How far is smart rotor research and what steps need to be taken to build a full-scale prototype?

L O Bernhammer¹, G A M van Kuik² and R De Breuker³
Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS
Delft, The Netherlands
E-mail: l.o.bernhammer@tudelft.nl

Abstract.

During the last decade research on the field of smart rotor has advanced significantly. Fundamental aerodynamics, structural and control concepts have been established and simulators created for distributed flaps on wind turbine blades, which are considered the most promising option. Also a proof of concept has been done under laboratory conditions. However, the results obtained under these conditions can only be partially transfer to the real application as the control authority of smart rotors is limited compared to full pitch control. The steps that need to be taken before smart rotors can be successfully exploited are in the design of reliable systems that can operate under environmental conditions without inspections. Besides that, other potential advantages of distributed control need to be established such as the effect on other components of a wind turbine for example the gear box or the power system. Finally, it is necessary to investigate what benefits can be achieved if blades are designed with distributed control right from the start instead of applying control schemes to already existing turbines.

1. Introduction

The up-scaling of wind turbines and especially offshore turbines to achieve more cost effective designs, poses a great challenge to the designers. Traditional design approaches get closer to their limits. New methods in the design and control of the blades are required to facilitate a further increase in turbine size. A method is the application of sophisticated load control techniques, the so-called 'smart rotor'. In this method, the blades are equipped with distributed aerodynamic control surfaces. During the last decade, the idea of the smart rotor has matured from an abstract concept to a proof of concept stage. It lies in the nature of the problem that a multidisciplinary approach needs to be chosen, including research in aerodynamics, control theory, material science and wind turbine structures. Each of these fields needs to be developed to a sufficient technology readiness level before the implementation into a full-scale turbine is feasible.

Various research institutes, among which DTU RISØ, TU Delft, University Stuttgart and Sandia National Laboratories, have been investigating the smart rotor concept and its

¹ PhD student, Wind Energy / Aerospace Structures and Computational Mechanics
² Scientific Director DUWIND, Professor, Wind Energy
³ Assistant Professor, Aerospace Structures and Computational Mechanics
subdomains, leading to advances in the design and analysis of such wind turbines. During the last decade 5 PhD theses have been devoted to this topic at TU Delft and at the Danish Technical University. This paper will analyze the progress made and indicate how the next steps towards the implementation of aerodynamic control surfaces in blades can be taken.

2. Active Aerodynamic Device Selection
The first step in the development of a novel technology is the generation of concepts. At the early stage of the research on smart turbines, many different concepts were considered as active aeroelastic devices. Among these are flaps, variable camber, microtabs and actuation systems that act on the boundary layer such as plasma or jet actuators. Johnson et al. [1] and Buhl [2] provide a very comprehensive overview of the different concepts. Despite the variety of concepts, most research has focussed on trailing edge flaps or microtabs. Barlas [3] attributes this to the fact “that the maximum control authority can be achieved by using trailing edge flaps in combination with mechanically amplified smart material actuation”. Baek [4] discards options that act on the boundary layer, as the wind turbine airfoils are operating in the linear regime of the lift curve. Consequently, the control authority achievable with those methods remains limited.

In fact it can be seen that all research institutes that are investigating smart rotors have opted for trailing edge flaps, as they offer besides the high control authority also a bandwidth that is larger than the frequencies of interest of up to 4 Hz, depending on the actuation type. Following this trend, research in this field has been focussed on developing the analytical and numerical tools to simulate such control devices. Among them are the studies of aerodynamic models and control and actuation methods of blades with trailing edge flaps. In the following part the readiness of these methods will be discussed.

3. Analysis Tools
Aeroservoelastic analysis tools for wind turbine need to be fast in execution as a large spectrum of load cases needs to be analyzed for certification and design purposes. It is evident that neither finite elements in computational fluid aerodynamics nor vortex methods can fulfil this requirement, especially not in combination with high fidelity finite element approaches to analyze the structural deformations. A tendency for two approaches can be seen. The first one is the usage of structural mode shapes combined with potential aerodynamics such as GH Bladed; the second one is the exploitation of multi-body codes such as HAWC or the aeroservoelastic tool of TU Delft. Alternative structural formulations could be based on equivalent beam or plate models. Similar to multi-body approaches, localized information would be handed in for efficient computation.

