Wind and Structures, *Vol. 22, No. 1 (2016) 1-16*
DOI: http://dx.doi.org/10.12989/was.2016.22.1.001

A review of the state-of-the-art in aerodynamic performance of horizontal axis wind turbine

Muhammad Ramzan Luhur*[1], Abdul Latif Manganhar[1a], K.H. Solangi[2b], Abdul Qayoom Jakhrani[3c], Kishan Chand Mukwana[3d] and Saleem Raza Samo[3e]

[1]Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan
[2]Department of Mechanical Engineering, University of Malaya, Kuala Lumpur, Malaysia
[3]Department of Energy and Environment Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

(Received March 16, 2014, Revised May 20, 2015, Accepted June 27, 2015)

Abstract. The paper presents the state-of-the-art in aerodynamic performance of the modern horizontal axis wind turbine. The study examines the different complexities involved with wind turbine blade aerodynamic performance in open atmosphere and turbine wakes, and highlights the issues which require further investigations. Additionally, the latest concept of smart blades and frequently used wind turbine design analysis tools have also been discussed. The investigation made through this literature survey shows significant progress towards wind turbine aerodynamic performance improvements in general. However, still there are several parameters whose behavior and specific role in regulating the performance of the blades is yet to be elucidated clearly; in particular, the wind turbulence, rotational effects, coupled effect of turbulence and rotation, extreme wind events, formation and life time of the wakes.

Keywords: horizontal axis wind turbine; aerodynamic performance; complexities; natural wind; turbine wakes; design analysis tools

1. Introduction

The wind turbines operate in atmospheric boundary layer exposed to turbulence and shear effects permanently. The atmospheric turbulence is a three-dimensional stochastic effect, which exists in different scales in the wind field and is impractical to predict (Pechlivanoglou 2013). The interaction of such complex and highly dynamic wind with turbine rotor blades leads to highly dynamic forces. Additionally, the aerodynamic loading, blade rotation, gravity, mass imbalance and gyroscopic effects also play an active role in the development of forces on wind turbine blades

∗Corresponding author, Assistant Professor, E-mail: luhur@quest.edu.pk
[a] Assistant Professor, E-mail: alatif_mgr@yahoo.com
[b] Ph.D. Student, E-mail: solangi.quest@gmail.com
[c] Assistant Professor, E-mail: aqunimas@hotmail.com
[d] Assistant Professor, E-mail: kcmukwana@quest.edu.pk
[e] Professor, E-mail: sfaizsamo@yahoo.com

http://www.techno-press.org/?journal=was&subpage=8 ISSN: 1226-6116 (Print), 1598-6225 (Online)

(Epaarachchi and Clausen 2006). All these effects generate three kinds of forces; steady, transient and alternating forces. The steady forces are not as harmful as transient and alternating forces. The latter two forces contribute to fatigue loading and damage the blade structure per load cycle.

The horizontal axis wind turbine (HAWT) is the most common and dominant type of the wind turbine. The HAWTs with less number of blades (i.e., two or three) are more efficient for power generation (Hau 2006, Burton *et al.* 2011). Rotor with more blades yields low tip speed ratio (TSR); thus, generates less power. Increase in number of blades causes increase in rotor torque but it does not improve the power generation. Further, increase in shaft speed using any type of gearing hurts the power output seriously; particularly in low wind speeds. Rotor with three blades gives the best compromise of TSR versus torque leading to high power coefficient.

For increased energy extraction from wind, the rotor efficiency is desired to be maximized within the affordable production limits, which needs significant optimization efforts. The maximum energy that a wind turbine can extract from the free stream is 59.3% of the available kinetic energy. This is referred as the Betz limit (Gasch and Twele 2002, Burton *et al*. 2011, Gorban *et al.* 2001). The Betz limit is based on constant linear velocity, it ignores the wake rotation as well as turbulence caused by drag or tip vortices that further reduce the maximum efficiency. Therefore, the maximum ideal efficiency is yet to be perceived (Yurdusev *et al*. 2006). The losses from latter phenomenon can not be ignored completely, however, such losses could be minimized through design improvements. The general steps to cut down the losses include: decrease in wake rotation by increasing TSR; selection of airfoils with high lift-to-drag ratio and specialized tip configurations (Schubel and Crossley 2012).

This paper provides a review of the state-of-the-art in aerodynamic performance of HAWT operating in open atmosphere and turbine wake and also highlights the complexities and issues that require further investigations. Additionally, the study reflects on the concept of smart blades and the design analysis tools in current use.

The paper is organized as follows. Sec. 2 presents the HAWT aerodynamics, blade sectional characteristics along the span, performance under natural wind and turbine wakes, and the concept of smart blades. Sec. 3 provides the status of current wind turbine design analysis tools. Finally, Sec. 4 summarizes the research progress in HAWT aerodynamics and performance, and enlists the issues which require further investigations.

2. Aerodynamics and performance of HAWT

The aerodynamics of the wind turbines is the study of wind flow pattern around and through the rotor, and the power extracted by the rotor. Fig. 1 shows the schematic of velocity and forces acting on a blade section of modern HAWT. A HAWT has an airfoil shaped rotor that extracts energy from the wind flowing around the blades. The bound circulation around the blades cause lift and drag forces, which produces mechanical energy with their combine effect. This mechanical energy is then converted either in electrical power or directly used for any other application. Compared to other types of wind turbines, HAWT is predicted to have superior characteristics particularly in terms of higher efficiency (Kishinami *et al.* 2005).

For efficient rotor design, aerodynamic performance is very basic aspect to consider (Maalawi and Badr 2003). The components of aerodynamic forces; the lift and drag forces have the key role in an appropriate rotor design. The lift force contributes to the power yield and drag force prevents the blade rotation. Thus, the objective is to maximize the lift and minimize the drag, i.e., high lift-to-drag ratio. The airfoil section typically with lift-to-drag ratio of more than 30 is recommended for rotor blade design (Griffiths 1977, Schubel and Crossley 2012, Maalawi and Badr 2003). The expression for lift-to-drag ratio is given by ϵ

$$\epsilon = \frac{C_L}{C_D} \tag{1}$$

where C_L is the lift coefficient and C_D the drag coefficient.

The structural considerations suggest the use of airfoils with high thickness-to-chord ratio at root part of the blades to withstand the high loads. The thick airfoils have usually low lift-to-drag ratio, therefore, for wind turbine blade design, thick airfoils should be produced carefully to maximize their lift (Fuglsang and Bak 2004, Van-Rooij and Timmer 2003). The mid-span and tip part of the blade require more consideration to aerodynamic properties (Fuglsang and Bak 2004). The blade tip part needs thin airfoils to have reduced loads, strong linear velocity and good aerodynamic performance. It is believed that the use of latest materials with advanced mechanical properties may permit the use of thin airfoils even for root part of the blade with higher lift-to-drag ratios (Schubel and Crossley 2012). More information on airfoil characteristics desired for different regions along the blade span can be found in Table 1.

