind turbine applications, has been conducted by Marrant, van Holten and van Kuik in the project ‘Smart Dynamic Rotor Control for Large Offshore Wind Turbines’. The results of this study are summarized in [38]. Research deals with the inventory of rotor design options and possible load reductions. The fluctuating loads on a wind turbine are described and possibilities of influencing fatigue loads or structural loads are discussed. Active rotor control concepts are presented which include pitch control concepts (collective, cyclic, higher harmonic), individual blade control (part-span pitch, aileron control, active twist) and active damping of blade and tower vibrations. Also, semi-active and passive control options are discussed (passive tips, self-twisting blades, compliant blades). Present techniques are summarized with regard to sensors, actuators, aerodynamic devices and control strategies, and their application on large offshore pitch regulated variable-speed wind turbines. Regarding sensors, strain gauges, accelerometers and force sensors are analyzed. Piezoelectric force sensors at the blade root are considered a feasible solution for the measurement of aerodynamic loads. Optical fibers are considered expensive and not well established for measuring strains on blades. Passive accelerometers are considered a good solution due to their bandwidth and low frequency limit. Regarding control strategies, four control strategies that had been developed to actively suppress vibrations in rotorcraft are analyzed: a feed forward adaptive control algorithm, a Fourier synthesis algorithm, a real-time adaptive neural network controller and an iterative learning controller. Considerations regarding the connection between controller design and wind turbine design are also pointed out. Regarding actuators, many categories are analyzed: conventional (pneumatic, hydraulic, electro-motors), smart materials (electrorheological, magnetorheological, shape memory alloys (SMA), electrostrictive, piezoelectric, magnetostrictive). It is concluded that the smart materials with the best prospective for actuation in wind turbine blades are piezoelectric and SMAs, which can be used for discrete or distributed (embedded) actuation if necessary, in combination with an amplifier. Furthermore, aerodynamic rotor control concepts are summarized (full-span and part-span pitch



Aerodynamic control devices	Actuators	Sensors	Controllers
Aerodynamic surfaces	**Conventional**	Strain gauges	PID
Trailing edge flaps	Electric motors	PZT sheets	LQR/LQG
Deformable trailing edge geometry	Hydraulic	Fiber optics	H_∞/H_2
Camber control (morphing)	**Smart materials**	Pitot tubes	RLC
Microtabs	PZT benders	LIDAR	PPF
Active twist	PZT stacks		
Boundary layer control	Embedded PZT sheets		
BL suction/blowing	Embedded MFC		
Synthetic jets	SMA wires		
Plasma actuators			

BL:boundary layer, PZT: lead zirconate titanate, MFC: micro fiber composite, LIDAR: light detection and ranging , PID: propotional integral derivative, LQR: linear quadratic regulator, LQG: linear quadratic Gaussian, RLC: repetitive learning control, PPF: positive position feedback control

Fig. 12. Concept matrix of available options for distributed smart rotor control.

control, blade twist control, microtabs, camber control, aileron control—flaps). Aerodynamic control with trailing edge flaps or microtabs was considered the most feasible concept due to high frequency capabilities and good structural and safety features.

A recent feasibility inventory was made by Barlas [56] for the UPWIND work package ‘Smart Rotor Blades and Rotor Control’. The state of the art in smart rotor knowledge is presented and analysis of different concepts is performed (see Fig. 12). The most important inventory analysis results are included in Section 4.

5.3. Control surfaces aerodynamics/aeroelastics investigations—modeling and experiments

In aerospace research, investigation of the performance of aerodynamic devices/surfaces always played a vital role in active control concepts. A lot of knowledge has been gained in this field regarding aerodynamic modeling and experimental evaluation of different options. For wind turbine blades, certain requirements exist for similar use of such concepts. In order to investigate the possibility to control fluctuating loads on wind turbine blades, research programs have focused on analyzing the aerodynamic efficiency of certain devices/surfaces, focusing on possible use for wind turbine blades load alleviation. Simulations and wind tunnel tests quantify parameters which are important for the intended control purposes.

5.3.1. Flaps

Trailing edge aerodynamic devices like flaps or ailerons have been considered as a concept of high potential. Trailing edge flap devices for wind turbine blades have been thoroughly investigated by Risø (The Danish National Laboratory for Sustainable Energy, now Risø DTU). Especially, attention has been drawn on the concept of variable geometry trailing edge (Fig. 13), 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 [58] a CFD (computational fluid dynamics) study is carried out to determine the effect of the size and shape of the variable trailing edge geometry on the aerodynamic characteristics of a wind turbine airfoil. Three different shapes of trailing edge geometry are analyzed: rigid, soft curved and strongly curved. From the static simulations it is 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 is concluded that the amplitude of the lift generated on an oscillating airfoil could be reduced significantly by the counteracting movement of the flap for a wide range of reduced frequencies[3] ($k = 0.09-0.36$).

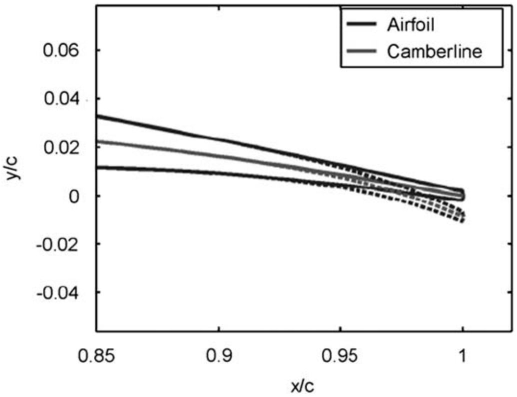


Fig. 13. Airfoil trailing edge camberline with deformable trailing edge geometry [81].

In [59] a 2D aeroelastic model is developed, based on a panel code and a spring-damper system for an airfoil with deformable trailing edge. For control, a simple PD (proportional derivative) 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 2 s simulations. All the other simulations (100 s turbulence, gust) show attenuation of the oscillation amplitudes, although not so effectively as in the first case.

In [63] 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 [64] and Leishman [62]), 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. [60,61], coupled with a linear spring/damper model for the elastic deformation of the airfoil. An optimal control strategy is used to minimize the

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[3] 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 resultant velocity at the blade section.

