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Review on Horizontal Axis Wind Turbine Rotor Design and Optimization

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ABSTRACT

The utilization of wind energy is not a new technology but draws on the rediscovery of a long tradition of wind power technology. It is no longer possible now to tell from the remainders of historical wind power plants just how important a role wind power played in the past. In this study a comprehensive review of wind turbine is presented. The objective of this literature is to review available literature for blade design, wind turbine airfoils and rotor wakes, Aerodynamic behavior of wind turbine and fatigue design of wind turbine rotor. Review on optimization is also taken in this work. The article reviews the details of design and optimization aspect of rotor of horizontal axis wind turbines.

Key words: Blade design, rotor wakes, aerodynamic behavior, fatigue design, optimization

INTRODUCTION

The conversion of wind energy to useful energy involves two processes: the primary process of extracting kinetic energy from wind and conversion to mechanical energy at the rotor axis and the secondary process of the conversion into useful energy (mostly electrical, but also mechanical for water pumps or chemical for water desalination or hydrolyses). This study concerns the primary process: the extraction of kinetic energy from the wind.

Thomsen and Srensen (1999) analyzed the wind power plants installed in the early 1980s suffered structural failures chiefly because of incomplete understanding of the wind forces (especially the turbulence component) acting on these large structures and in some cases because of poor quality in manufacture. Failure of the rotor blades was one of the principal and most serious structural failures. Failures from these causes are now somewhat better understood. An associated additional limitation to achievement of the full economic potential of wind energy is uncertainty about the long-term response of wind turbine rotor materials to the turbulent stochastic loadings to which they are subjected. Over their projected operational lifetimes (typically 20 to 30 years), these structures are subjected to as many as a billion stress cycles.

The design of wind turbine is not a trivial task. Because of the variability of the power source, it is little like designing a bridge that will use by a succession of vehicles having random weights. The bridge can be built as strong as you like, but sooner or later a vehicle too heavy may come along and destroy it.

ROTOR BLADE DESIGN

Small mixed airfoil wind turbine blades: The design and construction of sophisticated wind turbine blades performed by Habali and Saleh (1995) requires enormous amounts of data. The root has to take maximum moments and loads transmitted by aerodynamic forces through the blade to the rotor shaft and therefore, stresses and strains are concentrated in the root area. The geometry of the root is very complex and does not follow any known rules of construction, because an airfoil section must be continuously and smoothly coalesced to a circular cross-section at the hub flange. The working region is the portion of the blade which has the actual airfoil cross-section and the root region is the portion which compensates geometry between the profile and the circular section at the hub flange and therefore has no contribution to power generation. The two selected profiles will have to mix with one another somewhere along the blade length. The mixing must be smooth and therefore will be in terms of the two profiles, which require either scaling up or scaling down. The governing parameter for scaling will be the chord length. The thickest portion of the blade must be the root and viewing the blade from the edgewise position one concludes that the blade must be tapered down from root to tip for rigidity. The simplest taper is linear, which makes material distribution and manufacturing simple.

The material thickness at the root is set at 20 mm at each side for a two-shell construction and this must be tapered clown to the tip, but since the tip must have a finite thickness, a 12 mm thickness will be assigned for each shell. Allowing 1-2 mm for resin between them gives a total thickness of 25 mm at the tip. The thickness distribution is calculated in terms of the chord where the total thickness of the blade at any station will be a percentage of the chord length at that station. The two extreme thicknesses of the blade will be 210 mm at the root and 25 rnm at the tip. The thickness distribution must be linear between these two values and in order to avoid sudden changes, the distribution will be extrapolated. The higher point is at the edge of the steel flange, where this flange should have a curvature (outward) at the end to avoid stress concentration risers. The lower point, however, cannot fall on the blade because the tip will be chamfered to remove sharp edges for better aerodynamic performance.

Recommendations:

- In order to fully understand the mechanical behavior of rotor blades, the test should be carried further by conducting a thorough fatigue test program, although it is costly and time consuming
- Since the blade root exhibited durability and resilience during testing and operation, it is recommended that the design of the blade root be more theoretically investigated using the theory of elasticity with anisotropic materials and composites in three dimensions

Bending-torsion coupling of a wind-turbine rotor-blade: An investigation was performed by De-Goeij *et al.* (1999) for the implementation of bending-torsion coupling of a composite wind turbine rotor blade to provide passive pitch-control. Limited passive torsion deformation is realized with a structural coupling between flap wise bending and elastic twist of a constant speed rotor-blade. The blade and skin laminate configuration are analyzed with a FEM program, in which a complete blade with spar webs is modeled.

Bending torsion coupling is achieved through stiffness tailoring of the composite laminate and will introduce another design parameter. Wind turbine blades must be able to resist instabilities such as overloads due to gusts and to withstand a very high number of cycles (about $500X10^6$). They have to be non-corrosive and light. A wind-turbine blade has a design life of about 25 years, which should be reached with the necessity of few inspections. Being placed in remote areas or at sea, they are hard to inspect, so a damage-tolerant design philosophy, based on regular service intervals, cannot be applied.

In common design with FRPs, it is usual to obtain the optimal strength, which implies that one fiber-orientation is placed in the primary-load direction and at least two additional fiber-orientation angles are implemented to provide for strength in other directions, commonly using a quasi-isotropic lay-up. In the present blade-design, the goal is not only to reach a required stiffness, strength and lifetime, but also a certain directional stiffness. Changing the fiber orientation out of the primary load direction will inevitably result in a higher blade-flexibility and matrix strains. The conception that high structural rigidity is essential must be released. The increased amount of flexibility might force the choice towards a downwind rotor configuration, to prevent the blade from hitting the tower. The large number of parameters makes optimization procedures quite extensive. Firstly, it has to be established whether a desired amount of coupling can be reached while maintaining adequate strength and endurance:

- A wind-turbine blade with bending torsion coupling through laminate tailoring was analyzed using FEM. For a conventional design (two skin shells with two spar webs, no ribs), a reasonable amount of induced twist through bending torsion coupling was obtained, which would be sufficient for increasing energy output
- Reviewing the principal strains in the full blade model shows that the highest strains occur near the leading edge, where the fiber orientations are reversed. This causes a strain incompatibility and hence high principal strains. In combination with the joint that exists here, this is regarded as a possible source of failure
- The initial laminate composition with no fiber orientations along the longitudinal blade axis and hybrid (weave) lay-up introduces additional difficulties concerning fatigue resistance. For an acceptable fatigue-life, it is required that a third fiber-direction is implemented
- To account for structural and manufacturing disadvantages in a conventional design, alternative blade designs, implementing either a single box-spar or a double-box spar were investigated: the box beams are more effective and problems with strain incompatibilities at the joints are bypassed. It is inevitable that the bending torsion coupling is lower than for the conventional design. However, if this bending-torsion coupling is used to reduce the maximum loads on a blade (i.e., to achieve stability improvement), the required twist change and hence coupling is lower and the principle may still be applicable
- The bending torsion coupling capabilities of the double-box spar concept were investigated, both theoretically and experimentally. The two evaluated theories and a FEM analysis showed similar responses for bending torsion induced twist

Effect of rotation on the boundary layer: Design and analysis methods for wind turbines are presently based on relatively simple models of rotor blade aerodynamics, such as 2-D blade element/momentum theory (BEMT). Field investigations over the past few years have shown discrepancies between predicted and measured performance, owing to the effect of rotation on the wind turbine blade boundary layer distribution. By solving the 3-D integral boundary layer equations with the assumed velocity profiles and a closure model (including both laminar and turbulent boundary layer models), the effects of rotation on blade boundary layers are investigated by Du and Selig (2000).

In this Study the 3-D incompressible steady momentum integral boundary layer equations have been developed to study the effect of rotation on the boundary layer of a wind turbine blade. The following main conclusions are obtained by Du and Selig (2000).

- The rotation of the rotor has an important effect on the boundary layer of the wind turbine blade. The separation point on the surface of the blade is slightly postponed due to rotation, particularly for the inner half of a typical wind turbine blade. It is shown that rotation has a generally beneficial effect in delaying separation, which can give rise to higher lift and lower drag as compared with 2-D conditions
- Coriolis and centrifugal forces play an important role in 3-D stall-delay. The 3-D effects are essentially the consequences of the centrifugal acceleration causing radial flow in the boundary layer and Coriolis forces tending to accelerate the flow in the chord wise direction toward the trailing edge (a reduction in the adverse pressure gradient). This delays the occurrence of separation to a point further downstream. Still, however, the rotational effects are presently not fully understood and further investigations are needed

Reliability-based design against failure in ultimate loading: A probabilistic model for analysis of the safety of a wind-turbine rotor blade against failure in ultimate loading is presented by Ronold and Larsen (2000). Failure in ultimate loading of wind-turbine rotor blades exposed to wind and gravity loading is a failure mode that needs to be considered when the rotor blades are designed. The wind speed that causes bending of the rotor blades exhibits a natural variability and so does the stress response in the rotor blades. Also, the resistance of the rotor blades, in terms of their tensile strengths, exhibits a natural variability. Partial safety factors are used in structural design as factors on characteristic values of governing load and resistance quantities to account for variability and uncertainties in these quantities.

The design of a wind-turbine rotor blade against failure in ultimate loading in the normal operating condition for the wind turbine has been considered by Ronold. The wind climate as expressed in terms of the 10 min mean wind speed and the standard deviation of the wind speed has been modeled in terms of their respective probability distributions. Further, the bending moment response process in the rotor blades, conditioned on the wind climate, has also been modeled. This has been used to establish a model for the extreme load, i.e., the distribution of the largest bending moment response in an arbitrary 10 min period with an approximately stationary wind climate. The strength of the laminated polyester rotor blade has been modeled by its probability distribution. Only flap wise bending of the rotor blade has been considered and the blade root has been taken as the critical point of failure.