2.1 Airfoil characteristics and blade shape

The estimation of lift and drag forces are based on angle of attack (AOA), which is the angle between airfoil chord and apparent/relative wind. The airfoil sections along the blade span observe different apparent wind speed, thus, different AOA and different magnitude of lift and drag forces, which lead to different structural requirements. Therefore, the airfoil sections for different regions of blade along the span are required to be designed according to their local conditions.

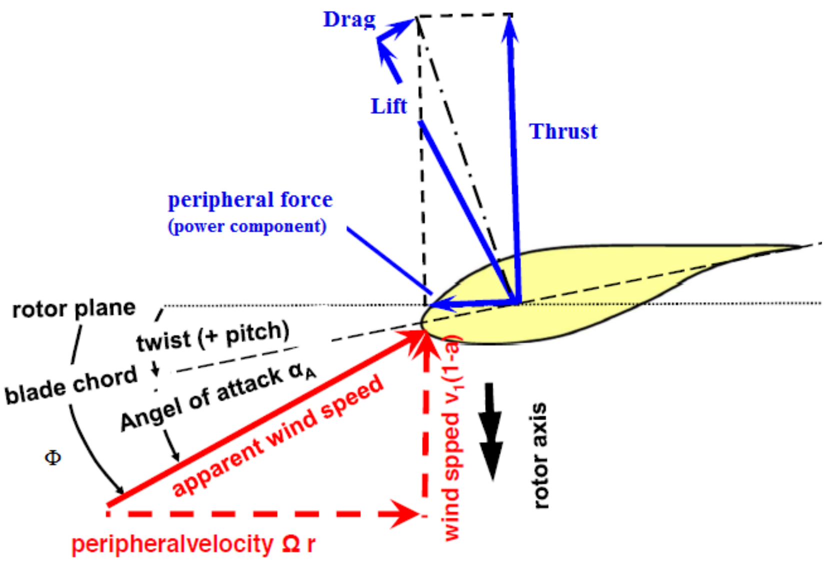

Fig. 1 Schematic of velocity and forces acting on HAWT blade element. Taken from Kühn (2013)

Table 1 Desirable characteristics for airfoils for different regions of the blade along the span. Reproduced from Fuglsang and Bak (2004)

Parameter Description	Root	Mid-span	Tip
Thickness-to-chord ratio	>27%	27%–21%	21%–15%
Structural load bearing requirement	xxx	xx	x
Geometrical compatibility	xx	xx	xx
Maximum lift insensitive to leading edge roughness	-	-	xxx
Design lift close to maximum C_L off-design	-	x	xxx
Maximum C_L and post stall behavior	-	x	xxx
Low airfoil noise	-	-	xxx

Here xxx=high, xx=medium and x=low

However, the root section airfoils are the thickest portions to sustain the loading from outer section of the blade. The maximum stresses develop at the root section of the blade (Tenguria *et al*. 2013). Moreover, manufacturing of whole blade using a single type of airfoil profile can also result in an ineffective design (Maalawi and Badr 2003). An efficient blade design may contain multiple airfoil profiles merged at an angle of twist ending at a round rim (Gasch and Twele 2002, Kong *et al.* 2005) as shown in Fig. 2.

For better efficiency, several simplifications may be considered including a reduction in twist angle, linearization of chord width and selection of reduced number of differing airfoil profiles. Currently most of the foremost wind turbine manufacturers are considering nearly all these optimization aspects, i.e., twist, variable chord length and multiple airfoil configurations (Schubel and Crossley 2012).

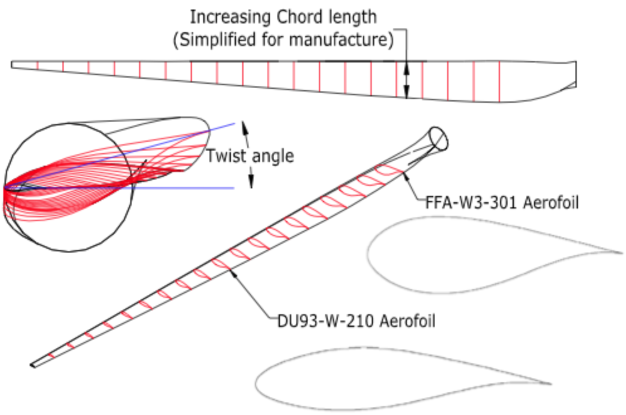

Fig. 2 HAWT blade with multiple airfoil profiles and shape distribution along the span. Taken from Schubel and Crossley (2012)

2.2 Performance under boundary layer and turbulence

Many studies considered aerodynamic characteristics of airfoils under steady low-turbulence flow (Fuglsang *et al.* 1998, Fuglsang *et al.* 1999, Timmer and Van-Rooij 2003), however, the characteristics in turbulent wind conditions still need to be determined. A wind turbine operating in open-air experience unsteady, three-dimensional and strong turbulent flows, as they operate in the atmospheric boundary layer known as surface layer. In this layer, the frictional forces and obstacles cause delay in wind, which result in variations in wind speed and direction. In addition, the existence of seas and large lakes contribute circulatory motions in air masses. The level of wind instability decreases with increase in height above the ground surface as the effects driven with interaction of earth surface get weaker (Bianchi *et al.* 2007). The decline of shear effects allows an increase in wind speed. For wind energy applications, the wind velocity follows the power law profile given by

$$u(z_2) = u(z_1)\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{2}$$

where $u(z_2)$ is the mean inflow wind velocity at height z_2 and $u(z_1)$ the mean inflow wind velocity at height z_1. The parameter α in Eq. (2) is the shape factor defined empirically based on local conditions of the site (Pechlivanoglou 2013). Collectively, the wind behavior at any location depends on the weather, the height from the ground surface and the geographic conditions including the roughness of landscape and surrounding obstructions (Bianchi *et al*. 2007). More precisely, the wind fields are complex and unsteady structures with fluctuating properties in time and space. To comprehend this complex wind dynamics and integrate for corresponding effects into a wind turbine design is one of the major challenges in present wind energy research and engineering.

In order to classify the wind situations, it is usual in engineering practice to use the turbulence intensity, expressed as ratio of inflow standard deviation σ_u to mean inflow $\langle u \rangle$ (Mücke *et al.* 2011, Schneemann *et al*. 2010)

$$T_i = \frac{\sigma_u}{\langle u \rangle} \tag{3}$$

where T_i is the turbulence intensity. The turbulence is believed to be the instability of laminar flow. In laminar flow (low Reynolds numbers), the wind may have regular and stable behavior, however, in turbulent flow (high Reynolds numbers), the wind fluctuations have irregular and chaotic behavior in time and space (Giacomazzi *et al*. 1999).