In the latter case, blade element momentum theory is used to determine the aerodynamic loading. This poses the requirement to have accurate models for the unsteady aerodynamics of airfoils. Such models models for flapping airfoils have been established by Leishman [5], ONERA [6] and Gaunaa [7]. The model of Leishman only provides a limited accuracy solution as it has originally been derived for helicopters and exploits corrected flat plate aerodynamic formulations. Also it is only valid in the linear part of the lift curve. The model formulated by ONERA is a dynamic stall model. Similarly, the model of Gaunaa has been expanded using a Beddoes-Leishman type dynamic stall model [8] by Andersen [9] to form a dynamic stall model for thick airfoils with deformable trailing edges. These models have been benchmarked against
2D test data. Andersen [10] combines these models with a dynamic inflow model and a near wake model provides a fast way of load calculation.

These models have been verified by means of wind tunnel testing. Both, the ONERA [6] and the Gaunaa model, have been tested for 2 dimensional flow [11]. With the latter one being tested with a flapped airfoil. Good agreement has been found. A next step would be to include radial components in the flow to quantify their effect, especially with regards to stall.

Structural models are even more mature than the aerodynamic models. Multi-body codes are widely used and commercial packages such as ADAMS are readily available. The combination of springs and rigid bodies provides a fast, easy to use approach to solve structural problems. If modelled in a co-rotational framework, such models can include geometric non-linearities, accurately representing large deflections of a rotor blade. The downside of the approach is, that by allocating the stiffness of a model in spring elements, information about the cross-sectional stress distribution is lost. Only models of moderate complexity can be analyzed and nothing can be said about stress concentrations. When using this approach, little can be concluded from such analysis types about failure due to ultimate loading. Another concept is the usage of modal representations. Modal reduction is a computationally necessary step, as repetitive solving of a full finite element model would be too time consuming. The modal approach provides detailed information on a local stress level of a structure of any complexity. The inherent disadvantage is that modal formulations are using linear combinations to calculate displacements. This makes modal formulations unable to deal with large deflections and rotations. Local effects can only be captured when a large number of modes is used. Certainly when considering large wind turbines, non-linear geometric effects start to lead to more pronounced effects. It is expected that the non-linearities lead to load alleviations and deflection reductions. The use of modal based codes during the design phase will most likely lead to a conservative design. The challenge in code development is to provide a concept that can both include high fidelity with non-linear formulations in a time efficient way. In research this problem has not been solved yet. All standard codes either opt for one of the two above presented options with GH Bladed using modal formulations and FAST, HAWC 2 and the aeroelastic code of TU Delft using multi-bodies.

4. Controller

The controller design is at a similar level as the aerodynamic modelling. The first steps have been set in a proof-of-concept experiment by TU Delft [12], [13], [14]. Besides this practical demonstration also the foundation for the theoretical side has been built. Barlas has studied a variation of control schemes numerically [3], among which are individual flap control, individual flap control using a Coleman transform and multiple feedback flap control all of which using decoupled single input single output feedback loops, resulting in 15 %, 9 % and 19% root reduction, respectively, for a free wind speed of 8 m/s. However these values decrease with higher wind speeds, eventually ending up at reduction values that are significantly smaller than what could be reached with individual pitch control.

With the established control schemes (Coleman and Feingold [15], van Wingerden et al. [16]), the simulation side seems to have reached a sufficient level to expand the research to a next level, i.e. the application of the technology in a prototype. The controller design can be obtained numerically by one of the dedicated aeroservoelastic analysis tools. For experiments, system identification is a more appropriate way to go. Van Wingerden [16] has developed a method to obtain models by novel subspace Linear-Parameter-Varying system identification.
algorithms both for open-loop and closed-loop systems. Due to the large number of tuneable parameters these systems are hard to design. Therefore a linear time invariant solution has been derived that is based on parameter dependent dynamics. These methods have been successfully applied in wind tunnel tests [17]. For a non-rotating experiment 90% reduction of the root bending moment has been achieved. For the rotational experiment the 1P and 3P mode could be reduced by 37% and 55% respectively.

The next step in controller design is the development of control schemes that include higher order vibration modes and to study the loads in the drive train. The challenge, besides the complexity of the controller lies in the high number of control inputs and outputs, which requires advances in computationally efficient algorithms. Rice and Verhaegen provide an overview of the advances on this field [18].

5. Implementation in Turbines

So far it has been established, that aerodynamic and structural models are advanced enough to use them for design purposes, despite the improvements that still should be made. This step from a simplified model to a detailed design remains one of the main unanswered questions concerning smart rotors. Despite the agreement on trailing edge flaps that is commonly shared by all major research institutes, the way the implementation is foreseen differs significantly. Many different concepts are proposed as a response to the requirements given by Barlas et al. [19]. Key requirements include a bandwidth for the active system from 0-6Hz and deflections of up to 12 degree for 10% of the chord. Also, Barlas et al. [19] describe the requirements that are derived from environmental conditions. Shielding from oxidation or lightning strikes, guaranteeing the performance throughout the life time and insensitivity of the actuators to fatigue are of highest importance in the design. As actuators form part of the control system, any concept with phase delays is not a viable option. When considering that any concept needs to be designed with the cost criterion in mind, it is evident that a very challenging design problem is faced.