The models for load and resistance have been used as a basis for defining a limit state function for failure in ultimate loading. First-order reliability analyses of the considered rotor blade against such a failure in flap wise bending have been carried out. One analysis was carried out for failure in the most severe 10 min period in the operational life only. Another analysis was carried out under consideration of failure events in all 10 min periods over the operational life. The reliability analyses were interpreted with respect to the probability of failure. The analyses revealed that it is important to include contributions to the failure probability from other 10 min periods than the most severe such period in the operational life. The inherent variability in the strength was found to be the single most important uncertainty source.

Statistical uncertainty in the quantities that are used to describe the bending moment response process have been ignored here, but are known to be present as long as these quantities are estimated on the basis of limited measurement data. There may also be natural variability in some of these quantities. The importance of properly representing these uncertainties should be investigated whenever the work presented herein is to be updated. The representation of the distribution of the extreme bending moment response in terms of the first four statistical moments of the bending moment response process could imply that a model uncertainty is present and this needs to be further checked. The cut-out wind speed has been modeled as a fixed value, but could certainly be considered as random depending on how it is implemented and complied with in practice. Other simplifications have also been made in this study whose effects on the estimated failure probabilities and calibrated safety factors should be investigated. For example, long-term environmental degradation effects owing to exposure to moisture and ultraviolet light have been left out of consideration. The inclusion of such effects would be desirable if data would permit. The tested reliability analysis scheme allows for modeling of a correspondingly time-varying material strength.

It is emphasized that the reliability-based safety factor calibration presented herein is site- and wind-turbine specific and only applicable to flap wise bending of rotor blades. Different safety factors may result for different sites, different wind turbines, different blade materials and different failure modes. Similar calibrations can be carried out for other wind turbines at other sites. A common set of partial safety factors for a class of wind turbines, sites and materials can then be optimized depending on the expected demand for each individual combination of wind turbine, site and material within the class. It is suggested that future work be devoted to investigations of a series of wind turbines for different sites and blade materials with the ultimate goal of developing a reliability-based optimal design code for rotor blades.

Optimal frequency design: Maalawi and Negm (2002) worked on the optimization strategy of maximizing the system natural frequencies, which are the true measure of the overall level of the stiffness-to-mass ratio. Higher natural frequencies are favorable for reducing both the steady state and transient responses of the structure being excited. The behavior of these frequencies and their variation with the selected optimization variables are investigated in detail. It is shown that global optimality can be attained from the developed structural model and a new concept for the exact placement of the system frequencies is also presented.

In view of the importance of exact placement of natural frequencies to avoid resonance, an appropriate optimization model for wind turbine design has been formulated and applied successfully to the ERDA-NASA MOD-0 machine. The maximization of a weighted sum of the natural frequencies is proved to be the most representative objective function, which ensures balanced improvement in both mass and stiffness. The exact rotating frequencies and mode shapes are obtained from an exact power series method. Global optimality is attainable from the proposed discretized structural model, which can be advantageous from the production and manufacturing requirements. Exact frequency placement can also be achieved by freely choosing its desired value and solving the associated eigenvalue problem in one of the design variables instead. Another important conclusion is the possibility of selecting the segment length as a main design variable for engineering design of multi-segment structures. This important variable is always missed in most of the previous research work dealing with structural optimization. Investigators who use the finite element method have not recognized the importance of including the element length as a main optimization variable. Finally, the developed model can be extended and applied to include lead-lag and torsional degrees of freedom as well. Similar problem formulation considering divergence and flutter optimization of the blades shall be investigated in a future study.

Mathematical model: A rod model given by Baumgart (2002) for slender, tapered, closed structures is presented and applied to a wind turbine blade. The mathematical model is solved as an eigenvalue problem and the results are compared with an experimental modal analysis. Even though the general model characteristics (position of nodal points, direction of motion) match quite well, the chord rotation for some mode shapes is significantly underestimated. The question remains as to what assumptions in the modeling process are the main sources of these differences (e.g., parameter uncertainties, unisotropic material, geometry, order of Taylor series expansion in x and y).

Nevertheless, the mathematical model presented is a serious alternative to commercial FE methods when computing first estimates for eigen frequencies and modal shapes. The very few degrees of freedom allow applications for systematic stability investigations and fast solution as an initial value problem. Due to its semi-analytical nature, the model can be and has been, extended to allow for rotation of the whole blade and the computation of gyroscopic terms (e.g., centrifugal stiffening) and periodic coefficients.

Structural health monitoring techniques: Wind turbine blades are made of fiberglass material to be cost effective, but they can be damaged by moisture absorption, fatigue, wind gusts or lightening strikes. It is important to detect the damage before the blade fails catastrophically which could destroy the entire wind turbine. In this paper, four different algorithms are tested by Anindya *et al.* (2000) for detecting damage on wind turbine blades. These are the transmittance function, resonant comparison, operational deflection shape and wave propagation methods. The methods are all based on measuring the vibration response of the blade when it is excited using piezoceramic actuator patches bonded to the blade.

These experiments indicate the feasibility of using piezoceramic patches for excitation and a SLDV (scanning laser Doppler vibrometer) or piezoceramic patches to measure vibration to detect damage. Further testing of different smaller damages and types of damage is needed to further verify the sensitivity of the methods. The RC (resonant comparison) method can be used for operational damage detection while the ODS (operational deflection shape) method produces non-symmetric contours that are an easily interpretable way to detect damage in a structure that is not moving.

Effects of squealer rim height on aerodynamic losses downstream of a high-turning: The effects of squealer rim height on three-dimensional flows and aerodynamic losses downstream of a high-turning turbine rotor blade have been investigated by Woo and Chae (2008) for a typical tip gap-to-chord ratio of $h/c = 2.0\%$. The squealer rim height-to-chord ratio is changed to be $h_{st}/c = 0.00$ (plane tip), 1.37, 2.75, 5.51 and 8.26%. Results show that as h_{st}/c increases, the tip leakage vortex tends to be weakened and the interaction between the tip leakage vortex and the passage vortex becomes less severe. The squealer rim height plays an important role in the reduction of aerodynamic loss when $h_{st}/c = 2.75\%$. In the case of $h_{st}/c = 5.51\%$, higher squealer rim cannot provide an effective reduction in aerodynamic loss. The aerodynamic loss reduction by increasing h_{st}/c is limited only to the near-tip region within a quarter of the span from the casing wall.

The clearance gap between the tip of a turbine rotor blade and the adjacent stationary casing wall forms a narrow flow passage. Due to the presence of pressure difference between the pressure and suction sides of the blade, there exists a strong leakage flow through the tip gap. Interacting with main passage flow, it rolls into a tip leakage vortex along the blade suction side. This undesirable tip leakage flow delivers not only an aerodynamic loss penalty but also an additional thermal loading to the blade tip. Total pressure losses at the exit of a turbine rotor stage are known to be directly proportional with the tip gap height. The interaction of the tip leakage flow with the main passage flow causes significant aerodynamic loss and results in stage inefficiency.

Effects of squealer rim height on the three-dimensional flow and aerodynamic loss downstream of a high-turning turbine rotor blade have been investigated for a typical tip gap-to-chord ratio, h/c, of 2.0%. The squealer rim height-to-chord ratio is changed to be $h_{st}/c = 0.00$ (plane tip), 1.37, 2.75, 5.51 and 8.26%. Major findings are summarized as follows:

- As h_{st}/c increases, the tip leakage vortex tends to be weakened and the interaction between the tip leakage vortex and the passage vortex becomes less severe
- With the increment of h_{st}/c, the mass-averaged total-pressure loss coefficient decreases noticeably meanwhile the mass-averaged profile loss coefficient remains almost unchanged
- The aerodynamic loss reduction by increasing h_{st}/c is limited only to the near-tip region within a quarter of the span from the casing wall

The squealer rim height plays an important role in the reduction of aerodynamic loss when $h_{st}/c = 2.75\%$. In the case of $h_{st}/c = 5.51\%$, however, higher squealer rim cannot provide an effective reduction in aerodynamic loss.

Research on wind turbine rotor models using NACA profiles: In this study, rotation rates and power coefficients of miniature wind turbine rotor models manufactured using NACA profiles were investigated by Vardar and Alibas (2008). For this purpose, miniature rotor models with 310 mm diameter were made from Balsa wood. When all properties of rotor models were taken into account, a total of 180 various combinations were obtained. Each combination was coded with rotor form code. These model rotors were tested in a wind tunnel measurement system. Rotation rates for each rotor form were determined based on wind speed. Power coefficient values were calculated using power and tip speed rates of wind. Rotor models produced a rotation rate up to 3077 rpm, with a power coefficient rate up to 0.425. Rotor models manufactured by using NACA 4412 profiles with 0 grade twisting angle, 5 grade blade angle, double blades had the highest rotation rate, while those manufactured by using NACA 4415 profiles with 0 grade twisting angle, 18 grade blade angle, 4 blades had the highest power coefficient.

Results indicate a strong correlation between rotor rotation rate and blade angle, between power coefficient and blade angle and between power coefficient and rotor blade number. An increase in wind speed rate resulted in a higher correlation between rotor rotation rate and wind profiles, between rotor rotation rates and wind speed, between power coefficient and blade profiles and between power coefficient and blade twisting. Best rotor models with high rotation rate are moderately effective in terms of power coefficient, while best rotor models with high power coefficients generate moderately successful results in terms of rotation rates.