In turbulent flow, the local AOA and the size of wind speed at rotor blades change continuously, which contribute to unsteady aerodynamic loads on the blades (Hansen and Madsen 2011, Kallesøe 2006). Even small-scale turbulence lead to a persistent unsteadiness in the wind flows approaching the rotor blades (Burton *et al*. 2011). The degree of unsteadiness related with the flow field and the turbine operating conditions can be determined using the relation (Leishman 2002)

$$k = \frac{\omega c}{2V} \tag{4}$$

where k is the reduced frequency which represents the level of unsteadiness of the flow, ω the characteristic physical frequency of the flow (circular frequency), $\frac{1}{2}c$ the blade semi-chord length and V the resultant local flow velocity at blade element. Eq. (4) gives information about the relationship between reduced frequencies and the unsteady disturbances to a flow. With respect to values of k, flow types can be described as $k = 0$ represents a steady flow, $0 < k \leq 0.05$ a quasi steady flow, $0.05 < k \leq 0.2$ an unsteady flow and $k > 0.2$ a strongly unsteady flow (Sebastian and Lackner 2013).

The unsteady aerodynamic loads stimulate structural vibrations that affect the local velocities and AOA. Consequently, it influences the aerodynamic loads directly (Hansen and Madsen 2011). The latter phenomenon leads to fatigue (alternating loads) (Hansen and Madsen 2011) as well as dynamic stall situation. The large variations in wind velocity at short time scales can have substantial effect on the wind turbine's extreme alternating loads (Kallesøe 2006, Mücke *et al.* 2011). The fluctuating loads cause variability in the turbulence spectrum as well as response statistics of the turbine (Saranyasoontorn and Manuel 2008). Extreme wind events and the resulting loads cause a major challenge for wind turbine development and optimization, particularly, the effects of extreme loads on rotor aerodynamics. Dynamic stall is a viscous effect on the airfoil properties, which generate the rotating motion of the fluid particles on the blade surfaces during stall (Snel 2003) leading to bigger amplitude transient forces (Pereira *et al*. 2013) and increased lift dynamics (Eggleston and Stoddard 1987, Leishman 2006, Wolken-Möhlmann *et al*. 2007, Holierhoek *et al*. 2013). The cost optimized wind turbines with minimal usage of material and relatively flexible structures can subject to increased loads due to increased response to turbulent inflow, wind shear and tower shadow effect (Kallesøe 2006).

For an effective design of a wind turbine, correct and effective prediction of the loads is mandatory (Breton *et al*. 2008). The current simulation methods to calculate the loads have various deficits especially in estimation of loads developed by rotational effects. The rotational effects cause stall delay phenomenon described by increase in lift coefficient and delay in flow separation at higher AOAs. The stall delay phenomenon is still questioned today (Breton *et al*. 2008, Sicot *et al.* 2008). The stall delay phenomenon modeled so far is incorrect mainly due to adjustment of two-dimensional (2D) aerodynamic data to account for three-dimensional (3D) rotational effects (Breton *et al.* 2008). The accuracy of dynamic stall models is also limited especially in deep stall regime, which needs further research and possible improvements (Holierhoek *et al.* 2013).

In practice, the industrial standard approach IEC 61400 (IEC 2005) used to classify the wind conditions, is mainly based on 10 minute mean values, standard deviation over same time span and the level of turbulence. These parameters belong to one-point statistics and is deficient effort to take hold of the roughness of the extremely volatile wind (Peinke *et al.* 2008, Wächter *et al.* 2012). Practically, it is never possible for a wind turbine to adjust within this 10 minute statistics criteria. The load variations on rotor blades, dynamic response of the wind turbine and the corresponding power output dynamics take place at time scale of order 1 second (Wächter *et al.* 2012). The power and torque curves at high-frequency (short time scales) dynamics depending on wind and rotational speeds, respectively, are shown in Fig. 3.

Fig. 3(a) shows the power output dynamics of a HAWT at high-frequency depending on wind inflow. The arrows in Fig. 3 represent the local power fluctuations driven by the turbulent wind at high-frequency and dots the stable (attractive) fix points of local power dynamics. The power curve based on stable fix points matching the industrial IEC standard 61400-12-1 (IEC 2005). Fig. 3(b) shows the torque dynamics depending on rotational speed. Here, the arrows represent the local torque fluctuations and dots the stable fix points of local torque dynamics (Wächter *et al.* 2012). Nevertheless, there are some other considerable drawbacks of standard 10 minute statistics also. For example, a wind turbine typically shuts down each time on the condition of 10 minute average wind speed exceeding cut-out wind speed (i.e., around 25 m/s) and the condition to resume operation is often based on 10 minute average wind speed drop below 20 m/s. This can have a pronounced negative effect on the energy production (Ackermann and Söder 2002).

The wind velocity is measured only at the hub height, which means at the lower-half of the wind turbine rotor. This assumption could be satisfactory for small size rotors, but for large wind turbines having large rotor sizes, situation is different. The high variable wind having large wind shear, turbulence and directional shear can lead to several complexities and significant effect on power curve (Wagner *et al*. 2009). Shear effects produce mechanical turbulence with spatial and temporal variations in wind speed (Hansen and Madsen 2011). Furthermore, wind shear leads to uneven pressure variations on blade surfaces which cause extreme fluctuations in thrust and power. Under such high fluctuations, the turbine may face critical structural and vibrational problems which could be harmful for wind turbine life (Sezer-Uzol and Uzol 2013). Therefore, to design a wind turbine, it is essential to consider as many physical factors as possible including 3D flow features, span-wise dependency and viscosity effects. These factors need to be included in a correct and effective way (Johansen *et al*. 2009). Further, the floating offshore wind turbines are even more difficult to design and need more considerations while designing (Kim and Kim 2015).

2.3 Performance under wind turbine wake

The wake of a wind turbine is one more factor which contributes to turbulence in wind farms. Observations manifest a 5 to 25% increase in turbulence level in the wake of a wind turbine (Sicot *et al*. 2006). The higher turbulence levels and wake velocity deficits in wind farms result in increased dynamic loads on the blades and reduced power production, respectively (Sanderse *et al*. 2011).

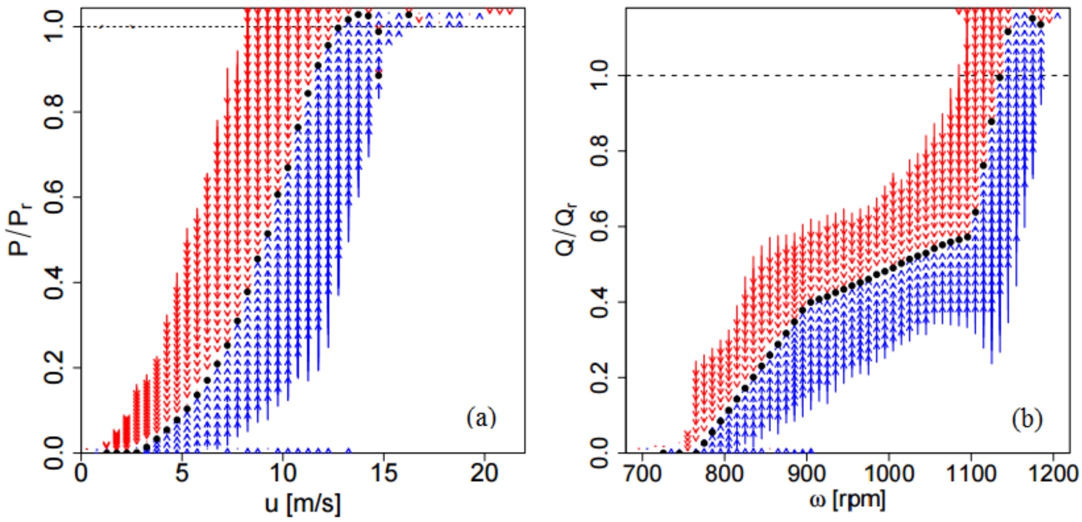

Fig. 3 Power output and rotor torque with drift function representing the local dynamics around stable fix points derived from wind turbine measurements. The stable fix points (black dots) are the points of attraction where drift function is zero. (a) Power output versus wind speed and (b) rotor torque versus angular speed. Power output and torque are normalized with their respective rated values. Taken from Wächter *et al.* (2012)