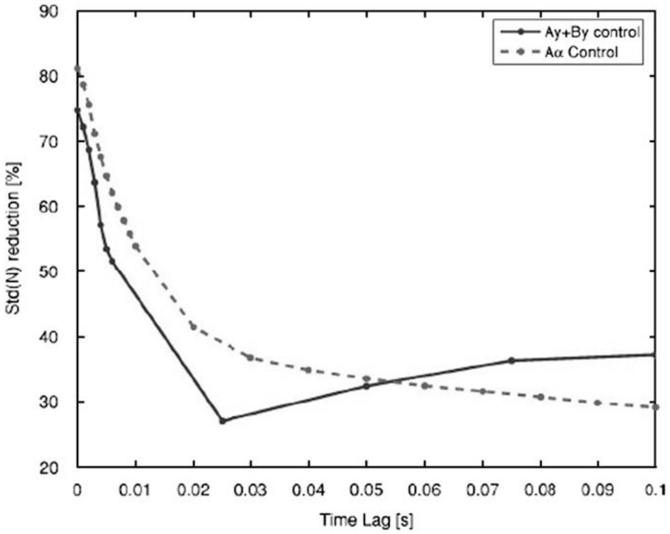

Fig. 14. Turbulent wind input response. The reduction of the standard deviation of the normal force as a function of the time lag. Ay,By: control based on airfoil flapwise position and velocity, $A\alpha$: control based on airfoil angle of attack [61].

fluctuations on the airfoil normal force. The analysis showed that when the airfoil experienced 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 is controlled by the input of the airfoil flapwise position and velocity, while reductions of up to 95% could be obtained when the flap is controlled by the input 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 is 75%. Calculations showed that the effect of a time lag in the actuators and sensors significantly reduces the efficiency of the control algorithm (Fig. 14). Likewise, the effect of a low maximum actuation velocity reduces the efficiency of the control algorithm.

The investigation of variable trailing edge geometry was further extended at Risø by building a prototype and performing wind tunnel tests [65]. A profile section of 2 m was fitted with 36 piezoelectric actuators (‘THUNDER’© actuators from FACE©) at 10% of chord length. The thin curved actuators were directly fitted 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 measured in the experiments were also modeled 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% in lift force was measured in a prescribed pitch and flap motion (with a phase shift of 40°).

5.3.2. Microtabs

The use of microtabs as aerodynamic devices for load control on wind turbine blades has been proposed and extensively investigated by van Dam et al. [66–70]. The effect of varying tab location, height and width has been simulated by van Dam et al. using CFD. Results show an increase up to 50% for the lift coefficient (Cl) in the linear range of the lift curve. The percentage is larger for low angles of attack and decreases at higher angles. 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 et al. it can be seen that an 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 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 [58]. 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. In the work of Oerlemans [72] 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 [70] in order to investigate the effect of gaps in the tabs. 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 $Re = 1 \times 10^6$ 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 [69] unsteady CFD simulations of deploying microtabs were performed. Results for the static cases were validated with the previous experimental ones. The studies show the unsteady aerodynamic behavior of the microtabs during deployment and compare it to the one of ‘microflaps’ (i.e. tiny trailing edge flaps). It was concluded that, in general, the global temporal response is independent of the aerodynamic device.

5.3.3. Boundary layer control devices

Except aerodynamic control surfaces used for aeroelastic control like flaps and microtabs, boundary layer flow control methods seem appealing to be used for the same concepts. Active flow control is a vast field of research on its own. An interesting overview can be found in [4]. Using such techniques for load reduction on wind turbine blades is an idea already proposed [56], but not thoroughly explored. In [73], the use of synthetic jets (SJ) for controlling blade flow and blade vibrations is investigated. Wind tunnel tests were performed. Global flow measurements were conducted, where the moments and forces on the blade were measured and also the flow field over the blade was quantified using particle image velocimetry (PIV). Using synthetic jets, the flow over the blade was either fully or partially reattached, depending on the angle of attack and the Reynolds number. Furthermore, proportional enhancement of the moments and forces, as well as the reduction of the blades vibrations were obtained, by either changing the momentum coefficient of the synthetic jets, the number of synthetic jets used, or by using different driving waveforms. In general, the potential for load reduction was shown, although limiting the investigations in the concept of solely reducing dynamic stall vibrations.

Also, the use of plasma actuators has been explored for wind turbine load control applications. In [77], surface-mountable, single dielectric barrier discharge (SDBD) plasma actuators on wind turbine airfoils are investigated computationally and experimentally. In one case a single SDBD plasma actuator is used close to the trailing edge that can achieve a $\Delta C_l = 0.08$ shift in the lift curve. It is stated that this performance add linearly with more actuators along the chord span. In another case, an airfoil is modified with flow separation ramps. It is shown that the actuator can recover the lost lift at lower angles of attack, providing a shift in lift of $\Delta C_l = 0.4$.

5.4. Wind turbine active load control simulations

Although quantification of the potential in load control can be seen in the previous ‘local’ investigations (2D models and experiments), the necessity of more global investigation of such concepts on full wind turbine models and integrated operation is obvious. During the past years various research efforts have investigated the global aeroservoelastic problem when using local aerodynamic surfaces on the blades. There is a variety of concepts and methods on this investigation, which are analyzed in this section.