Mathematical simulation and energy estimation: In this work Ahmed *et al*. (2009) deal with a new method based on analytical approach. In their design of rotor and its peak performance production, a blade is divided into 100 radial elements. The blade chord, its twist and its elementary power co-efficient at each station were determined. The iterative process required for the convergence of speed interference factor and for maximization of power coefficient. The design process begins right at maximum power point, rather than searching of point of maximum power and then doing the computations. Mathematical Simulation based on analytical approach for energy estimation correlate with practical reading of 10 kW H.A.W.T rotors at Rajeev Gandhi Proudyogiki Vishvavidyalaya (RGPV), Bhopal India.

Analysis of wind power potential on complex terrain: In this study the aim of Ahmed *et al*. (2010) was to design 700 kw wind turbine hub. The conventional hub used so far is of circular type but problem with such hub is that many casting defects arise; so it was decided to use straight beams of standard cross sections and fabricate them to make skeleton of hub. Initially the simplest triangular hub was designed but due to space problem it was decided to select hexagonal hub. The concept of this hexagonal hub is totally new and was never used earlier. All the loads caused by wind and inertia on the blades are transferred to the hub, so mechanical strength of hub becomes very vital in the wind turbine design. The design has been done according to type's approval provision scheme. The mechanical as well as other safety considerations have been considered in this design. The analysis involves use of modeling and simulation software. The stress and deflection were also calculated in this study. This is a static analysis and preliminary stage of design, so many more improvement can be incorporated in future.

Optimum design of rotor and hub: In this work Ahmed *et al*. (2007) recorded time series wind data for a period of ten years from Indian Meteorological Department near airport at 77°35' East longitude and 23°28' North latitude is analyzed for predicting wind energy potential at hilly site near Bhopal and wind flow modeling over complex terrain by considering influence of roughness of terrain, obstacle and topography in terms of contour were analyzed for determining regional wind climate and annual energy production by using Wind Atlas Analysis and Application Program (WAsP) Recorded daily wind speed data in meter per second and its direction of flow in degree at two hub heights of 10 m by a wind monitoring mast and 70 m by weather balloons. The recorded wind speed data is extrapolates and interpolate at 120 and 50 m heights by applying well known 1/7 power law. The site had an elevation of 530 m above mean sea level. It is seen from the analysis of the wind speed data and keeping the topographical variation of terrain, exploitable wind speed is experienced at 70 m or more. Also from the monthly average of wind speed, it can safely be recommended that a wind turbine generator with a cut in speed of 4 m sec^{-1} would be able to achieve economical levels of wind energy generation. It is also seen that the Annual Energy Production in the area from one MW WTG 2.040 GWh at 70 m hub height, indicating a satisfactory wind power density. This paper describes the methodology adopted for the evaluation of wind energy potential for the site.

WIND TURBINE AIRFOILS AND ROTOR WAKES

Study of the turbulent characteristics of the near wake field of a medium sized wind turbine operating in high wind conditions.

The analysis given by Apadopoulos *et al.* (1995) is based on experimental data obtained mainly under strong wind conditions by two masts erected upstream and downstream of a wind turbine. The field of wind turbulence is examined both in integral and spectral form. Observations show that the turbulent field varies from the edge to the center of the wake and strongly depends on the incident wind speed. Increased turbulent levels are observed near the blade tips, with evidence of a similar trend around the hub height for all wind speeds. Decreased wind turbulence is observed in mid frequencies inside the wake due to the reduced shear associated with the flat crosswind velocity profile.

The analysis done by Apadopoulos *et al.* (1995) is based on a more robust than usual handling of the reference conditions, combining measurements from both upstream and downstream conditions with the wind turbine rotor parked. The high wind speeds encountered during the experimental period has permitted the assessment of wake features under (stalled) conditions for which the rotor operates above the maximum of the Cp (turbine power coefficient) curve. Turbulence inside the wake depends on the location with respect to the center of the wake and on the incident wind speed. Increased turbulent levels are only observed near the blade tips and possibly around the hub height for all wind speeds. In the remaining part of the wake, the observation that essentially no turbulent energy increase is measured in attributed to the flat wake velocity profile and the absence of strong shear layers, which produce turbulence.

A limitation of this study is the terrain complexity in association with the fact that the prevailing winds were particularly high, leading to a relatively weak wake. However, the first factor may be considered as typical for a wind park, more systematic measurements are needed that cover a wide wind speed range with the aim of identifying the turbulent structure and its variation as functions of the incident wind speed and the location inside the wake.

Turbulence characteristics in wind-turbine wakes: An analysis given by Crespo and Hernandez (1996) for the evolution of turbulence characteristics in wind-turbine wakes has been carried out. Based on experimental results and on numerical results obtained with a CFD code, complemented with some theoretical considerations, simple analytical expressions are proposed for the estimation of the turbulent kinetic energy, k and its dissipation rate, ϵ. To obtain the turbulence spectra in the wake a classical law used for atmospheric turbulence is assumed, in which characteristic values of turbulence velocity and turbulence length are calculated by algebraic combinations of k and ϵ. So that when the effect of the wake is negligible the spectrum of the unperturbed basic flow is recovered.

The standard deviation of the component of velocity in the direction of the wind is often the parameter measured to characterize turbulence in wind-turbine wakes, whereas, in turbulence models that implicitly assume isotropic turbulence, k is the magnitude calculated and the separate contributions of the standard deviations of the three velocity components cannot be obtained from the model. Since, turbulence is isotropic neither in the atmospheric surface layer nor in the wakes, in order to validate the results of the numerical models it is necessary to make some complementary assumptions, based on measurements in wind farms that relate k to the standard deviation in the wind direction. Two regions of the wake are distinguished: the near wake (1D to 3D downstream), where an annular shear separating the inner core from the ambient flow is formed and a far wake. There is an intermediate region that is not considered in this work. The region just downstream of the rotor, where expansion occurs, is not considered in this analysis.

Phenomenological models for post-stall airfoil characteristics: This work of Tao *et al.* (1997) reports a progressive study of aerodynamic behavior of HAWT rotor blades (airfoil), focusing on modeling the stall-and post-stall characteristics as applied to the prediction of rotor performance under various field conditions. The methodology developed here may be generalized to provide a procedure used in the computer analysis.

There exist significant differences in airfoil aerodynamic characteristics between wind tunnel test data (Two Dimensional flow) and field test data (Three Dimensional flow). Through the Combined Experiment Program (CEP), efforts have been made to investigate proper approaches to analyze such differences so that it enables us to incorporate the results into wind turbine rotor performance codes to assist in optimal design of a horizontal axis wind turbine.

Several factors have been reported to contribute to the difference between the turbine blade under field conditions and the same airfoil in a wind tunnel test. They are:

- Flow along a blade and perpendicular to the wind i.e., the third dimension vector of flow field
- Turbulent characteristics of up stream wind
- Blade surface roughness due to contamination or frosting

Some effects of compressibility: Many small wind turbines operate at high tip speed ratio and this gives rise to situations where compressibility may influence performance. Compressibility significantly increases drag through the action of shock-stall. Compressibility ultimately degrades rotor performance; it may provide an inherent mechanism for over speed protection.

Wood (1997) performed calculations for wind speed U_0 = 0, 10, 20 and 30 m sec^{-1} note that variations in U_0 were assumed not to alter the Reynolds number, so that $U_0 = 0$ is the incompressible case. In terms of the conventional power and thrust coefficients, C_p and C_t, respectively, the effects of changing U_0 are shown in Fig. 1a and b At U_0 = 10 m sec^{-1}, there are no important Compressibility effects even at the highest values of λ (tip speed ratio) and λ_{run} (tip speed ratio runaway) remains at about 17. As U_0 is increased to 20 m sec^{-1} optimum performance is not degraded but λ_{run} reduces to about 13 as M_{tip} increases to 0.75. There are some interesting changes around $\lambda = 3$, as compressibility first degrades aerofoil characteristics at high angles of attack. At U_0 = 30 m sec^{-1}, both the maximum C_p and λ_{opt} (optimum tip speed ratio) have decreased as has λ_{run}; to about 10. Performance is not just dependent on Mach number. Firstly, runaway occurs at very different values of M_{tip}. Secondly, the results for U_0 = 30 m sec^{-1} at $\lambda = 5$ show a significant

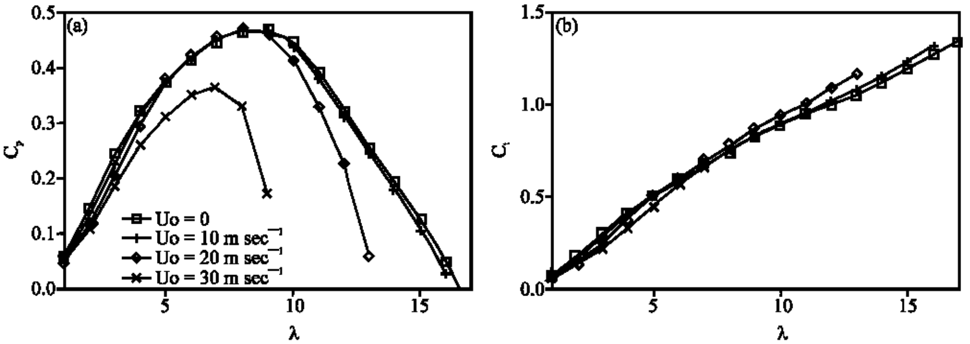

Fig. 1: Performance of test blade as wind speed changes. Uo = 0; + Uo = 10 m sec^{-1}; Uo = 20 m sec^{-1}; X Uo = 30 m sec^{-1}. (a) Power coefficient and (b) Thrust coefficient (Wood, 1997)

reduction in C_p whereas those for $U_0 = 10$ m sec^{-1} at $\lambda = 15$ do not for a similar value of M_{tip}. Shock stall could not be used for over speed protection on the test blade mainly because λ_{run} decreases less rapidly than M^{-1}. Thus it seems that to use shock stall for over speed protection would require an aerofoil of considerably lower M_{dd} (drag-divergence Mach number). The thinner the aerofoil section the higher the M_{dd} for no lift. However, as C_l (lift coefficients) increases, M_{dd} decreases more rapidly for thin sections than for thick sections with the crossover point being around $C_1 = 0.3$. This result is not encouraging, but it must be remembered that conventional aerodynamic design has been aimed at maximizing M_{dd}, whereas over speed protection provides a unique requirement to minimize M_{dd}. It could be very worthwhile to see whether a significant reduction could be achieved without seriously degrading the incompressible properties of the aerofoil.