The wake of the wind turbine not only affects the performance of the turbine generating it, but also the other turbines in wind farm. The wakes of the upstream turbines can also reduce the life time of the rotors (Ivanell 2009). The wakes generate from rotating blades making concentrated helical tip and root vortex structures. While considering the effect from upstream to downstream turbines, the formation and life time of the tip vortices are subjects of interest. The self-induced instabilities and atmospheric turbulence make the dispersal of tip vortices (Ivanell 2009).

The wakes behind wind turbines are classified into two groups; the near wake and far wake. The near wake represents the aerodynamics of the wake vortices and their relation to loading on blades and inflow conditions (Ivanell 2009). The near wake region is considered up to one or two rotor diameters downstream of the wind turbine (Sanderse *et al.* 2011). The turbulence intensity of the inflow can have strong inference on wake development (Medici and Alfredsson 2006). The higher the turbulence intensity, the faster the wake recovery due to variations in velocity distribution within the wake (Krogstad and Adaramola 2012). The parameters such as wake expansion, skew angle and induction factors change with change in yaw angle. The increase in yaw angle results in a decrease in loading and power coefficient as shown in Fig. 4. The variation in rotor yaw angle causes variations in AOA on the blades, which lead to variations in blade aerodynamics. The rotor yawing affects the relative wind velocity and rotor swept area. This could have severe implications in particular for free floating offshore wind turbines where yaw control is expected to be more difficult than onshore wind turbines (Krogstad and Adaramola 2012).

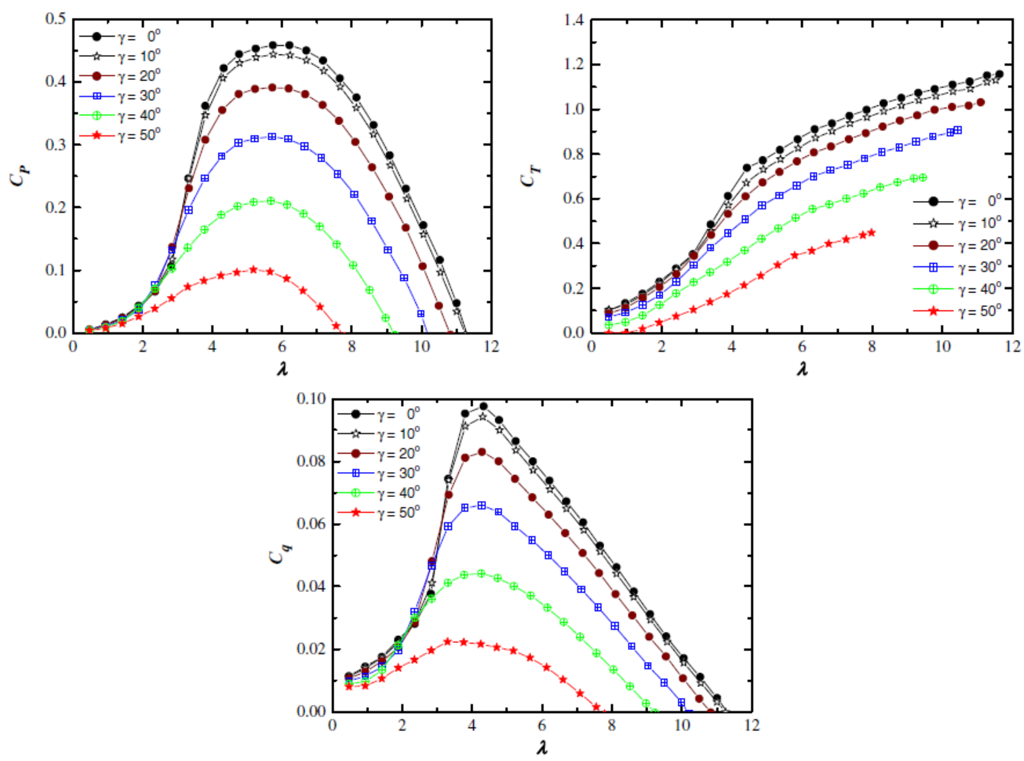

Fig. 3 Performance characteristics for a model turbine at different yaw angles. (a) Power coefficient and (b) thrust coefficient and (c) torque coefficient. Taken from Krogstad and Adaramola (2012)

The far wake study focuses on the influence of wind turbine wakes in farm situation and has less importance to modeling of actuator rotor. In far wake regions, the main and dominant physical process is the turbulence, which is the integration of atmospheric turbulence, mechanical turbulence and wake turbulence (Sanderse *et al*. 2011). The modeling of turbulence, wake interaction and topographic effects are of prime interest in far wake (Ivanell 2009). At present, the majority of the researchers are using computational fluid dynamics (CFD) to study the wind turbine wake aerodynamics. The particular focus is on improvements in turbulence modeling since turbulence is the main factor in the wake aerodynamics (Sanderse *et al.* 2011).

The effect of wind turbine wakes on the energy production and the loading in connection with farm design are key parameters to consider while designing a wind farm (ECN 2009). The unsteady wind fields within and around wind farms could not be well understood, until and unless more detailed models or measurements of the wind field in a wind farm would be available. A similar approach is required to understand the response of many wind turbines within a wind farm on the mutual wakes. The available measurements are inadequate and models have insufficient accuracy. The problem is, metrological masts are very expensive and a lot of research is based on measurements at the turbines. Due to limited number of masts, there is no information of the flow between the turbines. This has hindered the research on wind farm aerodynamics and control (Eecen 2008). For better understanding of the basic wake aerodynamics and experimental data analysis, the numerical simulations by either vortex wake models or full field CFD methods may be used (Ivanell 2009). The main problem for CFD to simulate wake flows is the resolution of length scales, i.e., ranging from blade boundary layer thickness to rotor diameter.