At DUWIND a preliminary comparison of different concepts for smart rotor control of wind turbines was carried out by Marrant [78]. Four different smart rotor blade concepts are compared based on their potential to reduce fatigue loads for particular dimensions, and on their aerodynamic efficiency, bandwidth and complexity. The fatigue load case during normal power production is examined, comparing load calculations for the conventional blade and the ‘smart’ blade. A 3D, one component turbulent model and a wind shear model are used for the time-varying wind field input. The benchmark wind turbine used is the DOWEC (Dutch Offshore Wind Energy Converter) concept 6 MW turbine. A time-marching BEM model is used with no structural dynamics for the blade, which is considered rigid and undeformed. The maximum load alleviation capacity of the smart structures is used in the analysis, where it is assumed that the smart rotor blade knows exactly the wind field state at every time step. Moreover, as a first approximation, the smart blade is assumed to react instantaneously to the load change, so, no controller is used. The four smart blade concepts compared are: 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 root bending moment are calculated for the baseline blade and the smart blade incorporating different spanwise lengths of smart devices. The smart devices reduce the loads by changing the ΔC_l or the angle of attack having full knowledge of the wind input. The limited bandwidth of the devices is 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 are used after that for determining the fatigue damage in order to compare the different concepts. The comparison value used is the ratio of the total fatigue damage of each smart concept over the conventional blade (overall relative damage ratio) (Fig. 15). The actuation of all concepts is based on piezoelectric actuators. The camber control concept is supposed to be actuated by an inflatable structure concept. The values of ΔC_l or $\Delta\alpha$ and maximum bandwidth of these actuation concepts are taken from literature. From the preceding analysis it can be seen that active trailing-edge flap control/active camber control ($\Delta C_l = \pm 0.4$) is about twice as effective as microtab control ($\Delta C_l = \pm 0.3$). Only microtabs with a larger tab at the lower surface ($\Delta C_l = -0.55$ to 0.3) 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 fatigue loads. Active twist achieves reasonable performance, but using actuators over the full blade length.

The first investigations with aeroservoelastic simulations of full wind turbine models with control devices were reported by NREL. In [31] 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 [32] 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 evident, but only quantified in time series plots of root flap bending moment in the references.

In later research work [33], the investigation of microtab aerodynamic devices for load control is carried out, in a full wind turbine model, using multi-input, multi-output state-space techniques. The multi-body dynamics code MSC-ADAMS©

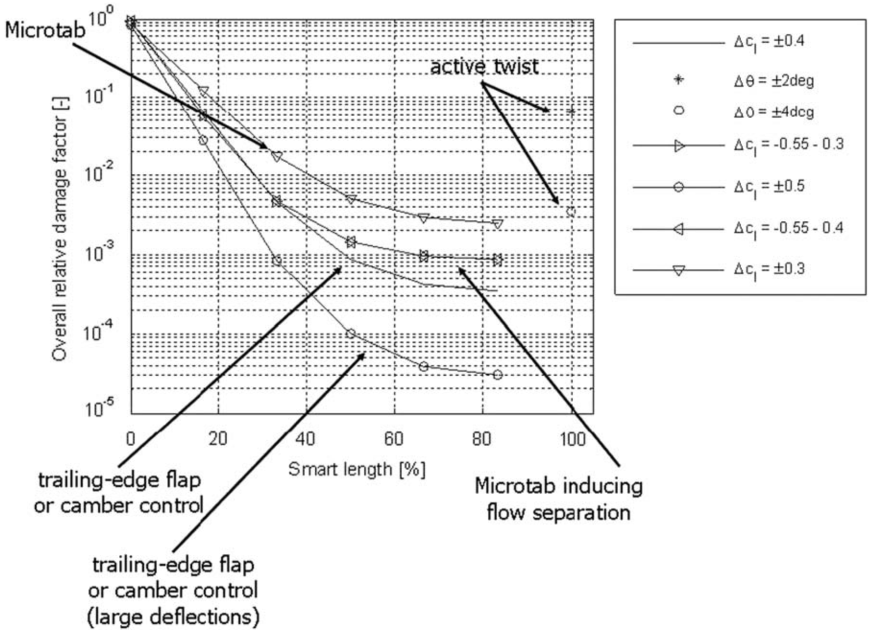

Fig. 15. Comparison of smart rotor blade concepts with infinite bandwidth [78].