Different approaches are being taken for the actuator design including electric motors (Sandia National Labs) [20], servo electric motors (University of Bristol) [21], pressurized rubber flaps (DTU RISO) [22] and flaps actuated by shape memory alloys (TU Delft, Hulskamp [23]). All these mechanisms are still in an experimental stage and have to be evaluated further before being implemented in a full scale wind turbine. When translating the requirements into design criteria, the requirement imposed by oxidation results into a seamless spanwise flap design. A similar conclusion can be drawn from a performance point of view, where a smooth transition to the flap results in the smallest losses. Lightning protection means that ideally no electricity should be applied. However most actuation systems are based on electricity, regardless of dealing with smart materials or with traditional concepts such as electric motors. Therefore shielding will most likely be necessary in full scale applications. The durability and fatigue requirements correspond to a low number of parts for easy inspection and long maintenance intervals.

All the presented concepts are having strong and weak sides. Electric motors are a conservative approach to the problem. Their advantage is that they are well developed and can provide the required bandwidth easily. Their drawback is the usage of electricity and the complexity of the system, which seems maintenance prone. Pressurized rubber flaps are a very promising concept as they excel on the field of the drawbacks of electric motors. Another advantage is that by pressurizing parts of the flap section, smooth shape transition is possible. The obstacle with pressurized flaps is that the pressure tubes need to be long to reach the position of the most efficient location of the flaps on the blade. This introduces a time delay between the
control signal and the actual control event, leading to a reduction in control efficiency or even to instabilities. The final concept of using smart materials to actuate the blade seems a promising option. Straub [24] discusses a range of smart materials and their advantages with regard to rotor control. A final option is the use of compliant structures in combination with any of the actuation systems in order to reduce the required forces that need to be generated to deflect the trailing edge flap. Saggere and Kota present such a concept in [25]. A second concept is presented by Bernhammer et al. [26], who is using a trailing edge tab as aerodynamic leaver to steer a control surface for load alleviation.

For wind tunnel testing the requirements on the rotor shift significantly. Due to scaling the bandwidth of the actuation system needs to be increased to more than 20 Hz. Other requirements like durability vanish for a proof of concept experiment. This leaves the bandwidth of the frequencies of interest as a major driver in the choice of the actuation system. This proof of concept of load alleviation has been done by TU Delft under laboratory conditions using piezoelectric materials [12], [13], [14]. Clearly such benders can only generate a small amount of force, but at very high frequencies, rendering them unsuitable for outdoor, full-scale experiments. As the requirements on the rotor design are very different for real turbines and wind tunnel studies, two different experimental pathways need to be followed to verify the simulation tools and to design a durable actuation system. The first experimental path is a full turbine set-up to test aerodynamic and control modelling. This way a full-turbine including tower motion can be simulated and analysis tools can be verified. The second avenue that needs to be taken is the design of blade sections with the actuation system in real size. Ideally these systems would be tested in a rotationary environment to include centrifugal forces, but in a first step it can be based on two dimensional aerodynamics. The full scale test allows investigations of the actuator behaviour under a realistic force field.

So far smart materials only have found application in laboratory environment as described by Hulskamp et al. [27]. As mentioned before, these experiments can only give a very limited view on the technology readiness level of the actuation systems as a different turbine scale is involved. To the authors’ knowledge, the only turbine equipped with flapping devices in a full scale field test is operated by Sandia National Labs [20]. However this turbine is involving electrical motors to actuate the flaps, a concept that does seem very maintenance intensive, which will be very expensive, certainly when going off-shore. The Sandia National Labs experiment has not completed any active control experiments to this point. Long term tests with active flaps have not been done either, therefore no conclusions can be drawn about the durability and maintenance requirements of such systems.