2.4 Concept of smart blades

The wind turbine rotor blades are continuously growing in size. The upcoming generation of the turbines intends to approach the size up to 20 MW, which could lead to several challenges such as increase in cost, weight and aerodynamic loads. To control the latter factor, modern research in blade design is aiming to realize blades that adjust their shape according to local wind situation. The concept could be important for wind turbines of size > 10 MW in particular. The general aim is to minimize the ultimate and fatigue loads to minimize the total cost of wind turbines. The research move for smart blades for the application of wind turbines is the continuation of concepts from helicopter control. Work in this direction, is being carried out by different wind energy institutes under different projects (Schubel and Crossley 2012, Barlas and Kuik 2010). For example, German Environmental Ministry (BMU) project “Smart blade” (2014), European Energy Research Alliance (EERA) initiated project “AVATAR” (2014), European Commission funded UpWind project “Smart rotor blades and rotor control for wind turbines” (Barlas 2007), the Delft University project “Smart dynamic rotor control for large offshore wind turbines” (Marrant 2014) and the Danish national project “ADAPWING”. The International Energy Agency (IEA) 50th and 56th topical expert meetings at Delft University in December 2006 and Sandia National Labs in May 2008, respectively on “The application of smart structures for large wind turbine rotors” also indicate the research progress in this direction (Barlas and Lackner 2006, Thor 2008).

Wind turbines with smart blades use different control concepts and include: distributed aerodynamic control surfaces, actuators, sensors and controllers as shown in Fig. 5 (Barlas and Kuik 2010). The control devices change the blade local aerodynamic characteristics and provide the required control actions. The actuator smart materials have the property to sense and drive in a controlled way in response to change in surrounding flow conditions (Schubel and Crossley 2012, Barlas and Kuik 2010). The concept of smart blades equipped with active flow control systems, is believed to replace the traditional pitch system and allow the manufacturing of even bigger size wind turbines (Pechlivanoglou 2013). However, such blades require smart control system with possibly high voltage may attract more lightning strikes than the conventional blades (Barlas 2007).

3. Design analysis tools

In order to carry out wind turbine design calculations, several approaches do exist today. These are based on Blade Element Momentum (BEM), Free Wake Vortex, Acceleration Potential and CFD methods (Vermeera *et al*. 2003, Leishman 2002, Conlisk 2001, Snel 1998, Van-Bussel 1995). These methods basically were developed to deal with propeller and helicopter aerodynamics, but later used to model the HAWT aerodynamics (Sant 2007).

Compared to engineering methods, high fidelity CFD methods are very time consuming in computational terms. In the case of large problems, CFD can take up to a week, while engineering methods need a few seconds to solve the same. CFD techniques solve numerically either Euler or Navier-Stokes equations and for wind turbine aerodynamics, are related to turbulence modeling in particular (Sumner *et al.* 2010). Generally, for the calculation of wind turbine aerodynamics, engineering methods represent the best choice; in particular for aeroelastic simulations (Åhlund 2004). Despite significant increase in computer power, CFD methods are still excessively expensive in computational terms. Furthermore, CFD is believed to be a separate skill of computations, which requires good knowledge to run and interpret the results (Montgomerie and Thor 2003). Nevertheless, future increased computer power may make it possible to replace the classical methods with more advanced models to integrate into aeroelastic codes (Sant 2007). In this context, four wide categories of CFD techniques believed to extend advancement over current design codes. These include actuator disc/surface/line technique, hybrid Reynolds Averaged Navier Stokes/Large Eddy Simulation (RANS/LES) approach, Full Blade and Rotor CFD method (overset CFD solver), and coupling between CFD and Computational Structural Dynamics (CSD) (Lynch 2011).

Looking at current situation, still most computational studies of wind turbine aerodynamics continue with simple and inexpensive classical BEM theory (Hansen and Madsen 2011). To predict aerodynamic loads, different aeroelastic design codes use BEM method; particularly because of its simplicity and computational efficiency. For attached flows (attached with blade element) in axial, BEM gives significantly accurate results. However, it lacks capability to model the complex flow fields around the rotor when handling with stalled and unsteady flows especially in rotor yaw (Sant 2007, Åhlund 2004). Therefore, BEM is used with some assumptions and correction models (Sant 2007), which include the airfoil data models and the inflow models. The airfoil data models correct 2D static airfoil data for 3D effects (i.e., blade tip/root losses, stall delay and dynamic stall) and the inflow models correct for uneven induced velocity distribution at rotor plane due to skewed wake effects in a yaw as well as conditions for heavy and unsteady loading on the rotor. Regardless, the validation studies have witnessed its good predictions for turbine loads and performance (Leishman 2002).

A brief description and features of some commonly used design codes are presented in Table 2, which are being used for calculation of wind turbines design parameters and modeling of its dynamic behavior.

Table 2 Design codes and their features

Design code	Features
AeroDyn	Plug-in type package for computation of aerodynamic forces on wind turbine blades. It estimates the elemental forces at desired location and time (Moriarty and Hansen 2005).
FAST	Fatigue Aerodynamics Structures and Turbulence (FAST). Dynamic analysis code for predicting extreme and fatigue loads of HAWTs with AeroDyn routines (Jonkman and Buhl 2005).
FAST-CHARM3D	Combination of FAST and CHARM3D (Bae and Kim 2011, 2014). Fully coupled dynamic analysis code for floating offshore wind turbine in time domain.
ADAMS/WT	Automatic Dynamic Analysis of Mechanical Systems/Wind Turbines with AeroDyn routines for aerodynamic analysis of wind turbines (Laino and Hansen 2001).
SIMPACK	Multi-Body Simulation Software with interface to AeroDyn for wind turbine aerodynamic forces analysis (Mulski 2012).
YawDyn	Dynamic analysis code used with ADAMS to simulate the yaw motions or loads of HAWT with a rigid or teetering hub (Hansen and Laino 1998).
DHAT	A traditional in-house wind-turbine-specific aeroelastic code. For aerodynamic calculations it uses the BEM, dynamic and turbulent wake conditions, and dynamic stall options (Buhl and Manjock 2006).
DUWECS	Delft University Wind Energy Converter Simulation in-house package in time domain for simulation and analysis of flexible wind turbines (Kühn 2001).
FLEX5	Simulates wind turbine dynamics with one to three blades, fixed or variable speed generator, pitch or stall power regulation (Ø ye 1999).
BLADED	An integrated simulation package for wind turbine design and analysis (Garrad Hassan 2013).
GAST	General Aerodynamic and Structural prediction Tool (GAST) for wind turbines (Vasilis and Voutsinas 1997).
HAWC2	Horizontal Axis Wind turbine simulation Code 2nd generation for simulation of HAWT response in time domain (Larsen and Hansen 2007).
FLEXLAST	Flexible Load Analyzing Simulation Tool used by Dutch industries for wind turbine and rotor design (Visser 1996).
PHATAS	Program for Horizontal Axis wind Turbine Analysis and Simulation (PHATAS). Program for time-domain estimation of the dynamic behavior and the corresponding loads on the main components of a HAWT (Lindenburg 2005).
VIDYN	Simulation tool for static and dynamic structural analysis of HAWTs (Ganander and Olsson 1998).
AERFORCE	Subroutine package for the prediction of aerodynamic forces on the wind turbine rotors intended for use in aeroelastic codes (Björck 2000a, Ahlström 2006).
ONERA	Semi-empirical model based on a set of non-linear differential equations, which describe the unsteady airfoil behavior (Holierhoek *et al*. 2013).
DYNSTALL	Subroutine package with Beddoes-Leishman dynamic stall model for calculation of 2D unsteady airfoil aerodynamics (Björck 2000b).
TURBU Offshore	Tool for combine frequency/time domain analysis of offshore HAWTs to assess the turbine dynamic behavior in different sea-states and wind conditions (Van-Engelen and Braam 2004).
ADCoS	AeroDynamic Consult GmbH (ADC) for load simulation of onshore wind turbines using Finite Element approach (Passon and Kühn 2005).
SOLVIA	Commercial Finite Element program for modeling of structural dynamics (Ahlström 2005).
EllipSys3D	Navier-Stokes solver program for complete 3D CFD computations considering steady state conditions with a moving mesh method (Johansen *et al*. 2009).
FLUENT/CFX	FLUENT and CFX for simulation of wind turbulence and aerodynamic characteristics (Dalpé and Masson 2008).

