SIMULATION OF WIND TURBINES UTILISING SMART BLADES

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ABSTRACT

Wind turbine smart blades change their aerodynamic characteristics in response to changes in operating condition, aiming at enhancing the power capture capability or controlling the power and aerodynamic load. Smart blades span a wide range of technologies. Some of these technologies have been proposed and developed specially for wind turbines, while some others have been borrowed from aircraft applications. Adaptive blades, telescopic blades, morphing blades, blades equipped with active control surfaces are some examples of smart blades. This paper presents a summary of wind turbine smart blades and advances in simulation and design of these blades.

INTRODUCTION

Wind turbines are designed to produce maximum power at the most probable wind speed. At high wind speeds, the generated power by a wind turbine far exceeds the generator capacity. To protect wind turbine operation at high wind speeds it is needed to limit the generated power otherwise it overloads the generator. While power control is an essential control for all wind turbines, aerodynamic load control is the main challenge for large wind turbines. As the size of wind turbine increases, larger blades and larger aerodynamic loads demand for either new blade materials or fast-response load alleviation mechanisms in place.

Pitch control and stall regulation are the most popular power control systems both based on controlling the flow angle of attack. Stall regulation is mechanically the simplest controlling strategy. In stall regulated wind turbines the blades have been designed to stall in high winds without any other control. The rotor is built with the blades fixed on the hub therefore it is rather simple in construction and the pitch of the blades are adjusted only once when the wind turbine is erected. In order to achieve stall-regulation at appropriate wind speeds, the wind turbine blades operate closer to stall and result in lower aerodynamic efficiency below rated power. Stall regulated wind turbines normally do not have a perfectly flat power curve above the rated wind speed.

While stall regulation is the simplest power control mechanism, pitch control is the most common means of controlling the rotor mechanical power. It also can be used for quasi-steady aerodynamic load control. Conventional pitch control systems are used to limit the rotor mechanical power at a its rated value and to optimise the energy capture below that value. Individual pitch control systems have been successfully developed and utilised to alleviate low-frequency fluctuating loads by pitching the blades individually (Caselitz 1997, Bossanyi 2003, Lovera 2003, Larsen 2005, van Engelen 2006). The concept of individual pitch control was first introduced for helicopter rotor blades (Johnson 1982). Still some disadvantages are evident, especially for the large scale application for wind turbine blades. The response time for individual pitch control systems is not fast enough for high frequency load fluctuation. Moreover, actuation of massive large blades requires significant actuation force and energy.

As a result of the significant growth of wind turbines in size, blade load control has become the main challenge for large wind turbines (Nijssen 2006, Johnson 2008 and Barlas 2010). Many advanced techniques have been investigated aiming at developing control devices to ease blade loading. Individual pitch control system, adaptive blades, trailing edge microtabs, morphing aerofoils, ailerons, trailing edge flaps, and telescopic
blades are among these techniques. Generally speaking, power and blade load control can be carried out either through devices installed on blades (or blade itself), or via mechanism affecting the rotor as a whole. Figure 1 classifies and shows different conventional and nonconventional power and load control mechanisms affecting the blade performance. Some of these control systems respond only to wind variations with large time scales, while some other have shorter response time and therefore can be used for controlling the effect of wind variations with smaller time-scales.

Adopting from the helicopter blade technology, passive blade twist control is a relatively new field in the wind turbine industry. This approach, known as adaptive or intrinsically smart blades, employs the blade itself as the controller to sense the wind velocity or rotor speed variations and adjust its aerodynamic characteristics to affect the wind turbine performance. Earlier work was carried out on the project at Reading University by Karaolis (1989) and Kooijiman (1996) and then progressed by other investigators. These blades are made of anisotropic composite materials and change their shapes in response to the variations in wind turbine operating conditions. It has been shown that these blades potentially can be used for both blade load alleviation and enhancing energy capture capabilities (Lobitz, 2001, Maheri 2006, Maheri et al 2006a, 2006b, 2007a, 2007b and 2007c, Maheri and Isikveren 2009, Maheri and Isikveren 2010 and Zhang 2013).

A different kind of aerodynamic device proposed for load alleviation is microtabs (Baker and Mayda 2005, Chow 2007, van Dam et al 1999, Wiratama 2012, Wiratama and Maheri 2014, Macquart 2014, Macquart et al 2014 and Macquart and Maheri 2015). Microtabs are small aerodynamic control surfaces with deployment height of order of magnitude of 1% of local chord, installed close to the trailing edge of the blade. Morphing blades, a concept adopted from aircraft morphing wings, has also the potential to improve the system performance over the wind turbine operational envelope (for example see Stuart 1997, Farhan 2008 and Barlas 2010). The morphing concept includes a wide spectrum of shape adaptations such as variation in camber, twist, span and plan form area. Camber control is a type of morphing aerofoils and an effective way of controlling the aerodynamic forces by directly changing the shape of the aerofoil. This action has direct effects on the force distribution on the blade, so it can be used for active load alleviation purposes (Farhan 2008, Maheri and Isikveren 2011).