Wood (1997) found that the wind speed had to be of the order of 30 m sec^{-1} before there was a significant reduction in optimum performance. It was obvious from the results that shock stall could not be used for over speed protection, but it was suggested that it may be possible to design an aerofoil for earlier onset of shock stall without seriously compromising its incompressible performance.

The near wake of a model-I HAWT: This study of Ebert and Wood (1997) describes measurements in the wake of a small horizontal-axis wind turbine. The turbine had two constant-chords, constant-pitch blades which drove a hydraulic pump against a known load to extract power from the wind. This power was measured using a specially constructed dynamometer. The main limitation of the experiment was the high blockage so measurements were confined to the first two chord lengths downstream of the blades.

This study considered firstly the conventional mean velocities in the axial and circumferential direction for tip speed ratios of 2, 4 and 6. The axial velocity was nearly uniform at the operating condition closest to that giving maximum power as was the circulation determined from the circumferential velocity. Because of the small amount of wake expansion the bound circulation must also be nearly constant. To introduce the three-dimensional measurements, the downstream development of the circumferential profiles of the mean velocities and turbulent energy were presented for tip speed ratios of 2 and 4. These measurements were obtained in the region away from the tip and hub vortices and so are dominated, in terms of turbulence, by the wakes of the blades.

At the higher tip speed ratio, the turbulence levels indicate apparently two wakes, one rotating away from the blades and one which does not rotate. The latter wake was ascribed to unsteadiness acting on the large circumferential gradients in the mean axial and circumferential velocities caused in turn by the bound vorticity of the blade. Using the assumptions of traditional blade element theory, these velocities were compared to panel code predictions of the velocities induced by an aerofoil of the same section at an angle of attack appropriate to the measured circulation. Since, the panel calculations assume no separation and a zero wake thickness, it is not surprising that the comparison was significantly better at the higher tip speed ratio.

AERODYNAMIC BEHAVIOR OF WIND TURBINE

Yaw control for reduction of structural dynamic loads: An important goal in research and development of modern wind turbines is to reduce the cost per unit of delivered electrical energy. With automatic control it is possible to reduce this cost in several ways, e.g., by increasing the aerodynamic efficiency. A leading control issue for wind turbines is to regulate the aerodynamic power. Effective power control does not only increase the energy capture, it also reduces the construction cost; lower design safety margins can be used when it is possible to control the power.

The two most common ways to actively regulate internal loads, as well as power, are by pitching the turbine blades and/or controlling the reaction torque of the generator. This study of Thommy (2000) investigates the potential for active load reduction by controlling the torque of the yaw servo. Horizontal axis wind energy converters need some means to direct the turbine towards the wind. Usually this is accomplished actively with an electrical or hydraulic servo. A wind vane, placed on top of the nacelle senses the wind direction. However, the nacelle is mechanically parked most of the time. The servo is activated only when the mean relative wind direction exceeds some predefined limits.

If the yaw parking mechanism is stiff then large dynamic loads appear in its components and the tower. It may be better to make it flexible, for instance, with mechanical suspension devices. An alternative is to use the yaw motor continuously, instead of parking the nacelle. The same dynamic behavior as with a spring and damper suspension can theoretically be obtained with feedback of the yaw angle. The disadvantage of this concept is the increased demands on the yaw servo. Continuous operation leads to increased wear. The ratings of the motor, for example, the maximum torque and speed, may have to be improved. Furthermore, additional or improved measurements may be required. However, continuous yaw control has more potential than merely substituting a spring and/or damper. It may also be possible to actively attenuate structural dynamic oscillations, since the yaw motion is dynamically coupled with the tower and the blades.

Soft-stall control for variable-speed stall-regulated wind turbines: A variable-speed, fixed-pitch wind turbine control strategy was investigated by Muljadi *et al.* (2000) to evaluate the feasibility of constraining rotor speed and power output without the benefit of active aerodynamic control devices. A strategy was postulated to control rotational speed by specifying the demanded generator torque. By controlling rotor speed in relation to wind speed, the aerodynamic power extracted by the blades from the wind was manipulated. Specifically, the blades were caused to stall in high winds. In low and moderate winds, the demanded generator torque and the resulting rotor speed were controlled and the wind turbine operated near maximum efficiency. Turbine models were developed and simulations of operation in turbulent winds were conducted. Results indicated that rotor speed and power output were well regulated.

A control strategy was postulated for variable-speed, stall-regulated wind turbines. A computational model was developed and operation simulations were conducted for turbulent winds. The following conclusions may be drawn from the simulation results. Wind-turbine cost and reliability were not considered in this study. These issues, as well as those related to changes in atmospheric density, blade soiling and site-specific conditions, will be the subject of future studies.

Prediction of aerodynamic forces turbines in free yaw and turbulence: A free vortex lattice model is used to stimulate the flow field of a rotor at either a steady yaw angle to the wind or undergoing a changing yaw angle, for which cases the flow field itself and the aerodynamic forces on the rotor are unsteady. The model is run from an impulsive start and continues until an asymptotic (typically periodic) state is reached. This technique is used to analyze three situations: steady yaw, sinusoidally oscillating yaw and a random time history of yaw generated by an incident turbulent wind. Because of the computational expense of the oscillating yaw and turbulence computations, an investigation is carried out by Pesmajoglou and Graham (2000) to study the accuracy of using the force time histories from steady yaw computation in indicial fashion to simulate the unsteady yaw cases.

Horizontal axis wind turbines are subject to changing conditions of yaw due to veering of the wind direction not followed by the yaw drive and yaw motion of the rotor and nacelle in the case of free yawing machines. In these cases, the rate of change of yaw angle can be significant in terms of the time scale for the wind to travel one rotor diameter. In other cases, such as change in yaw angle due to operation of a yaw drive, the rates are small and a quasi-steady yaw analysis is appropriate.

For the rotor in yawed flow, the flow is essentially unsteady and it is therefore appropriate to use a method, which advances the solution with time. A free wake is more expensive than a prescribed wake because of the much large number of points, where the velocity field must be evaluated, but should be more accurate because of lack of a priori knowledge about the exact position of the wake in yawed flow. In the present work, the flow over the blades and in the wake is represented by a vortex lattice free wake method. A first-order time marched scheme is used to predict the evolution of the wake and the resulting distribution of aerodynamic loads and moments on the rotor blades. The results of the method are compared against wind-tunnel measurements of a model rotor in yaw and against field measurements for a Marlec machine. The computational model was set up to study the effects of unsteady yaw induced by a turbulent approach flow with the rotor axis assumed fixed and also the situation of a rotor oscillating in yaw about the wind direction. Turbulence was represented in the calculation by a Gaussian random noise time series filtered to stimulate a spectrum of turbulence appropriate to the terrain and height of the rotor.

A free wake model for inviscid flow over a horizontal axis wind turbine rotor operating in yaw has been developed and run for incident turbulence and yaw oscillations and also compared with wind tunnel measurements. A more efficient indicial method of computing the numerical simulation to predict long time histories of yaw moment and other forces under more general conditions has been set up. The results can be used to derive statistical measures of yaw moment response of a rotor in a turbulent wind. Computations of yaw damping moment for forced sinusoidal oscillations of a rotor in yaw show that quasi-steady methods tend to overestimate the aerodynamic damping and hence the stability of an upwind rotor in yaw at moderate- to-high frequencies of yaw oscillation.

Numerical simulation of unsteady aerodynamics effects: The study of Bermudez *et al.* (2000) deals with the numerical simulation of unsteady aerodynamics effects in horizontal-axis wind turbines. In particular, an unsteady three-dimensional potential method is presented whose aim is to predict time-dependent forces and moments on wind turbines operating in a field environment. The algorithm structure is such that the wake is not prescribed; instead, its shape and motion are obtained self-consistently from the solution of the problem. Flow separation effects are not considered.

The objective is to predict steady and unsteady aerodynamics behavior of horizontal-axis wind turbines. The numerical algorithm is a low-order potential-based three dimensional panel method whose structure is such that the wake shape and motion are not prescribed but obtained self-consistently from the solution of the problem. The validation campaign of the solver has shown that for small values of the reduced frequency (of the order of 0.1), the results do not depend significantly on the type of unsteady Kutta-Joukowsky condition used in the modification. However, this issue becomes critical when the reduced frequency becomes larger. In addition, the sensitivity of the solver has been tested versus the size of the latest wake panel, the numerical time step and the number of panels used for surface definition. It has been found that the quality of the solution increases with finer surface definitions, smaller time steps and accurate latest wake panel resolution.

Increasing the efficiency: The rotational speed of the wind blades can be increased using steering aerofoil surrounding the blades. The blade profiles are designed using the theory of aerodynamics. The steering airfoils are fixed surrounding the wind blades at an optimum distance. The number of the airfoils and the angle of inclination (tilt) of the foils can be changed. In the experiment performed by Varol and Varol (2001) the ambient conditions are held constant. Because of the optimum adjustment of the distance and angle of the airfoils the rotational speed of the blades can be increased by 32% on the experimental device.