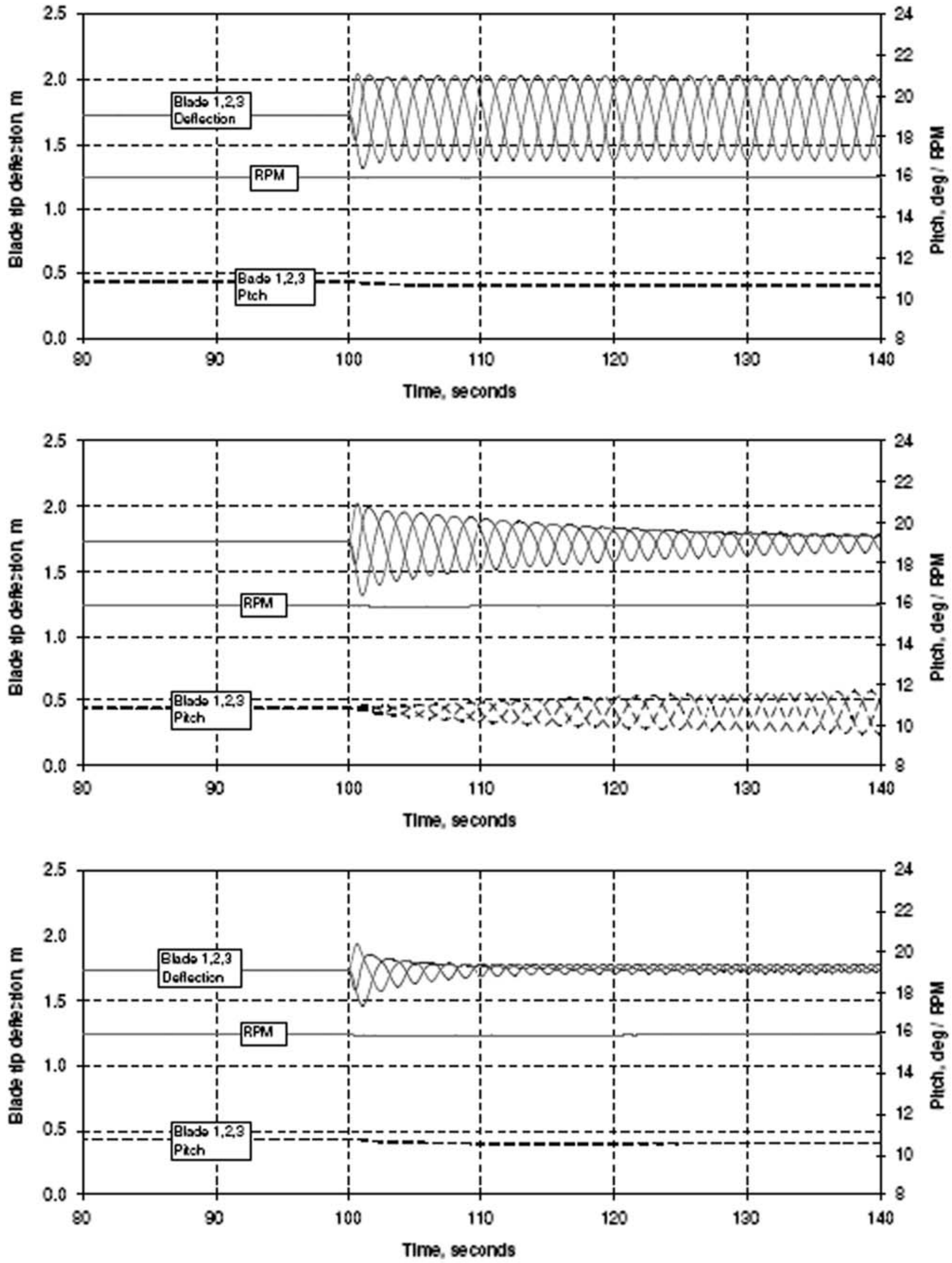

Fig. 16. Comparison of load reduction using (from top to bottom) collective pitch, individual pitch, and microtabs controls for a step change in wind shear at 14 m/s [33].

(connected with the AeroDyn aerodynamic module) is used. The aerodynamic effects of the microtab devices were incorporated only in the form of adjustment in static lift and drag based on the experimental and computational results of van Dam et al. [66–68]). The full aeroelastic model is linearized and expressed in the fixed reference frame, using a multi-blade coordinate transformation (see [87]). A control strategy based on a LQR (linear quadratic regulator) state space controller with full state knowledge 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 with a traditional PI controller for (collective) blade pitch, individual pitch and microtab control were compared in terms of reduction of blade tip deflections. Also peak and fatigue loads were calculated based on IEC (International Electrotechnical Commission) load cases. The variations in tip deflection were quickly reduced with the microtabs. 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. It is seen 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 (Fig. 16). Similar work with integration of microtabs in aeroelastic modeling and control is also presented in [80], by using FAST.

In [81] the research work at Risø on the 3D modelling of a wind turbine rotor with actively controlled, deformable trailing edge geometry is presented. BEM is used together with the elastic modeling of a rotating blade, which includes the spanwise distributed control surfaces. The unsteady flap aerodynamics and camberline dynamics are the same as described in [60,61,63]. The blade is modeled as a cantilever beam using modal expansion. The turbine in this case is using a 33 m long blade. PID

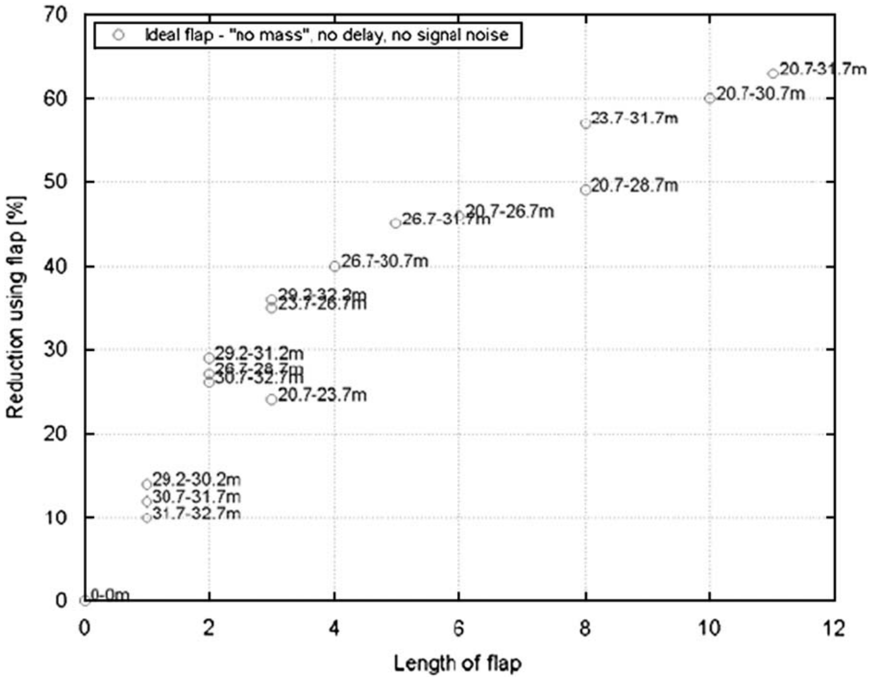

Fig. 17. Equivalent load for the flapwise root bending moment for undivided large spanwise flaps as function of the spanwise length of the flap [81].

(proportional integral derivative) controllers using input signals from local flapwise deflections or accelerations on the flapped sections are implemented. Effects of system time lag, flap power consumption and signal noise are included. Rainflow counting and Wöhler curves are 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 show 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 are investigated (Fig. 17). It can be seen that a 11 m flap gives equivalent load reduction of more than 60%. Also, split flaps of different lengths are investigated. With this way it is possible to more effectively damp out energy from more vibrational mode shapes if the flapping sections are divided.

In a recent research work [82], spanwise distributed deformable trailing edge geometry (DTEG) actuators are integrated in a full aeroelastic model of the Upwind/NREL 5 MW reference wind turbine, using the code HAWC2. The unsteady aerodynamics of these sections are modeled based on the work presented in [83,84]. The normal baseline torque and pitch controllers of the reference wind turbine are used as developed by NREL. A non-traditional control scheme, based on physical reasoning, is used to control the individual deflections of the DTEG below and above rated for load reduction. The advanced flap controllers use a combination of input signals: inflow measurements (angle of attack and resultant local velocity) from Pitot tubes located at the leading edge of the flapped sections, blade root bending moments and blade pitch signal. The DTEG signal contributions from the inflow measurements and the blade pitch angles are based on theoretical models. The performance of the integrated DTEG controllers is shown, under various turbulent wind conditions (Fig. 18) and wind step cases. A fatigue reduction of 33% in the tower root moment is obtained for 7 and 18 m/s turbulent wind cases. Furthermore, a reduction of 16% in the tower ultimate root moment over a 10 min series is seen at 18 m/s. The fatigue in the flapwise blade root moment is also decreased 48% using an 18 m/s averaged wind. Depending on mean wind speeds and choice of control parameters, it is seen that the mean power can also be regulated. An increased mean power production of 1.5% is seen.