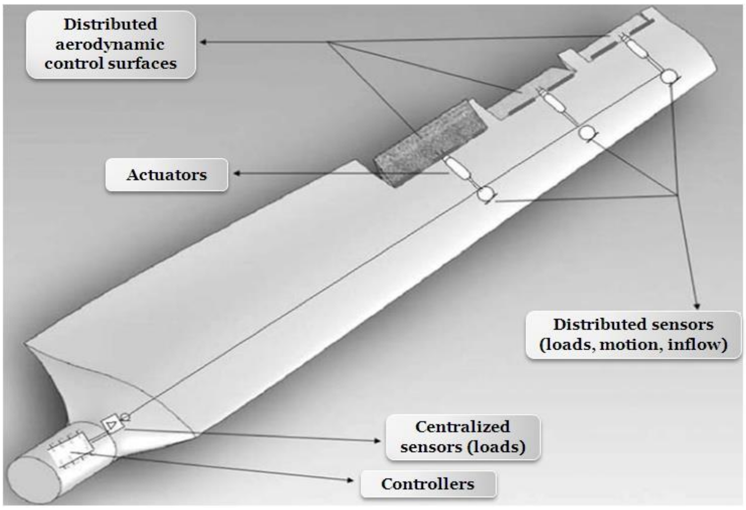

Fig. 5 Design view of a smart rotor blade. Taken from Barlas and Kuik (2010)

4. Conclusions

State-of-the-art techniques in aerodynamic performance of the modern HAWT have been studied under natural wind and turbine wakes. The modern concept of smart blades has also been reflected. The investigation made through this literature survey shows significant progress towards wind turbine aerodynamic performance improvements in general. However, still there are several parameters whose behavior and specific role in regulating the performance of the blades is yet to be clearly elucidated. In particular, wind turbulence, rotational effects, combine effect of turbulence and rotation, extreme wind events, formation and life time of the wakes need further detailed research.

The design optimization tools developed are mostly based on engineering methods and still have some limitations to assess the influence of various parameters accurately, especially when 3D computations are involved. The CFD techniques are very time consuming and require faster and expanded computer memory to be fully integrated into wind turbine design codes. For CFD, still much development is needed before applying for full scale calculations of the wind turbine design analysis.

Some issues which require further investigation include:

- Aerodynamic characteristics of airfoils under turbulent wind conditions
- Development of a simple and efficient approach to describe the variability in the inflow turbulent random field
- Development and dissemination of extreme loads through rotor aerodynamics caused by extreme wind events
- Better understanding of fatigue loads under unsteady aerodynamics and improvements in dynamic stall modeling especially in deep stall regime
- Proper understanding and correct modeling of stall delay phenomenon caused by

rotational effects

- Characterization of wind situations on short-time (high-frequency) scales and the resulting interaction with wind turbines
- Power performance and load analysis considering distributed wind measurements over the rotor swept area
- Development and life time of the wind turbine wakes while considering the impact on downstream turbines in wind farm
- Study of relationship between inflow turbulence intensity and wake length
- Understanding of wind turbines response within a wind farm on mutual wakes

References

Ackermann, T. and Söder, L. (2002), "An overview of wind energy-status 2002", *Renew Sust. Energ. Rev.*, **6**, 67- 128.

Ahlström, A. (2005), *Aeroelastic simulation of wind turbine dynamics*, Ph.D. thesis, Department of Mechanics, KTH, Stockholm, Sweden.

Ahlström, A. (2006), "Emergency stop simulation using a finite element model developed for large blade deflections", *Wind Energy*, **9**(3), 193-210.

Å hlund, K. (2004), *Investigation of the NREL NASA/Ames wind turbine aerodynamics database*, Scientific report ISSN 1650-1942, Swedish Defence Research Agency.

AVATAR (2014), "AdVanced Aerodynaic Tools for lArge Rotors (AVATAR)", *Available online: http://www.eera-avatar.eu/home/*, accessed 05 July 2014.

Bae, Y.H. and Kim, M.H. (2011), "Rotor-floater-mooring coupled dynamic analysis of mono-column-TLP-type FOWT (Floating Offshore Wind Turbine)", *Ocean Syst. Eng*., **1**(1), 93-109.

Bae, Y.H. and Kim, M.H. (2014), "Coupled dynamic analysis of multiple wind turbines on a large single floater", *J. Ocean Eng.*, **92**, 175-187.

Barlas, T. (2007), *Smart rotor blades and rotor control for wind turbines*, Up-Wind project report, Delft University Wind Energy Research Institute (DUWIND), the Netherlands.

Barlas, T. and Lackner, M. (2006), "The Application of Smart Structures for Large Wind Turbine Rotor Blades", *Proceedings of the IEA Topical Expert Meeting*, Delft University of Technology, the Netherlands.

Barlas, T.K. and van Kuik, G.A.M. (2010), "Review of state of the art in smart rotor control research for wind turbines", *Prog. Aerosp. Sci*., **46**(1), 1-27.

Bianchi, F.D., Battista, H.D. and Mantz, R.J. (2007), *Wind Turbine Control Systems-Principles, Modelling and Gain Scheduling Design*, Springer, London, UK.

Björck, A. (2000a), *AERFORCE: Subroutine package for unsteady Blade Element Momentum calculations*, Technical report FFA TN 2000-07, Aeronautical Research Institute of Sweden.

Björck, A. (2000b), *DYNSTALL: Subroutine package with a dynamic stall model*, Technical report FFAP-V-110, Aeronautical Research Institute of Sweden.

Breton, S.P., Coton, F.N. and Moe, G. (2008), "A study on rotational effects and different stall delay models using a prescribed wake vortex scheme and NREL phase VI experiment data", *Wind Energy*, **11**(5), 459-482.

Buhl, M.L.J. and Manjock, A. (2006), "A comparison of wind turbine aeroelastic codes used for certification", *Conference paper NREL/CP-500-39113*, National Renewable Energy Laboratory, USA.

Burton, T., Sharpe, D., Jenkins, N. and Bossanyi, E. (2011), *Wind Energy Handbook*, (2nd Ed.), John Wiley & Sons.