A set of the wind turbine was designed and constructed at the laboratory in order to study the effects of the airfoils. The top tip (edge) of the airfoils was 160 mm while the bottom edge was 240 mm and the length 500 mm. The airfoils were constructed using 2 mm nominal thickness steel. The airfoils were fixed on an octagonal fan and their angles could be changed. The wind was created using an axial ventilator. The ambient temperature was held constant during the experimental period. Changing the rotation speed of the ventilator can change the resulting wind velocity. The wind speed is measured using anemometers. When the wind velocity is very high it can be decreased by adjusting the angle of the airfoils. It is possible in this way to decrease the axial force at least 100 times. The rotation speed of the wind blade's rotor can be held constant by changing the angle of the airfoils. When the wind speed typically is 6.55 m sec^{-1} the rotation speed of the wind blades is 287 min^{-1} without using the airfoils. If the experiments continue with airfoils by a 6.55 m sec^{-1} wind speed the rotation speed can be increased to a value of 382 min^{-1}. It means the 94 min^{-1} rotation speed is created using the airfoils, which surround the wind blades and the increase in the rotation speed is equal to 32%.

The power produced at the axle of the wind blades is increased in the form of rotation speed and the moment generated, the higher the wind velocity the higher the rotation speed. The angle of the airfoils can be changed whilst maintaining the other values constant. But it should be mentioned that if the angles of the airfoils are not optimum it can affect the rotation speed negatively.

Viscous–inviscid method for the simulation of turbulent unsteady wind turbine airfoil flow: Implementation of design improvements by the wind turbine industry is hampered by the lack of practical prediction tools having the appropriate level of complexity. The reason is that simulation of flow around wind turbines is one of the most challenging tasks a numerical fluid dynamist may face up. The fact that the flow is incompressible, three-dimensional, unsteady, turbulent and very often separated to a large extent, means that its numerical analysis is very complex and costly. Furthermore, engineering design practice is mainly concerned with inverse design problems and this means that prediction tools must be robust and time efficient because a very large number of combinations of parameters have to be explored. In this context, it is understandable that prediction tools used by industry are mostly based on suitably evolved blade element methods, plus semi-empirical correlations to account for 3-D effects, boundary-layer separation and unsteady flow conditions.

A viscous-inviscid interaction method of Bermudez *et al.* (2002) has been presented that allows for the efficient computation of unsteady airfoil flow. Both attached flow and light stall conditions, characterized by unsteady turbulent boundary-layer separation size up to 50% of the chord length, can be predicted with reasonable accuracy.

The development has been carried out bearing in mind the objective of generating a simulation tool suited for wind turbine engineering design applications. As it stands now, the algorithm could be used to evaluate unsteady aerodynamics behavior of airfoil blade profiles. Accordingly, specific emphasis has been placed on the numerical robustness of the algorithm and, also, on the computational time demands that have been kept to a minimum. The results of the validation campaign show that accuracy of the prediction of the integrated lift coefficients is of the order of 10-20%. On the other hand, CPU computational time requirements are limited to 20 min per oscillating cycle in a personal computer. This is very important because the next natural step is to couple this Viscous–inviscid algorithm to the 3-D unsteady potential method so as to build up a simulation tool that could predict realistic wind turbine flow.

The grid sensitivity analysis that has been performed shows that simulation of unsteady lift strongly depends on the selection of the computational parameters. Another conclusion is that refinements on prediction accuracy could only be achieved at the expense of increasing dramatically the computation time. If the objective is to compute lift with an integrated error ranging from 10 to 20% without spending more than 20 min on a PC per oscillating cycle, the solution is to make the following choice: 60 panels for airfoil modification, 50 chords for the wake length, 0.1 as the dimensionless integration time-step and 200×250 points for the boundary-layer discretisation. The theoretical aspects of the relation between the airfoils and wind blades are not investigated here.

Stochastic gust model for design calculations: A new probabilistic method has been developed by Wim and Cheng (2002) in order to determine the long term distribution of the extreme response of wind turbines. The probabilistic method relies on the quick determination of the response to a single gust, with given amplitude, by means of the so-called constrained simulation. If several wind turbine simulations are performed, for the same gust amplitude and mean wind speed, a conditional distribution of the loading can be determined. In order to obtain the distribution of the loading caused by a gust with an arbitrary amplitude (and given mean wind speed), the distributions for different gust amplitudes should be weighted with the occurrence probability of the individual gusts. The overall final distribution is obtained by weighting with the occurrence probability of the mean wind speed (Weibull) and can be extrapolated to the desired return period, e.g., 50 years.

The theoretical expression for the mean shape of gusts as well as the occurrence probability of gusts has been verified by measurements. The more accurate description of extreme loading enables wind turbine manufacturers to build more reliable, optimized wind turbines. A basic premise of the New Gust project is that the extreme wind turbine loads correspond to extreme wind speed gusts. For pitch regulated wind turbines the extreme loads may not be connected with extreme wind gusts but with other extreme situations, e.g., gusts with a given extreme rise time (rather than amplitude) or extreme wind direction changes. This should be further investigated from load analysis for different types of wind turbines. The constrained simulation technique is a general method. It may be suitable to adapt it to the other extreme wind situations mentioned before and to a three dimensional turbulent wind field. The New Gust method can be implemented into any stochastic wind field generator.

Airfoil aerodynamics in high turbulence: Wind turbines very often have to operate in high turbulence related, for example, with lower layers atmospheric turbulence or wakes of other wind turbines. Most available data on airfoil aerodynamics concerns mainly aeronautical applications, which are characterized by a low level of turbulence (generally less than 1%) and low angles of attack. The work of Devinant *et al.* (2002) presents wind tunnel test data for the aerodynamic properties-lift, drag, pitching moment, pressure distributions of an airfoil used on a wind turbine when subjected to incident flow turbulence levels of 0.5-16% and placed at angles of attack up to 90°. The results show that the aerodynamic behavior of the airfoil can be strongly affected by the turbulence level both qualitatively and quantitatively. This effect is especially evidenced in the angle of attack range corresponding to airfoil stall, as the boundary layer separation point advances along the leeward surface of the airfoil.

The purpose work presented here is first to characterize the aerodynamics of a wind turbine airfoil experimentally, so that the results obtained constitute a two-dimensional experimental results database to be used in the three dimensional calculations, based on the lifting-line assumption, mentioned above. Moreover, the data can be analyzed to exhibit the effect of high turbulence levels on these characteristics, at least for the configuration considered.

The near wake of a model horizontal-axis wind turbine at runaway: In this work Ebert and Wood (2002) completes a series which describes measurements within two chord lengths of the blades of a small horizontal-axis wind turbine over a wide range of operating conditions. Prior to the present experiment, the turbine was rebuilt to allow operation at its runaway point, where no power is produced. Runaway can be viewed as the upper limits on wind turbine performance at which thrust and wake expansion are maximized. The measurements, which approximate the mean and fluctuating velocity fields seen by an observer rotating with the blades, were obtained from a stationary X-probe hot-wire anemometer by the technique of phase-locked averaging. It is shown conclusively that there is negative (power-producing) angular momentum extracted from the wake, but a balancing positive angular momentum resides in the tip vortices. The mean velocity through the blades increases significantly with radius, in contrast to the near-constant velocity when the turbine is producing its maximum power. Comparisons with conventional blade calculations suggest that the circulation in the wake is related to the difference between the circumferential components of the lift and drag, rather than the magnitude of the lift as is often assumed. Within the range and accuracy of measurement, the pitch of the tip vortices is constant and proportional to the inverse of the tip speed ratio.

The starting and low wind speed behavior of a small HAWT: In order to extract the maximum possible power, it is important that the blades of small wind turbines start rotating at the lowest possible wind speed. The starting performance of a three-bladed, 2 m diameter horizontal axis wind turbine was measured in field tests and compared with calculations employing a quasi-steady blade element analysis. Accurate predictions of rotor acceleration were made for a large range of wind speeds, using a combination of interpolated aerofoil data and generic equations for lift and drag at high angles of incidence. Also, significantly different values for the wind speeds at which the turbine rotor starts and ceases to rotate were determined, indicating limitations in the traditional method of describing starting performance with a single cut-in wind speed based on 10 min averages of wind speed and turbine power. The blade element calculations suggest that most of the starting torque is generated near the hub, where as most power producing torque comes from the tip region. The significance of these results for blade design is discussed by Wright and Wood (2004).

Data from the field testing of a three-bladed 600 W wind turbine was analyzed to identify various characteristics of its starting performance. The blades started rotating at a wind speed of 4.6 m sec^{-1} on average, but this varied between 2.5 and 7 m sec^{-1} and generally coincided with increasing wind speed. Predictions of rotor acceleration up to a power producing level were made using a quasi-steady adaptation of blade element analysis employing composite lift and drag data and also generic equations for high angles of attack. Given the uncertainty associated with lift and drag data at high angles of attack and low Reynolds numbers, these predictions compared well with 160 measured occurrences of rotor acceleration over a large range of wind speeds. The acceleration and deceleration of the rotor at speeds below its controlled maximum speed and for a range of wind speeds was calculated and compared with data.

This method of analysis of the low wind speed performance of a small wind turbine has potential as a relatively simple design tool. The simplicity of the generic equations for lift and drag has particular appeal and is probably a good starting point for lift and drag approximation for many blades. Starting is not usually the primary concern of the designer; however a simple method of predicting a turbine's starting performance is useful, particularly if siting turbines in low or unsteady winds. The method described and tested here is suitable for this purpose. Furthermore, most starting torque is generated near the hub and most power extracting torque comes from the tip region, so that it should be possible to optimize starting performance while maintaining good power performance.