Lackner [86] also investigated the integration of trailing edge flaps on a full wind turbine model using GH Bladed©. The Upwind/NREL 5 MW reference wind turbine is used as baseline. The research work addresses how trailing edge flaps perform for fatigue load reductions, and how they perform relative to an individual pitch control (IPC) approach. A feedback control approach is implemented for load reduction, which utilizes a multi-blade coordinate transformation (see [87]), so that variables in the rotating frame of reference can be mapped into a fixed frame of reference. Single input single output control techniques for linear time invariant systems are then employed to determine the appropriate response of the trailing edge flaps based on the loads on the blades. No distributed control was investigated (i.e. one flap per blade). The use of trailing edge flaps and this control approach is shown to effectively reduce the fatigue loads on the blades, relative to a baseline controller. The load reduction potential is also compared to an alternative individual pitch control approach. It is seen that active flap control is comparable to IPC but can also contribute to high frequency load reduction.

In [85], a more advanced aeroservoelastic modeling approach is used, utilizing vortex-theory based aerodynamic models. First, a 2D investigation on a section with trailing edge flap is carried out, using a panel code with viscus–inviscid interaction formulation. The structural responses with and without a simple PID flap controller at impulsive and sinusoidal excitations are shown. A 3D investigation, on the blade level, was also carried out, using a free-wake vortex particle model coupled with a FE-type beam model for the Upwind/NREL 5 MW reference wind turbine rotor. An excitation caused by an exponential wind shear with exponent 0.2 is used. A maximum reduction of 30–35% is achieved in the range of the flapwise blade root moment using flap angles of $\pm 6^{\circ}$. It is

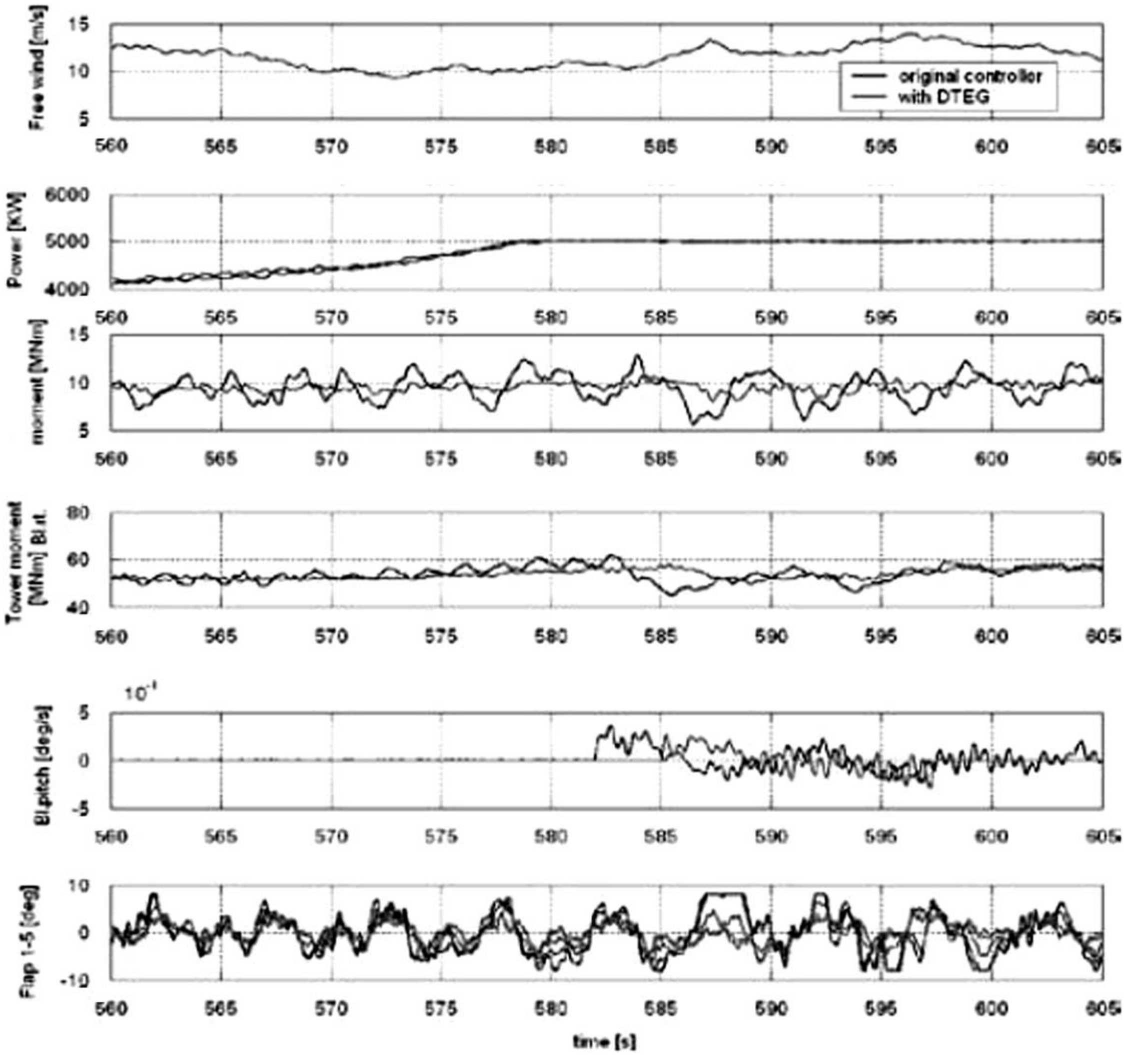

Fig. 18. (from top down) Free wind at hub height, electrical power, flapwise blade root moment, tower root moment in flow-wise direction, collective pitch speed, flap deflection angles for 11 m/s turbulent wind input [82].

concluded that the flap concept as a means of load reduction has been confirmed using these advanced models.

5.5. Power regulation with smart rotor control

The main focus of smart rotor concepts is certainly the active load control objective. Nevertheless, the ability to affect aerodynamic loads (Cl, Cd) can also influence other operational parameters and give the possibility to focus on other objectives. Depending on the control strategy, smart rotor devices can also regulate rotor torque, and thus power.