6. Challenges and Opportunities

Until this point, research has been focussed on creating a control system that takes over the functionality of individual pitch control, thereby reducing the root bending moment of the rotor blades. However Baek [4] has shown that the most significant contribution to fatigue loading is in an operational regime, where the control authority of the trailing edge flaps is low. According to Baek [4], 98 % of the load cycles occur for root bending moments of below 6 MNm for the 5 MW reference turbine. These cycles only contribute to 2 % of the fatigue damage. One has to note that this value does not take into account the mean value of the amplitude of vibrations. But even on doing so, the load cases that contribute most to fatigue damage are above the 2 MNm that can be counteracted by flaps that are covering the outboard 20 % of the blade with a limit of 10 degrees deflection. It seems obvious that for this simple reason, flaps can only be a complimentary control system to individual pitch control. A common short coming of both individual pitch and individual flap control is that they can only have limited effect on the
edgewise bending moment. This moment is largely gravity driven and the control authority on
the edgewise bending moment is low for both approaches. It is expected that moving to larger
turbines will increase this problem.

Still it is not possible to draw the conclusion that distributed flap control can only contribute
very little to a well-tuned individual pitch controlled turbine. So far research has been only
considering individual flap control to reduce the root bending moment. However, it might still
very well be possible that other components of the turbine such as gear boxes or generators
are more sensitive in terms of fatigue to a large number of cycles with a low amplitude than
the blade root section is. Therefore it is subject of discussion, whether the possible increase in
annual energy production of 2.5 % estimated by Baek [4] due to possible blade size increment by
up to 3 %, should be seen as low compared to the costs of applying active aerodynamic devices,
when purely regarding the blade root moment as design criterion. These costs might partially be
covered by cost reductions in other wind turbine components due to reduced loading on them.
Baek [4] did a first analysis of the load spectrum of the main turbine components, showing that
the hub and tower top fatigue loads decrease significantly, when using individual flap control.
This trail needs to be followed to fully understand the impact of the application of smart rotors.
Baek’s findings [4] are in strong contrast to earlier research executed by Barlas [3], who reports
load reductions in the order of 20% for the blade root moment. This discrepancy calls for further
analysis of a full turbine under all certification load conditions, including detailed analysis of
other elements of the turbine.

As smart rotor control systems of deflectable trailing edges can cover the entire range of
interest of vibrations of a wind turbine as identified by Barlas [3] between 0 and 6 Hz opposed
to an individual pitch system that cannot cover this bandwidth. Consequently, individual pitch
control is not suited for suppression of aerodynamic instabilities as flutter. For the current
generation of wind turbines, flutter is not critical but on increasing the wind turbine diameter
in an effort to have a higher energy output, flutter might become problematic [28]. Apart from
flutter suppression, other instationary effects due to fluctuating inflow can be corrected better
by active aerodynamic devices, as the frequencies where excitation occurs for example due to
wake meandering are too high to be corrected by pitch controlled systems [29]. Bossanyi [30]
states in a similar fashion that individual pitch control can experience difficulties with stochastic
components in the wind inflow. Thus individual flap control can form a complementary control
scheme to individual pitch control. Lackner and van Kuik [31] have studied the combination of
individual flap control and individual pitch control. A conclusion is reached that individual pitch
control shows superior load alleviation capacities than individual flap control for low frequency
vibration, notably the peak in the PSD of 1P can be reduced more. While the individual
pitch control limits its effectiveness to a region around the 1P mode, distributed control can also
alleviate loads that occur at higher frequencies.

A last topic that has been given very little attention until this point is the inclusion of the
smart rotors in the design spectrum. So far all approaches are modifying existing turbines. By
definition, a weight and cost penalty will be paid when including a set of sensors and control
devices to an already existing design. Besides the required devices, also the structure needs to be
locally enforced to withstand the forces introduced by the flaps. The full benefit of smart rotors
can only be achieved, when such control systems are included in the design right from the very
beginning as weight benefits can be achieved, which in turn would lower the gravitational load,
thereby allowing to further reduce the weight. An efficient combination with other technologies
under developement like torsion-bending coupling of rotor blades as developed by the university
of Stuttgart [32], might be able to enhance the control authority of a localized control systems.
Benefits can be especially be expected when it comes to the tip deflection of the rotor, an issue that is gaining more importance with increasing rotor size. Local control systems with high bandwidth could be able to enforce a certain tip path, thereby reducing the requirements on tower clearance. In combination with torsion-bending coupling, the rotor blade could be used to lever up the effect of the forces generated by the control devices such that large displacement corrections seem feasible.

Conclusions

Smart rotor research has taken the first steps towards implementation in full scale wind turbines. Analysis tools and models are in place, albeit improvements in the level of detail of the solution and speed of the computation can be made. The next big step remains the design of a viable concept. Many concepts have been suggested, albeit each still has significant deficits that need to be overcome. This will be the major challenge towards smart rotors. Also, research should be given a slight twist from root bending moment reduction to more attention of secondary benefits of individual flap control on the entire turbine in terms of performance optimization and load alleviation of hub, nacelle and tower.

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