Aileron is another concept borrowed from aerospace industry. It originally was used for aerodynamic breaking of wind turbines. Results of research on ailerons via simulating the behaviour of a wind turbine in turbulent wind indicates that aileron load control can assist in power regulation and reduce root flap bending moments during a step-gust and turbulent wind situation (Migliore 1995, Stuart 1996, Enenkl 2002).

Recently, the concept of variable length blades has been also proposed as a means of controlling the load and increasing the energy yield of the turbine. Telescopic blades retract/extend in response to the variations in wind speed (DOE 2005, GE Wind Energy 2006, Pasupulapati 2005, Shrama 2007).

Figure 2 classifies smart blades into two categories, namely, intrinsically smart and extrinsically smart. This classification is associated with the type of control in place: passive control for intrinsically smart and active control for extrinsically smart blades.

SIMULATION

Aerodynamic load on blades and rotor mechanical power can be found via aerodynamic simulation of wind turbine. In intrinsically smart blades (adaptive blades), the aerodynamics of the blade is modelled in conjunction with the blade structural characteristics and, in case of unsteady analysis, the blade
In extrinsically smart blades, the aerodynamic of the blade is modelled integrated with the controller characteristics and, in case of unsteady analysis, the blade aeroelastic characteristics.

**Intrinsically Smart Blades (Adaptive Blades)**

Due to structure aerodynamic interaction in intrinsically smart blades, the aerodynamic performance simulation of these blades cannot be carried out independent of structural analysis as shown in Figure 3 (Maheri 2010).

WTAB (Wind Turbine Adaptive Blades) (Maheri et al 2006a) and its extended version (Maheri 2012), perform a complete aero-structural simulation (see Figure 4). This code consist of three main modules, namely, WTAero, the BEMT-based wind turbine aerodynamic analyser; ABMesh, the in-line adaptive mesh generator (Maheri 2007d); and TRIC, the natural mode formulated finite element solver. Figure 5 shows the data flow in a coupled aero-structure simulation in WTAB. While WTAB was proved to be very efficient and reliable in simulation of adaptive blades, including a finite element analysis (FEA) in an iterative process was the motivation of the development of WTSID (Wind Turbine Simulation and Integrated Design) (Wiratam 2012 and Zhang 2013). In contrary to WTAB, in which structural analysis is carried out via FEA, in WTSID the structural analyser is based on mathematical models (Zhang et al 2012a, 2012b, Zhang 2013 and Zhang and Maheri 2014). Figure 6 shows the cross section of a blade made of different materials, as in adaptive blades and Figure 7 shows the graphical user interface of Zhang’s structural analyser in WTSID.
Extrinsically Smart Blades

In extrinsically smart blades, the aerodynamic performance depends on the characteristics of the control system in place (type, response time, controlling parameter, controllable parameter, etc) as well as the wind turbine rotor characteristics (e.g. blade topology and size, number of blades and rotor angular speed) and the operating condition (e.g. mean wind speed at hub elevation, wind direction and turbulence level). Hence, the performance of the controller itself should be properly integrated as part of the simulation process. Very few software tools developed for simulation of extrinsically smart blades, amongst them are WTSID for steady state simulation and WTAC (Macquart and Maheri 2015), which can perform both steady state and unsteady simulation. The approach taken for the integration of the controller into simulation is different.

a) Steady Simulation

In WTSID, the controller is simulated through solving an optimisation problem. It is assumed that the controller is capable of delivering the expected functions perfectly. This implies that the controlling parameter is always adjusted at its best possible value, which leads to the best (goal) performance. Adapting this approach, the optimum (best possible) controlling parameter, which optimises the performance measure(s) can be found via solving the optimisation problem of Equation 1 for power control and the optimisation problem of Equation 2 for load control:

$$\max \ P(q_i) ; \ i = [1,2,\ldots,n_q]$$

subject to

$$P \leq P_{rated}$$

$$q_{i,j} \leq q_i \leq q_{i,u} ; \ i = [1,2,\ldots,n_q]$$

$$\min \ L(q_i) ; \ i = [1,2,\ldots,n_q]$$

subject to

$$q_{i,j} \leq q_i \leq q_{i,u} ; \ i = [1,2,\ldots,n_q]$$

where $P$ is the rotor mechanical power at a given wind speed, $L$ is a representative load (e.g. flap bending moment at the blade root), $q_i$ stands for the i-th controlling parameter limited to the interval $[q_{i,j}, q_{i,u}]$. Number of independent controlling parameters, $n_q$ depends on the type of the blade and the rotor (constant speed or variable speed).