A preliminary investigation of using trailing edge flaps for power regulation and load control instead of full-pitch control has been carried out by Joncas [79]. Steady cases are simulated using BEM, and flap aerodynamic parameters are based on look-up tables generated with XFoil.[4] Results provide interesting first order design guidelines. Different flap configurations are investigated. When compared to the full span pitch control system on a representative three bladed 5.5 MW upwind rotor design, it is 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 is found that flaps located close to the tip, of spanwise lengths of 25%R and chordwise lengths of 20%, were sufficient to regulate power output with flap deflections of less than -5°.

On a recent research investigation presented above [86], it is found that on below rated operation, the load control function of flaps can have negative effect on power production. Reduction of up to 1.4% in average power is predicted. On the other hand, in above rated operation, the collective flap angle (through the Coleman transform, in a similar way to the collective pitch angle in individual pitch control) can help in power regulation in connection with the collective pitch angle. Reduction of up to 11.2% in the standard deviation of power fluctuations is predicted.

In [82], reduction in average power up to 0.8% is also found when operating distributed flaps for load reduction in below rated operation. On the other hand, when flap controllers are designed to target an optimal aerodynamic power conversion, up to 1.5% increase in average power is obtained. Similar results for reduced power in below rated operation when using individual pitch control for load reduction are reported by Veldkamp [126], based on field measurements.

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[4] Xfoil is a 2D panel code for airfoil analysis and design, including viscus–inviscid interaction.

5.6. Closed-loop control experiments

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 is evident. In [73], as already mentioned above, the potential of using synthetic jet actuators for flow control has been shown. Moreover, feedback control wind tunnel tests are performed, activating the synthetic jets oscillation at the presence of stall. In this way, stall-induced vibrations are largely alleviated, reducing the overshoot and contributing to faster decay of oscillations.

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 [88,89,125]. Unlike the previous work mentioned, the potential for load alleviation is shown at various realistic operating conditions. The design of the experimental setup, the detailed scaling, design and manufacturing of the blade as well as some of the first results are shown in [90]. The ultimate goal of the approach is 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 90 cm long blade model, with a 12 cm constant chord, constant thickness and no twist along the span, is attached to the (specially designed) pitch system at the TU Delft Low Speed Low Turbulence Wind Tunnel test section ceiling, and it is free to deflect over a table at the free end (Fig. 19). The table ensures that no tip effects would occur that add uncertainties to measurement data.[5] The pitch system can change the angle of attack at the blade with high speed and precision. The straight blade simulates a wind turbine tip equipped with aerodynamic control devices.

Fig. 19. Smart blade at the TU Delft LSLT wind tunnel test section [89].

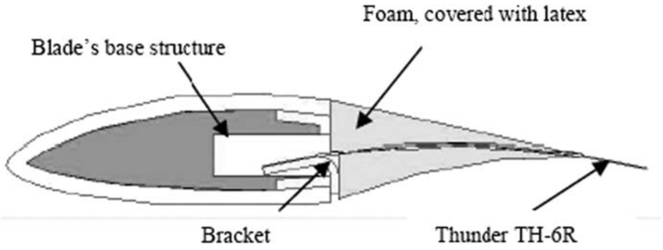

Fig. 20. Design and mounting of the actuators [90].

The glass-epoxy composite blade is designed to be representative of the dynamics of a large scale wind turbine blade. The scaling parameter used is 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 is tailored during the structural design of the blade, by tuning the stiffness. The aerodynamic excitation is simulated by the pitch excitation system. The scaled 1P, 3P and first flapping natural frequency of the blade are 3.5, 10.5 and 12.5 Hz, respectively. The aerodynamic control devices used are based on the concept of deformable trailing edge. Four Thunder© TH-6R piezoelectric bender actuators are used, forming two different flaps of 50% chord length size placed near the tip. The thin actuators are 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. 20). A piezoceramic patch is 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. Control is applied using a dSpace© system linked to the Control Desk GUI in Matlab Simulink©. The main tests that are 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 ware carried out. Furthermore, measurements at different mean angles of attack of interest are performed, also at stall conditions. The sensitivity of the phase angle between the two motions is examined. In this way the maximum reduction in the fluctuating loads for prescribed (known) motions of excitation and actuation is shown. The maximum reduction ranges is up to 90%, especially close to the natural frequency of the blade, were vibrations are amplified. A representative result is shown in Fig. 21.

For the feedback control tests, a linearized model of the dynamics of the system is extracted, for every wind speed, 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 is designed, tuned and applied in dSpace. The input excitation cases are 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 is very good, 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, Fig. 22). For the random signal (representative noise signal) mimicking turbulence with 1P and 3P 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. 23.

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[5] The aerodynamic table was also removed for part of the measurements, in order to investigate the influence of tip effects on the outboard flap.