Conlisk, A. T. (2001), "Modern helicopter rotor aerodynamics", *Prog. Aerosp. Sci*., **37**(5), 419-476.

Dalpé, B. and Masson, C. (2008), "Numerical study of fully developed turbulent flow within and above a dense forest", *Wind Energy*, **11**(5), 503-515.

ECN. (2009), “Wind farm aerodynamics”, *Available online: http://www.ecn.nl/en/wind/rd-programme/windfarm-aerodynamics*, accessed 28 April 2009.

Eecen, P.J. (2008), *The ECN Scale Wind Farm Facility Available online*, Global Wind Power Report, Beijing, China.

Eggleston, D.M. and Stoddard, F.S. (1987), *Wind turbine engineering design*, (1st Ed.), Springer, New York, USA.

Epaarachchi, J.A. and Clausen, P.D. (2006), “The development of a fatigue spectrum for small wind turbine blades”, *J. Wind Eng. Aerod*., **94**(4), 207-223.

Fuglsang, P., Antoniou, I., Dahl, K.S. and Madsen, H.A. (1998), *Wind tunnel tests of the FFA-W3-241, FFAW3-301 and NACA 63-430 airfoils*, Scientific Report Risø-R-1041(EN), Risø National Laboratory, Denmark.

Fuglsang, P. and Bak, C. (2004), “Development of the Risø wind turbine airfoils”, *Wind Energy*, **7**(2), 145-162.

Fuglsang, P., Dahl, K.S. and Antoniou, I. (1999), *Wind tunnel tests of the Risø-A1-18, Risø-A1-21 and Risø-A1-24 airfoils*, Scientific report Risø-R-1112(EN), Risø National Laboratory, Denmark.

Ganander, H. and Olsson, B. (1998), *VIDYN simuleringsprogram för horisontalaxlade vindkraftverk*, Technical report TG-R-98-14, Teknikgruppen AB.

Garrad Hassan, G.L. (2013), “Wind Turbine Design Software”, *Available online: http://www.glgarradhassan.com/en/Software.php*, accessed 30 May 2013.

Gasch, R. and Twele, J. (2002), *Wind Power Plants*, Solarpraxis, Berlin, Germany.

Giacomazzi, E., Bruno, C. and Favini, B. (1999), “Fractal modelling of turbulent mixing”, *Combust. Theor. Model*., **3**(4), 637-655.

Gorban, A.N., Gorlov, A.M. and Silantyev, V.M. (2001), “Limits of the turbine efficiency for free fluid flow”, *J. Energ. Resour-ASME.*, **123**(4), 311-317.

Griffiths, R.T. (1977), “The effect of aerofoil characteristics on windmill performance”, *Aeronaut J.*, **81**, 322- 326.

Hansen, A.C. and Laino, D.J. (1998), *USER’S GUIDE to the Wind Turbine Dynamics Computer Programs YawDyn and AeroDyn for ADAMS*, Technical report, University of Utah, USA.

Hansen, M.O.L. and Madsen, H.A. (2011), “Review paper on wind turbine aerodynamics”, *J. Fluid. Eng*., **133**(11), 114001.

Hau, E. (2006), *Wind Turbines: Fundamentals, Technologies, Application, Economics*, (2nd Edition), Springer, Berlin, Germany.

Holierhoek, J.G., deVaal, J.B., van Zuijlen, A.H. and Bijl, H. (2013), “Comparing different dynamic stall models”, *Wind Energy*, **16**(1), 139-158.

IEC. (2005), “International Standard 61400-12-1, Wind Turbines: Power performance measurements of electricity producing wind turbines”, International Electrotechnical Commission.

Ivanell, S.S.A. (2009), *Numerical Computations of Wind Turbine Wakes*, PhD thesis, Department of Mechanics, KTH, Stockholm, Sweden.

Johansen, J., Madsen, H.A., Gaunaa, M. and Bak, C. (2009), “Design of a wind turbine rotor for maximum aerodynamic efficiency”, *Wind Energy*., **12**(3), 261-273.

Jonkman, J.M. and Buhl, M.L.J. (2005), *FAST User’s Guide*, Technical report NREL/EL-500-38230, National Renewable Energy Laboratory, USA.

Kallesøe, B.S. (2006), “A low-order model for analyzing effects of blade fatigue load control”, *Wind Energy*, **9**(5), 421-436.

Kim, H.C. and Kim, H.M. (2015), “Global performances of a semi-submersible 5 MW wind-turbine including second-order wave-diffraction effects”, *Ocean Syst. Eng.*, **5**(3), 139-160.

Kishinami, K., Taniguchi, H., Suzuki, J., Ibano, H., Kazunou, T. and Turuhami, M. (2005), “Theoretical and experimental study on the aerodynamic characteristics of a horizontal axis wind turbine”, *Energy*, **30**(11-12), 2089- 2100.

Kong, C., Bang, J. and Sugiyama, Y. (2005), “Structural investigation of composite wind turbine blade considering various load cases and fatigue life”, *Energy*, **30**(11-12), 2101-2114.

Krogstad, P. and Adaramola, M.S. (2012), "Performance and near wake measurements of a model horizontal axis wind turbine", *Wind Energy*, **15**(5), 743-756.

Kühn, M. (2001), *Dynamics and Design Optimization of Offshore Wind Energy Conversion Systems*, PhD thesis, Delft University Wind Energy Research Institute (DUWIND), the Netherlands.

Kühn, M. (2013), *Rotor Aerodynamics and Blade Element Momentum Theory*, Advanced Wind Energy Technology lecture notes, Carl Von Ossietzky University of Oldenburg, Germany.

Laino, D.J. and Hansen, A.C. (2001), *User's Guide to the Computer Software Routines AeroDyn Interface for ADAMS*, Technical report, University of Utah, USA.

Larsen, T.J. and Hansen, A.M. (2007), *How 2 HAWC2, the user's manual*, Technical report ISSN 0106- 2840, Risø National Laboratory, Denmark.

Leishman, J.G. (2002), "Challenges in modeling the unsteady aerodynamics of wind turbines", *Wind Energy*, **5**, 85-132.

Leishman, J.G. (2006), *Principles of Helicopter aerodynamics, Cambridge Aerospace Series*, (2nd Ed.), Cambridge University Press, New York, USA.

Lindenburg, C. (2005), *PHATAS Release "NOV-2003" and "APR-2005" USER'S MANUAL*, Technical report ECN-I-05-005, Energy Research Centre of the Netherlands.

Lynch, C.E. (2011), *Advanced CFD methods for wind turbine analysis*, PhD thesis, School of Aerospace Engineering, Georgia Institute of Technology, USA.

Maalawi, K.Y. and Badr, M.A. (2003), "A practical approach for selecting optimum wind rotors", *Renew Energ*., **28**(5), 803-822.

Marrant, B. (2014), *Smart Dynamic Rotor Control for Large Offshore Wind Turbines*, PhD research project (on going), Delft University of Technology, Faculty of Aerospace Engineering, the Netherlands.