The 300kW AWT-27 was taken as the case for study. This wind turbine is simulated with extrinsically smart blades instead of its original blades. The results of simulations are shown in Figures 10 through 15 (Wiratama 2012). The smart blades used...
for these simulations have the same topology (aerofoil, pretwist and chord distributions) as the original blades. With reference to these figures the following conclusions can be drawn.

- Using telescopic blades enhances the power capture capability significantly at lower wind speeds for both constant speed and variable speed rotors.
- Telescopic blades provide a full and smooth control.
- The bending moment at the root of the blade increases significantly by using telescopic blades.
- Microtab and flap have been initially developed for load alleviation purposes. These controlling devices, however, can be used to regulate and enhance the rotor mechanical power to some extent.
- Microtab and flap slightly improve the power coefficient for constant speed rotors.
- Although microtab is not as efficient as flap or pitch control systems, it increases the load on blades significantly when used for power enhancement.
- Flaps, when used in conjunction with another controlling system such as rotor speed, the accompanied controlling system dominates the control process. This conclusion can be extended to microtabs by observing similar effect of both controlling systems on the power curve.

FIGURE 10-ROTOR POWER-CONSTANT SPEED

FIGURE 11-ROTOR POWER-VARIABLE SPEED

FIGURE 12-POWER COEFFICIENT-CONSTANT SPEED

FIGURE 13-POWER COEFFICIENT-VARIABLE SPEED

FIGURE 14-BLADE ROOT BENDING MOMENT-CONSTANT SPEED

FIGURE 15- BLADE ROOT BENDING MOMENT-VARIABLE SPEED
b) Unsteady Simulation

In the second approach, as in WTAC, the controller is designed and implemented as part of the blade aeroelastic model. The overall model takes into account the interaction between the blade aerodynamic and its structure as well as the controller. Figure 15 demonstrate this interaction schematically and Figure 16 shows a typical control structure (Macquart 2014).

In extrinsically smart blades, power and/or load control is due to changes in the aerodynamic characteristics of the blade, mainly as a result of sectional lift coefficient. Figure 17 shows typical variation of lift coefficient of an aerofoil due to the deployment of a control surface (flap or microtab).

The comparison between the original and controlled flapwise root bending experienced by the NREL 5 MW wind turbine blade is presented in Figure 18 (Macquart 2014). Reduction in dynamic load can have significant effect on the fatigue life of blades and other components of wind turbines Macquart and Maheri (2015). In Figure 18, the smart blade is equipped with multiple control surfaces employing P and PD controllers combined with high-pass filter.

FIGURE 15 - UNSTEADY SIMULATION OF EXTERINSICALLY SMART BLADES

FIGURE 16 - TYPICAL EXTERINSICALLY SMART BLADES CONTROL STRUCTURE

FIGURE 17 – TYPICAL VARIATION OF LIFT COEFFICIENT OF AN AEROFOIL DUE TO THE DEPLOYMENT OF A CONTROL SURFACE: (a) STEADY STATE, (b) DYNAMIC RESPONSE PRE-STALL AND (C) DYNAMIC RESPONSE POST STALL ANGLE OF ATTACK

FIGURE 18 - FLAPWISE ROOT BENDING MOMENT: MULTIPLE CONTROL SURFACE LOAD ALLEVIATION OF THE NREL 5MW WIND TURBINE BLADE USING P AND PD CONTROLLERS (18m/s TURBULENT WIND FIELD)
DESIGN APPROACHES

In design of smart blades, researchers take one of the following approaches:

- Retrofitting, in which elastic coupling or active devices are added to an existing blade design, without any modification to the blade topology.
- Modification, in which the original topology of the base design is modified.
- Design from scratch.

Examples of retrofitted designs include Figures 9-14 and 18 reported in this paper. Further modification of the wind turbines of Figures 9-14 using a genetic algorithm-based blade optimisation tool (Maheri and Isikveren 2009 and Wiratama 2012) leads to better performance of these blades. For example, see Figures 19 and 20. Figure 19 shows the modified pretwist of the blade of AWT-27 wind turbine. The pretwist of the blade is optimised towards maximising the wind turbine power extraction capability when flaps are installed along 25% of the span.

Not all of the modification-based designs employ an optimisation tool to find the optimum topology. Maheri et al. (2006) presented a simple method for modifying a conventional blade to an adaptive blade without any search-based optimisation.

As adding more modifications to the original blade improves the performance of the smart blade, a design from scratch, in which there is no initial rigidity on the design space, is more likely to yield to the optimum solution. Design from scratch is more complicated than a modified base design. In a design from scratch, an integrated design approach should be taken. Figure 21 shows a schematic diagram of an integrated adaptive blade design (Maheri et al. 2007a).
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