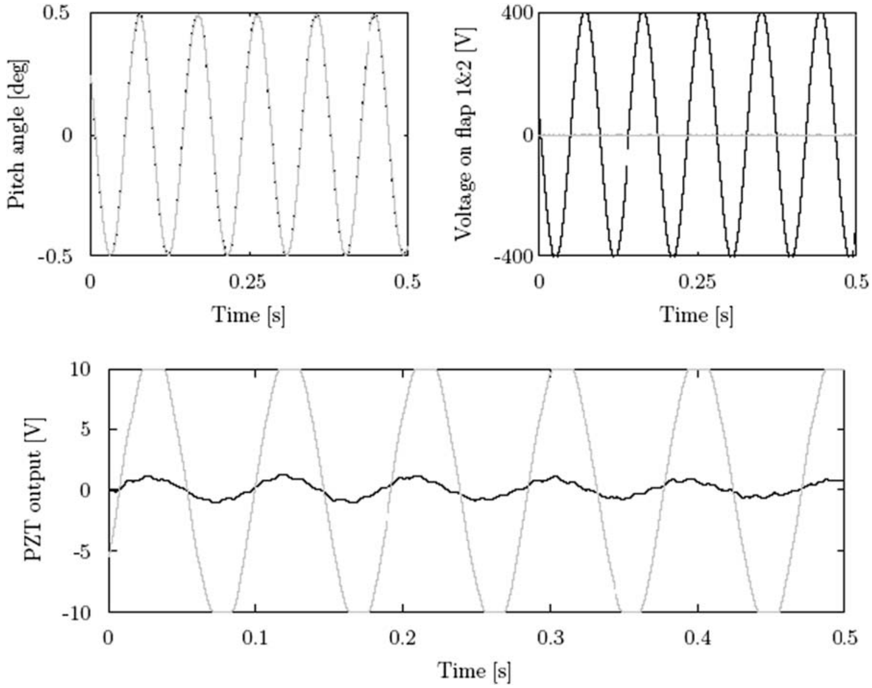

Fig. 21. Reduction in root strain fluctuations in the case of a sinusoidal pitch excitation of 12.5 Hz with 0.5° amplitude around angle of attack of 5° at 45 m/s with prescribed counter-acting flaps motion (feed forward control) (1 V = 21.3μ strain). Gray line: without flaps, black line: feed forward control of flaps. Experimental results [88,125].

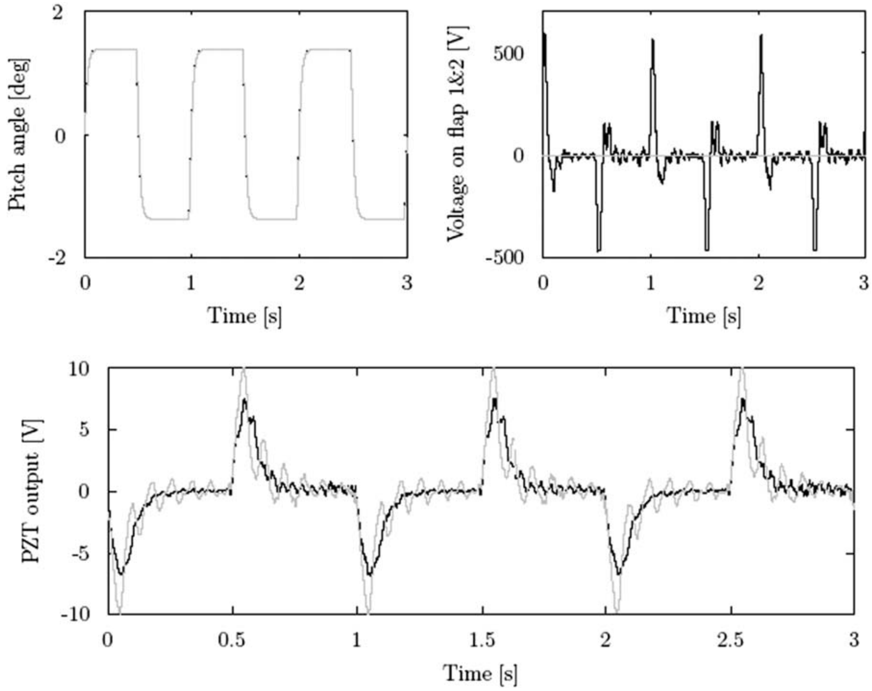

Fig. 22. Reduction in root strain fluctuations in the case of a step pitch disturbance at angle of attack of 5° at 45 m/s with feedback controlled flaps motion (1 V = 21.3μ strain). Gray line: without flaps, black line: feedback control of flaps. Experimental results [88,125].

6. Modeling issues

In order to conduct further research in application of smart rotor control on wind turbine blades, certain requirements for the design and simulation of concepts must be set. Accurate models of smart wind turbine rotors are necessary for the design of the controllers and the evaluation of the performance of systems in load reduction. Although state of the art in wind turbine aeroelastic analysis tools is improving, the application of smart structures and dynamic control on wind turbine blades includes aspects that are not included in the modern standards of wind turbine analysis and design. Summarizing the most important issues, we can define such requirements for models.

In order to model efficiently the use of aerodynamic control devices located on the blades, airfoil unsteady aerodynamic models, including control surfaces, are required. This comprises

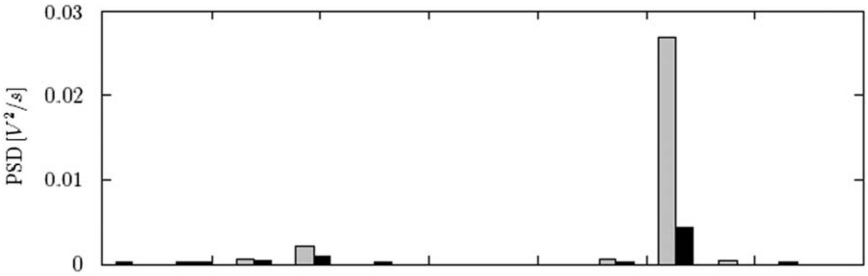

Fig. 23. PSD of measured strains with (black line) and without (gray line) feedback control for the case of a representative noise signal. Experimental results [88,125].

the inner problem of describing the aerodynamic environment of a rotor, which is modeling the resulting local unsteady aerodynamic response at each of the blade elements. Quasi-steady aerodynamic models for the airfoil region are considered not realistic for such an application. The fast transient changes in inflow, combined with the fast actuation of the control devices, create a high unsteady aerodynamic environment at the blade element level [99]. The changes in aerodynamic loads from such unsteady phenomena must be calculated accurately, modeling the perturbations to the local angle of attack and velocity field by all elements of aerodynamic forcing and the unsteady response and phase lag connected with them [15]. Also, the unsteady aerodynamic forces under non-attached flow conditions (dynamic stall) should be modeled [84]. The possibility of using aerodynamic control devices for alleviating fast powerful changes in inflow (e.g. gusts) requires that the aerodynamics of that region should be simulated correctly. Generally, the widely used potential flow based unsteady models [64,62,63] usually perform well in predicting the 2D unsteady aerodynamic loads. It must be noted, though, that although they predict the time lags and the frequency of unsteady aerodynamic phenomena, usually overestimate the magnitude of the aerodynamic forces (for e.g. when compared with CFD results—see [58]). Moreover, analytical unsteady aerodynamic models of other control device concepts (e.g. microtabs) should be developed. Microtabs behave in a slightly different way than trailing edge flaps (see [69]), and their short-term transient unsteady aerodynamic response should be accurately modeled.