Efficient models for wind turbine extreme loads using inverse reliability: The turbine model introduced by Saranyasoontorn and Manuel (2004), gives rise to relatively compact analytic expressions for the average power output in stochastic wind fields. It may be an efficient tool to assess the effect of wind speed fluctuations on the average power output of a wind turbine. The model is particularly suitable to examine the dynamic effect of turbulent wind fields which can be described by standard models of boundary layer meteorology. In a simplified shutdown model, wind fluctuations tend to weaken the relaxation towards standstill. Moreover, in the case of a special stationary power curve, we find a dynamic enhancement of the average power output with increasing turbulence intensity.

Aerodynamic performance prediction of a 30 kw counter-rotating wind turbine system: In the present work of Jung *et al.* (2005) gives the aerodynamic performance prediction of a unique 30 kW Counter-Rotating (C/R) wind turbine system, which consists of the main rotor and the auxiliary rotor, has been investigated by using the quasi-steady strip theory. The near wake behavior of the auxiliary rotor that is located upwind of the main rotor is taken into consideration in the performance analysis of the turbine system by using the wind tunnel test data obtained for scaled model rotors. The relative size and the optimum placement of the two rotors are investigated through use of the momentum theory combined with the experimental wake model.

Through use of the proposed model, the relative size and the optimum placement of the auxiliary rotor and the main rotor in the C/R system were identified. Regarding the relative dimension of the two rotors, the size of the auxiliary rotor should be smaller than one-half of the main rotor diameter. It is also; found that the power output was significantly affected by the interval between the two rotors: a best performance was achievable when the interval remained at around one-half of the auxiliary rotor diameter. The full-scale test data for the performance of the C/R wind turbine system were compared with the present prediction results. A fairly good correlation between the two results was obtained based on the prediction results as well as the field test experience, the current C/R system thought to be quite effective in extracting energy from the wind. The maximum power coefficient reached as high as 0.5.

Dynamic stall model for wind turbine airfoils: A model is presented by Larsen *et al.* (2007) for aerodynamic lift of wind turbine profiles under dynamic stall. The model combines memory delay effects under attached flow with reduced lift due to flow separation under dynamic stall conditions. The model is based on a backbone curve in the form of the static lift as a function of the angle of attack. The static lift is described by two parameters, the lift at fully attached flow and the degree of attachment. A relationship between these parameters and the static lift is available from a thin plate approximation. Assuming the parameters to be known during static conditions, non stationary effects are included by three mechanisms: a delay of the lift coefficient of fully attached flow via a second-order filter, a delay of the development of separation represented via a first-order filter and a lift contribution due to leading edge separation also represented via a first-order filter. The latter is likely to occur during active pitch control of vibrations. It is shown that all included effects can be important when considering wind turbine blades. The proposed model is validated against test data from two load cases, one at fully attached flow conditions and one during dynamic stall conditions. The proposed model is compared with five other dynamic stall models including, among others, the Beddoes-Leishman model and the ONERA model. It is demonstrated that the proposed model performs equally well or even better than more complicated models and that the included non stationary effects are essential for obtaining satisfactory results. Finally, the influence of camber and thickness distribution on the backbone curve is analyzed. It is shown that both of these effects are adequately accounted for via the static input data.

Decoupled aerodynamic and structural design of wind turbine adaptive blades: The study of Maheri *et al.* (2007) presents a method for decoupled design of Bend-Twist Adaptive Blades (BTABs) in which the aerodynamic and structural designs take place separately. In this approach the induced twist is considered as an aerodynamic design parameter, whilst its dependency on the structural characteristics of the blade is taken into account by imposing a proper constraint on the structure design. The main advantage of this method is the significant reduction in evaluation time by replacing a finite element analysis (FEA)-based coupled-aero-structure (CAS) simulation in the aerodynamic objective evaluation by a non-FEA-based CAS simulation. Through a re-design case study an ordinary blade has been converted to a BTAB and the efficiency of the method in performing decoupled design of BTABs has been illustrated.

Traditional design methods of ordinary wind turbines are not efficient when applied to design of wind turbines with BTAB. This is due to the presence of an interaction between the aerodynamic and structural characteristics of the blade. This interaction makes the aerodynamic and structural designs coupled and consequently not only the simulation of the turbine becomes a CAS process but also the number of design parameters that must be known for objective evaluation increases.

Treating the induced twist as a design parameter decouples the aerodynamic and structural design process and consequently the traditional design methods become functional for BTABs again. By doing this, in the aerodynamic design no structural characteristics are directly involved, but the outcome of the blade aerodynamic design is associated with the structural constraint of having a reference tip induced twist at a reference wind turbine run-condition. This constraint identifies the required level of elastic coupling in the blade.

To introduce the induced twist as a proper design parameter, it is expressed by a combination of two independent parameters of normalized induced twist, which is predicted through an analytical model and the tip induced twist, which plays the role of the design parameter. It has been shown that for the case of constant shell thickness and fiber orientation the accuracy of the model developed for normalized induced twist has no significant effect on the overall accuracy. However, more investigation must be carried out to develop models in which the effect of the span-wise variations of the shell thickness and fiber angle are taken into account. The simplified re-design case study illustrates the efficiency of the method in performing decoupled design of BTABs. However, still more optimization on the pre-twist, chord and aerofoil distributions can be carried out to gain greater energy capture enhancements.

Rotational and turbulence effects on a wind turbine blade: The work done by Sicot *et al.* (2008) evaluates experimentally the rotation and turbulence effects on a wind turbine blade aerodynamics, focusing particularly on stall mechanisms. The wind tunnel tests consisted in surface pressure measurements on a horizontal axis wind turbine airfoil subjected to free stream turbulence levels varying from 4.5 to 12%. A method to determine the position of the separation point on the rotating blade, based on the chord wise pressure gradient in the separated area, is proposed. The results showed an influence of the free stream turbulence level on the separation point position. Experimental results in the literature showed lift augmentation for a rotating blade. In this case, the study of the separation point position coupled with the pressure distributions on the airfoil shows that this lift augmentation seems related to a lower value of the pressure in the separated area rather than to a stall delay phenomenon.

In this study, the aerodynamic properties of a wind turbine airfoil were investigated, particularly, the influence of the inflow turbulence level (from 4.5 to 12%) and of rotation on the stall mechanisms on the blade. A local approach was used to study the influence of these parameters on the separation point position on the suction surface of the airfoil, through simultaneous surface pressure measurements around the airfoil.

A method to determine the position of the separation point and the value of the chord wise pressure gradient in the separated area has been proposed. It shows that, for the same angle of attack, the separation point is nearer to the trailing edge when the inflow turbulence level increases (a stall delay). Comparisons between pressure distributions and separation point position were performed between rotating and non-rotating blades. On the basis of the experiments presented on this paper, the following conclusions were drawn. In presence of important free stream turbulence level, rotation seems to have no significant effects on the separation point position whereas, for the same angle of attack, the pressure on the suction surface is significantly lower for the rotating blade.

Nevertheless, further experiments are necessary to fully understand the mechanisms responsible for the three-dimensional flow fields on the blade and help to build complete physical models. Moreover, due to the rotational motion and the high free stream turbulence level, the aerodynamic behavior of the blade is highly unsteady. It therefore seems interesting to study the unsteady pressure signal obtained during the tests performed and this work is currently in progress.

The methodology for aerodynamic study on a small domestic wind turbine: The aim of this study done by Wang *et al.* (2008) is to investigate the possibility of improving wind energy capture, under low wind speed conditions, in a built-up area and the design of a small wind generator for domestic use in such areas. The final design of scoop boosts the airflow speed by a factor of 1.5 times equivalent to an increase in power output of 2.2 times with the same swept area. Wind tunnel tests show that the scoop increases the output power of the wind turbine. The results also indicate that, by using a scoop, energy capture can be improved at lower wind speeds. The experimentally determined power curves of the wind generator located in the scoop are in good agreement with those predicted by the CFD model. This suggests that first the developed computer model was robust and could be used later for design purposes. Second the methodology developed here could be validated in a future study for a new rotor blade system to function well within the scoop. The power generation of such a new wind turbine is expected to be increased, particularly at locations where average wind speed is lower and more turbulent.

Evaluation study of a navier-stokes cfd aeroelastic model of wind turbine airfoils in classical flutter: A new Navier-Stokes CFD aeroelastic model with two coupling schemes (explicit and implicit) and two turbulence models (with wall functions and wall treatment) has been presented by Baxevanou *et al.* (2008) evaluated against linear theory and existing numerical results from two previous CFD models in the case of classical flutter of wind turbine blade sections. In the new model the space discretization is carried out with TVD schemes. The TVD scheme and the implicit coupling scheme were not used in previous CFD aeroelastic models for similar studies.

The present CFD predictions have been found in fair agreement with previous CFD studies, a fact indicating the validity of the present model despite the different formulations. The use of the present implicit coupling scheme has the advantage of increasing the time-step and, thus, reducing the computational cost. From the present parametric study it may be concluded that the results are mainly affected by the turbulence model used and not by the coupling scheme. In the particular case of classical flutter, even with different turbulence models, the influence of the coupling scheme is small with the implicit scheme moving the flutter limit to slightly higher values of reduced frequency k. While, the change of turbulence model from using wall functions to wall treatment moves the flutter limit to lower values of k.

The results of the parametric study show that the linear theory is certainly on the safe side. However, the damping ratio in the torsion mode is always very low suggesting a definite need for other damping means. Finally, the comparison with two previous CFD models indicates that different space discretization schemes and different time steps may affect the frequencies of both modes, but they do not affect seriously the aeroelastic behavior. The CFD method can be used as a virtual wind tunnel and this has been validated. It is now being used to test the proposed rotor design options, including hub shapes and blades configuration.