Medici, D. and Alfredsson, P.H. (2006), "Measurements on a wind turbine wake: 3D effects and bluff body vortex shedding", *Wind Energy*, **9**(3), 219-236.

Montgomerie, B. and Thor, SE. (2003), "Aerodynamics for Wind Turbines", *Summary of IEA R&D Wind-16th Joint Action Symposium*, Boulder, USA.

Moriarty, P.J. and Hansen, A.C. (2005), "AeroDyn Theory Manual", Technical report NREL/EL-500-36881, National Renewable Energy Laboratory, USA.

Mücke, T., Kleinhans, D. and Peinke, J. (2011), "Atmospheric turbulence and its influence on the alternating loads on wind turbines", *Wind Energy*, **14**(2), 301-316.

Mulski, S. (2012), "SIMPACK multi-body simulation", *Proceedings of the Wind and Drivetrain Conference*, Hamburg, Germany.

Ø ye, S. (1999), *FLEX5 User Manual*, Technical report, Danske Techniske Hogskole, Denmark.

Passon, P. and Kühn, M. (2005), "State-of-the-art and Development Needs of Simulation Codes for Offshore Wind Turbines", *Proceedings of the Offshore Conference*, Copenhagen, Denmark.

Pechlivanoglou, G. (2013), *Passive and active flow control solutions for wind turbine blades*, PhD thesis, Technical University of Berlin, Germany.

Peinke, J., Anahua, E., Barth, S., Gontier, H., Schaffarczyk, A.P., Kleinhans, D. and Friedrich, R. (2008), "Turbulence a Challenging Issue for the Wind Energy Conversion", *Proceedings of the EWEC*, Brussels, Belgium.

Pereira, R., Schepers, G. and Pavel, M.D. (2013), "Validation of the Beddoes-Leishman dynamic stall model for horizontal axis wind turbines using MEXICO data", *Wind Energy*, **16**, 207-219.

Sanderse, B., van der Pijl, S.P. and Koren, B. (2011), "Review of computational fluid dynamics for wind turbine wake aerodynamics", *Wind Energy*, **14**(7), 799-819.

Sant, T. (2007), *Improving BEM-Based Aerodynamic Models in Wind Turbine Design Codes*, PhD thesis, Delft University Wind Energy Research Institute (DUWIND), the Netherlands.

Saranyasoontorn, K. and Manuel, L. (2008), "On the propagation of uncertainty in inflow turbulence to wind turbine loads", *J. Wind Eng Ind Aerod*., **96**(5), 503-523.

Schneemann, J., Knebel, P., Milan, P. and Peinke, J. (2010), "Lift measurements in unsteady flow conditions", *Proceedings of the Scientific EWEC*, Warsaw, Poland.

Schubel, P.J. and Crossley, R.J. (2012), "Review: Wind turbine blade design", *Energies*, **5**, 3425-3449.

Sebastian, T. and Lackner, M.A. (2013), "Characterization of the unsteady aerodynamics of offshore floating wind turbines", *Wind Energy*, **16**(3), 339-352.

Sezer-Uzol, N. and Uzol, O. (2013), "Effect of steady and transient wind shear on the wake structure and performance of a horizontal axis wind turbine rotor", *Wind Energy*, **16**(1), 1-17.

Sicot, C., Devinant, P., Laverne, T., Loyer, S. and Hureau, J. (2006), "Experimental study of the effect of turbulence on horizontal axis wind turbine aerodynamics", *Wind Energy*, **9**(4), 361-370.

Sicot, C., Devinant, P., Loyer, S. and Hureau, J. (2008), "Rotational and turbulence effects on a wind turbine blade. Investigation of the stall mechanisms", *J. Wind Eng. Ind. Aerod*., **96**(8-9), 1320-1331.

Smart Blade (2014). *Available online: http://smart-blade.com/*, accessed 05 July 2014.

Snel, H. (1998), "Review of the present status of rotor aerodynamics", *Wind Energy*, **1**, 46-69.

Snel, H. (2003), "Review of aerodynamics for wind turbines", *Wind Energy*, **6**, 203-211.

Sumner, J., Watters, C.S. and Masson, C. (2010), "CFD in wind energy: The virtual multiscale wind tunnel", *Energies*, **3**(5), 989-1013.

Tenguria, N., Mittal N.D. and Ahmed, S. (2013), "Structural analysis of horizontal axis wind turbine blade", *Wind Struct*., **16**(3), 241-348.

Thor, S. (2008), "The application of smart structures for large wind turbine rotor blades", *Proceedings of the IEA Topical Expert Meeting*, Sandia National Labs, USA.

Timmer, W.A. and Van-Rooij, R.P.J.O.M. (2003), "Summary of the Delft University wind turbine dedicated airfoils", *J. Sol. Energ. Eng*., **125**(4), 488-496.

Van-Bussel, G.J.W. (1995), *The Aerodynamics of Horizontal Axis Wind Turbine Rotors Explored with Asymptotic Expansion Methods*, PhD thesis, Delft University of Technology, the Netherlands.

Van-Engelen, T.G. and Braam, H. (2004), *TURBU Offshore, computer program for frequency domain analysis of horizontal axis offshore wind turbines*, Technical report ECN-C-04-079, Energy Research Centre of the Netherlands.

Van-Rooij, R.P.J.O.M. and Timmer, W.A. (2003), "Roughness sensitivity considerations for thick rotor blade airfoils", *J. Sol. Energ.- T ASME*., **125**(4), 468-478.

Vasilis, V.A. and Voutsinas, S.G. (1997), "A general aerodynamic and structural prediction tool for wind turbines", *Proceedings of the European union wind energy conference*, Dublin, Ireland.

Vermeera, L.J., Sørensen, J.N. and Crespo, A. (2003), "Wind turbine wake aerodynamics", *Prog. Aerosp. Sci*., **39**(6-7), 467-510.

Visser, B. (1996), "The aeroelastic code FLEXLAST", *State of the Art of Aeroelastic Codes for Wind Turbine Calculations 28th meeting of experts*, Lyngby, Denmark.

Wächter, M., Heißelmann, H., Hölling, M., Morales, A., Milan, P., Mücke, T., Peinke, J., Reinke, N. and Rinn, P. (2012), "The turbulent nature of the atmospheric boundary layer and its impact on the wind energy conversion process", *J. Turbulence*, **13**.

Wagner, R., Antoniou, I., Pedersen, S.M., Courtney, M.S. and Jørgensen, H.E. (2009), "The influence of the wind speed profile on wind turbine performance measurements", *Wind Energy*, **12**(4), 348-362.

Wolken-Möhlmann, G., Knebel, P., Barth, S. and Peinke, J. (2007), "Dynamic lift measurements on a FX79W151A airfoil via pressure distribution on the wind tunnel walls", *J. Phys. Conf. Ser*., **75**, 012026.

Yurdusev, M.A., Ata, R. and Cetin, N.S. (2006), "Assessment of optimum tip speed ratio in wind turbines using artificial neural networks", *Energy*, **31**(12), 2153.

CC