Unsteady aerodynamic effects are, in part, a consequence of the time-history of the induced velocity from the vorticity contained in the shed wake, coupled with the induced velocity contributed by the circulation contained in the trailed wake [15]. The inner problem is associated with the unsteady airfoil aerodynamics, as discussed. The outer problem is to model the effects of the induced velocity field produced by the vortical wake trailed from behind each blade. The fast time-varying and spanwise varying load distributions on the blades caused by the aerodynamic control devices, in the case of a smart rotor, will induce a very unsteady and asymmetrical wake environment. The physics of such phenomena must be modeled accurately in order to predict realistic effects on the combination of aerodynamic control devices and rotor aerodynamics. This involves the spatial as well as the temporal changes in the wake. Specifically, any changes in the aerodynamic rotor loads will change the induced velocity field. The reaction of the induced velocity field will tend to partly compensate changes in the global rotor loads, but this reaction does not occur instantaneously. This is generally referred to as dynamic inflow. High fidelity models, already exist based either on finite-state formulations [122] or vortex methods [123]. Also, accurate wind field modeling should be incorporated, including all unsteady effects (turbulence, tower shadow, wind shear, and possibly other wind turbine wakes) in order to simulate realistically effects causing unsteady loads.

Considering flow control techniques, the essential physics of the flow under control need to be captured. There is a lot of knowledge on this field from research in aerospace and other type of applications. Issues on modeling of active flow control methods are well summarized in [4]. Generally, the use if reduced order models (ROM) is required. In fluid systems there are a variety of approaches that can be taken to construct ROMs, based on physics, mathematics and data filtering. The resulting physical based models can vary from low fidelity to high fidelity aerodynamic models (e.g. potential flow, boundary layer equations, Reynolds averaged Navier–Stokes, RANS, equations, detached eddy simulation, DES, large eddy simulation, LES). Mathematical models can be constructed also using proper orthogonal decomposition techniques. Filtering techniques involve the use of system identification, neural networks or evolutionary algorithm techniques.

Considering the structural part of the problem, the use of advanced dynamic models of wind turbine structural components is considered necessary (especially for the blades), since it affects the design, performance and realization of the control objective. Modern models using multi-body dynamics, modal shape methods or FE-type beam models, are considered adequate for such kind of analysis. A detailed overview of structural modeling methods is presented in [127]. Attention should be paid, though, in representing the structural dynamics accurately, for example when considering large deformations of long, slender blades [124]. Also, it is important to include the dynamics of the control devices located on the blades in the model of the dynamics of the wind turbine rotor. The mass and stiffness distribution, the inertia forces of the blades and the device performance will change by including the structural properties of the actuation devices on the blade span. Furthermore, the use of smart materials on the blades for actuation purposes (camber control, active twist, deformable trailing edge) requires that the structural behavior of such an approach should be modeled correctly. Structural models of blade-smart actuator with induced strain actuation are required, or equivalent reduced order models. The behavior of surface-mounted or embedded actuators and the interaction with the blade structure should be time-depended. There is existing knowledge on this field from helicopter research, where various fidelity models have been used, ranging from reduced order models (linear or non-linear, including piezoelectric hysteresis effects [133] to beam theory or laminate plate theory with piezoelectric layers or embedded SMA wires [5]). Other approaches appear in aircraft aeroelasticity research, where the smart structure actuator dynamics appear as additional control modes superimposed on the normal structural modes of the wing structure. The voltage–strain relationships of piezoelectric sheets are then added on these modes (see [128–130]).

There are important lessons to be learned from previous research in aerospace applications, considering the general aeroservoelastic modeling of the problem, which is essential for stability analysis and controller design. The usual methods employed in that sense in wind turbine aeroelastic investigations (for an overview see [127]), involve full non-linear modeling of the structural dynamics and the rotor aerodynamics and then derivation of linear state-space models using either numerical linearization or system identification techniques. On the other hand, in aircraft aeroservoelasticity it is common to construct the full linear state-space model (or an equivalent frequency domain formulation) including linearized structural models (e.g. modal approach), aerodynamic models (e.g. rational function approximations of frequency domain aerodynamics), control surface models (e.g. third order models) and additionally stochastic gust models. Additional non-linearities of interest are added on that model (e.g. aileron free-play). This approach should be considered also for wind turbine applications, although major differences in structural and aerodynamic requirements (e.g. non-uniform wake induction or large blade deflections) will require a slightly different approach. In a 2D modeling environment, things are of-course simpler and wind turbine active control research has employed similar techniques to wing sections aeroservoelastic modeling (see for example [60,61]). Finally high fidelity aeroservoelastic model can be employed for detailed description of specific problems of interest, but certainly not for design purposes. This involves 'numerical' or 'computational' aeroelasticity methods, using coupled CFD and FEM models (also referred to as fluid–structure interaction). In this way a detailed description of the geometrical features is used (including the control features), but also more physical precise description of the flow and internal structure behavior. For an overview of methods in aircraft applications see [131,132].

Closing the modeling loop, the design of the necessary controllers depends on the sensors, actuators and aerodynamic control devices chosen. Appropriate control strategies must be used or developed, which fulfil the specific application on a smart rotor. Traditional controllers on wind turbine design tools do not allow control strategies for embedded and spanwise distributed aerodynamic control. Current methods must be extended and possible solutions for traditional feedback controllers or modern adaptive controllers must be investigated. Also, the combination of all control objectives for a wind turbine rotor (full-span pitch and generator torque control for power regulation, and smart rotor control for load reduction) should be included in a full wind turbine model for a realistic representation of all control systems and performance and possible combination of control loops.

7. Discussion

The potential for load reduction by using smart control concepts for wind turbines has been proven with various approaches. Helicopter and aerospace experience also has shown promising results both in simulations, small scale experiments and full scale applications. 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, scaled experimental setups and field tests are scheduled. After successful application, the next stage will be full scale prototypes, and field testing of such concepts. Research concerning smart rotor concepts for wind turbines is ongoing. Continuous research projects are also expected to investigate the subject in the future.

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 wind turbines. Parallel research activities will have to be combined in an integrated multi-disciplinary approach, 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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