Assessment of wind energy potential: Wind speed data (in meters per second) and direction (in degrees) were recorded by Ganesan and Ahmed (2008) at hourly intervals for a period of 1 year from September 2004 to August 2005 at two mast heights of 10 and 25 m. The data recorded were analyzed and the regional wind climate determined using the WAsP 8.2 program and a vector map of the region covering 12×12 km. The orography of the area was characterized by elevation contours at 5 m intervals. On the basis of details obtained from the aerial photographic images, the roughness classes were also assigned. The time series wind data were analyzed and the Weibull distribution for the two projected heights of 50 and 70 m as per the requirement of the proposed Wind Turbine Generator (WTG) was evaluated. It is seen that the annual energy production in the area from 1MW WTG is 3.712 GWh at 50 m hub height and 4.431 GWh at 70 m hub height, indicating a satisfactory wind energy generation potential. This study describes the methodology adopted for the evaluation of wind energy potential for the site.

FATIGUE DESIGN OF WIND TURBINES

A simulation model for fatigue loads: The effects of turbulence intensity, mean wind speed, wind shear, vertical wind component, dynamic stall, stall hysteresis and blade stiffness was examined by Noda and Flay (1999). When all these effects were simulated it is found that a reduction in life occurs between a low wind speed low turbulence intensity sites, compared to a high wind speed high turbulence intensity site.

The wind speed probability distribution is modeled and the aerodynamic load developed on the blade is calculated using blade element theory. The blade itself is assumed to behave as a single-degree-of-freedom system hinging about a point near the blade root. The resulting stress history is rain flow counted to decompose the data into appropriate stress cycles. A cumulative damage law is used to estimate the fatigue damage and hence life. The use of simulations to determine the load history and hence fatigue life of wind turbines is standard amongst the wind turbine industry. This research used a similar approach to analyze the fatigue damage occurring at the blade-root of a typical three-bladed Danish-type turbine.

Fatigue loading parameter identification in complex terrain: An analytical methodology is introduced by Mouzakis *et al.* (1999) for parameter identification tasks. The tool developed is based on multiple regression analysis with a backward elimination technique in order to exclude the statistically insignificant parameters. The method is applied for the parameter identification of the fatigue loading of wind turbines and the results support the view that it comprises a promising method for reliable and efficient parameter identification tasks based on extensive experimental results. The parameters chosen to comprise the model set describe the deterministic part of the wind, the main turbulence characteristics, the turbulence length scale as well as the wind speed distribution. The dependent variables examined were the equivalent load range of the flap wise and edgewise blade root bending moments, the shaft yaw and tilt bending moments, the tower torsion and the tower bottom bending moment. The effect on fatigue of the wind parameters was captured and quantified. It was revealed that the turbulence structure of the incoming wind is the primary fatigue inducing parameter. Secondary effects of significant magnitude were found to be induced by the deterministic wind parameters and the wind distribution and coherence parameters. Using the same methodology, the effect of terrain complexity was quantified by introducing, as independent parameters, wind turbulence magnitudes that suitably reflect the terrain complexity. These parameters include the lateral and vertical turbulence ratios as well as the turbulence length scales. It was shown that the increase of fatigue loading of wind turbines operating in complex terrain sites can reach values over 30% when compared to the fatigue loading in flat terrain.

Fatigue loads for wind turbines operating in wakes: Loads for a wind turbine operating in the wake of an upstream wind turbine was investigated by Thomsen and Srensen (1999) with the objective of identifying the load generating changes in the wind field parameters compared to a free flow situation. The investigation was based on the measurements from the offshore wind farm Vindeby in Denmark. The following wind field parameters were included in the wind field analysis: Wind speed deficit, turbulence intensity, horizontal shear and turbulence spectrum length scale.

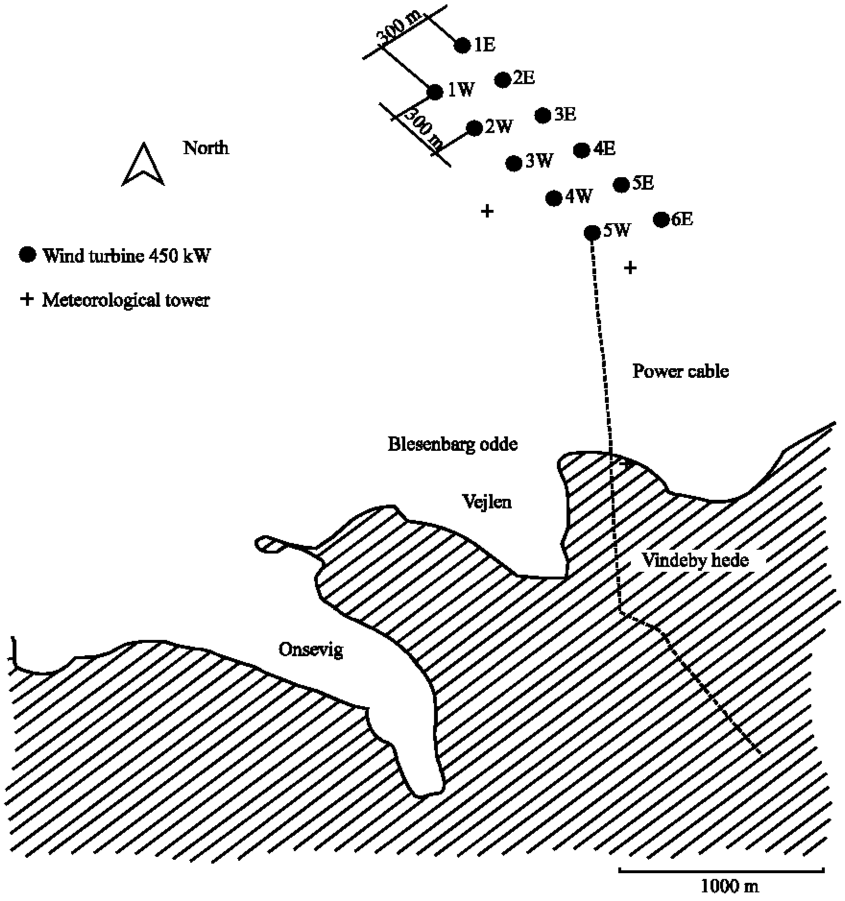

Fig. 2: The vindeby site Srensen Poul

The Vindeby wind farm consists of 11 wind turbines in two rows (Fig. 2). The wind farm is owned by the Danish utility ELKRAFT. It is placed 1.5 to 3 km off the shore of the Danish island Lolland in shallow water (depth varies from 2 to 5 m). Two of the turbines (4W and 5E, Fig. 2) were instrumented for load measurements. A large number of parameters were monitored but the analysis was focused on the flap wise blade bending moment measured on the blade extension. The wind turbine data were logged with a frequency of 20 Hz in 30 min runs and on-line rain flow counting was performed on the bending moment time series. The results of the rain flow counting were saved along with the statistics for each run.

Kenneth Thomsen studied four different changes in the wind field parameters for a wind turbine operating in the wake of an upstream turbine. These were: wind speed deficit, turbulence intensity, horizontal shear and turbulence length scale. Furthermore, he investigated the importance of the parameters and he found that for the present wind farm layout, the turbulence intensity and the length scales (and coherences) were the most important load-generating parameters. For a smaller distance between turbines the horizontal shear would be more important than for the present wind farm layout.

He investigated the load increase for a wind turbine installed in two typical wind farms, an array and a full wind farm. For the two layouts, he studied the load increase for a land site and an offshore site and found that the increased turbulence intensity for a land site caused the fatigue loads to be higher in the free flow than for the offshore site in the wind farm flow.

The load increase for a turbine installed in an array compared to the free flow at a site was approximately 5% for both sites and for a wind farm the load increase was 15%. He observed the same relative increase in fatigue loads for an offshore wind farm and a land site wind farm. As mentioned earlier, other investigations conclude that the load increase for low-ambient turbulence sites is higher than for the high-ambient turbulence sites. This was not the result of our investigation. A reason for the discrepancy might be found in our definition of a high turbulence site, having a turbulence intensity of 13% for all wind speeds. For land sites with a high degree of roughness elements the turbulence intensity can be significantly larger and the relative load increase for these sites may be lower. This investigation was based on the Vindeby experiment and the findings are only valid for wind farm layouts comparable to the Vindeby wind farm layout. The spacing of the turbines was rather high at Vindeby, 8.5 times the rotor diameter and for closer spaced turbines the results may not be the same.

Reliability-based fatigue design of wind-turbine rotor blades: Wind-turbine rotor blades exposed to wind loading are vulnerable to cumulative fatigue damage owing to the cyclic nature of the loading. The wind speed that causes bending of the rotor blades exhibits a natural variability, such that the load amplitudes become random and limited load measurements imply that interpreted load distributions are encumbered with statistical uncertainty. Moreover, the S-N curve that gives the number of stress cycles to failure and represents the resistance of the rotor blade material.

The design of a wind turbine rotor blade against fatigue failure in flap wise bending has been considered by Ronold *et al.* (1999). The load history in the design life has been modeled on the basis of observed distributions of bending moments at the blade root of an instrumented prototype rotor blade subjected to wind loads. Statistical uncertainty in the distribution parameters has been estimated and taken into account. The resistance has been modeled in terms of an e-N curve. Uncertainties in the variables that describe this curve have been estimated and have also been taken into account. The cumulative damage that eventually leads to a fatigue failure has been predicted according to a Miner's sum formulation. The models for load, resistance and cumulative damage have been used as a basis for defining a limit state function for fatigue failure and a first-order reliability analysis of the considered rotor blade against such a failure in flap wise bending has been carried out. The reliability analysis has been interpreted with respect to the probability of failure as well as identification of important uncertainty sources. The inherent variability in the fatigue life as represented by the uncertainty in the residual of the e-N curve has been found to be the single most important uncertainty source.

A reliability-based calibration of partial safety factors for design of the rotor blade against fatigue failure in flap wise bending has been carried out. A load factor ã$_f$ has been applied to all stresses and all strengths have been divided by a material factor γ_m. A target lifetime reliability corresponding to an acceptable annual probability of failure of 10^{-5} has been applied for the calibration. Based on a specific choice of characteristic values for load and resistance, a requirement to the product of load factor and material factor $\gamma_f\ \gamma_m = 1.252$ has come out. Based on the uncertainty importance information from the underlying reliability analysis, a particular robust set of partial safety factors that fulfill this requirement has been determined, hence $\gamma_f = 1.088$ and $\gamma_m = 1.150$.

Parametric models for estimating fatigue loads for design: International standards for wind turbine certification depend on finding long-term fatigue load distributions that are conservative with respect to the state of knowledge for a given system. Statistical models of loads for fatigue application are described and demonstrated by Manuel *et al.* (2001) using flap and edge blade-bending data from a commercial turbine in complex terrain. The long-term distribution of ranges is determined by integrating over the annual distribution of input conditions. In this work the first study is based on long-term loads derived by integration over wind speed distribution alone, using standard-specified turbulence levels. Next, he performed this integration over both wind speed and turbulence distribution for the example site. Results are compared between standard-driven and site-driven load estimates. Finally, using statistics based on the regression of the statistical moments over the input conditions, the uncertainty (due to the limited data set) in the long-term load distribution is represented by 95% confidence bounds on predicted loads.

Fatigue load spectra are essential elements of wind turbine design, analysis and certification. However, the spectra alone only tell a portion of the story. It would seem preferable to design with a margin consistent with the statistical uncertainty inherent in the loads data. Fewer data implies greater uncertainty and should require a larger margin while more data implies less uncertainty and ought to require a modest margin. Safety factors are still required to account for other non-statistical sources of uncertainty. The parametric models presented in this paper offer a systematic method of analyzing loads data to provide a definition of the loads as a function of the inflow conditions. The example data set and loads analysis presented here illustrate how this process may be conducted. The load data sets studied here were first truncated to eliminate undamaging fatigue ranges that distort the analysis. Such truncations can usefully improve fits of the model to the loads data while not underestimating fatigue-related damage.

New fatigue data for wind turbine blade materials: The work of Mandell *et al.* (2003) reports on recent fatigue data of interest to the wind turbine industry in several areas: (a) very high-cycle fatigue data; (b) refined Goodman Diagram; (c) effects of fiber waviness; and (d) large-tow carbon fibers. Tensile fatigue results from a specialized high-frequency small strand testing facility have been carried out to 10^{10} cycles in some cases, beyond the expected cycle range for turbines. While the data cannot be used directly in design due to the specialized test specimen, the data trends help to clarify the proper models for extrapolating from standard coupons to higher cycles. The results for various fiber and matrix systems also provide insight into basic failure mechanisms. For spectrum loading predictions, a more detailed Goodman Diagram has been developed with additional R-values (R is the ratio of minimum to maximum stress in a cycle). The data of greatest interest were obtained for tensile fatigue with low cyclic amplitudes, close to $R = 1.0$, to clarify the shape of the diagram as the cyclic amplitude approaches zero. These data may significantly shorten lifetime predictions compared with traditional Goodman Diagram constructions based on more limited data. The effects of material/process induced flaws on properties continue to be a major concern, particularly with large-tow carbon fabrics. The results of a study of fiber waviness effects on compressive strength show significant strength reductions for severe waviness which can be introduced in resin infusion processes.

The results show much higher static strength and fatigue resistance than for conventional coupons (in the moderate cycle range). The fatigue data support the use of a power law representation. Only small improvements are found at high cycles with a toughened resin. Additions to the Goodman Diagram show shorter than expected lifetimes at low amplitudes. These data may reduce predicted spectrum fatigue lifetimes, bringing them into closer agreement with experiments. Fiber waviness can be a major flaw in composite structures, particularly with large-tow carbon fibers using infusion methods. Data show a systematic reduction in compressive strength as wave severity increases. Tensile strength is affected only by severe waviness.

Early data for large-tow, low-cost carbon fiber composites show good tensile fatigue performance, but marginal compression fatigue performance. The compression static and fatigue data are lowest for the woven fabrics and improve for stitched fabrics. Prepreg composites with large tows and epoxy resins provided improved performance. The compression results indicate that caution should be exercised in using these fabrics for blade applications; further testing and full consideration of statistics and knockdown factors are needed to gain confidence with the large-tow carbon fiber materials. In infusion processes, the potential for introduction of severe waviness requires careful monitoring.

Simulation of fatigue failure in a full composite wind turbine blade: Lifetime prediction of a horizontal axis wind turbine composite blade is considered by Shokrieh and Rafiee (2006). Load cases are identified, calculated and evaluated. Static analysis is performed with a full 3-D finite element method and the critical zone where fatigue failure begins is extracted. Accumulated fatigue damage modeling is employed as a damage estimation rule based on generalized material property degradation. Since, wind flow (loading) is random, a stochastic approach is employed to develop a computer code in order to simulate wind flow with randomness in its nature on the blade and subsequently each load case is weighted by its rate of occurrence using a Weibull wind speed distribution.

In this study, the accumulated fatigue damage model was presented and applied based on CLT. that employs stiffness degradation as a single measure of damage estimation. Several checks were carried out on the model in order to assure proper simulation of the damage progress. All load cases are identified, calculated and evaluated and negligible cases are ignored. By performing finite element modeling, the critical zone of the blade is obtained. Fatigue phenomenon is studied in the selected critical zone using accumulated fatigue damage modeling. Based on a stochastic approach, random load cases are weighted by their rate-of-occurrence from wind patterns of the Manjil region. The results are bounded between 18.66 years and 24 years as lower and upper limits. Moreover, 1.59 years as the standard deviation shows a small range of scatter in the range of obtained results. These results show that presented accumulated fatigue damage model and the employed stochastic method are able to simulate the fatigue damage progress in a wind turbine composite blade. Considering the conservative nature of the employed technique, the investigated blade will have 18.66 years in the worse situation and 24 years in the best situation.

Non-linear dynamics of wind turbine wings: The paper of Larsen and Nielsen (2006) deals with the formulation of non-linear vibrations of a wind turbine wing described in a wing fixed moving coordinate system. The considered structural model is a Bernoulli-Euler beam with due consideration to axial twist. The theory includes geometrical non-linearities induced by the rotation of the aerodynamic load and the curvature, as well as inertial induced non-linearities caused by the support point motion. The non-linear partial differential equations of motion in the moving frame of reference have been discretized, using the fixed base eigenmodes as a functional basis. Important non-linear couplings between the fundamental blade mode and edgewise modes have been identified based on a resonance excitation of the wing, caused by a harmonically varying support point motion with the circular frequency. The aim of this work is to analyze various non-linear phenomena by a Galerkin reduced degrees-of-freedom model using the undamped fixed base eigenmodes as shape functions. Especially, the important non-linear couplings between the fundamental blade mode and the fundamental edgewise mode are identified by reducing the model to a two-degrees-of-freedom system.

A non-linear two-degrees-of-freedom model modeling the non-linear interactions between the fundamental blade and edgewise modes has been devised, retaining non-linear terms up to cubic order. The model includes inertial nonlinearities from support point motions and geometrical non-linearities from a non-linear description of the curvature and rotation of the aerodynamic loads caused by the deflection of the beam. Assuming a harmonic variation from the support point causing primarily quasistatic displacements in the blade direction, the important non-linear couplings are identified and a somewhat reduced system is indicated, retaining all terms of importance for the quantitative and qualitative behavior of the system.

The development of a fatigue loading spectrum: The paper of Epaarachchi and Clausen (2006) gives a formulation to create a fatigue loading procedure for the blade of a small wind turbine using a combination of detailed short-term aeroelastic and wind measurements and averaged long-term wind data from the Australian Bureau of Meteorology. Detailed aeroelastic measurements from the blade of an operating small wind turbine were acquired simultaneously with wind speed measurements and show that the blade does not respond instantaneously to all changes in wind speed. A methodology has been developed to create a fatigue loading procedure using the blade stress cycles determined from the detailed measurements in conjunction with long-term wind data. The proposed method overcomes the necessity to acquire long-term detailed operational data before developing a blade fatigue loading procedure without compromising on accuracy.

A critical assumption in developing this procedure was that the blade responded instantaneously to all changes in wind speed. The aeroelastic data acquired from this blade indicated that the blade's flap wise response followed the average wind speed but not the instantaneous variations in the wind speed, possibly due to blade inertia and structural damping. Large blades appear to exhibit a similar response, although without the data it is difficult to determine how their responses compare with a smaller blade. It is likely that smaller blades will be relatively stiffer than their larger counterparts especially if the blade is solid. This means that small blades will experience fewer flap wise fatigue
cycles than large blades but may experience an increased number of lead-lag cycles due to the higher blade rotational speeds. The fatigue effect of lead-lag cycles, principally due to gravity, was found to be negligible for the 2.5 m blade.

Both the detailed and averaged data were found to be modeled well by a Weibull distribution. A relationship between wind cycles and both the average and maximum velocity was determined using the detailed wind data and subsequently used to estimate the missing fatigue cycles from the Bureau's data. A joint probability relationship has been proposed which distributes the fatigue cycles to all nominated stress levels and associated R ratio bins. Using this relationship, a year long loading spectrum consisting of 1,803,705 cycles corresponding to wind velocities between 1 and 20 m sec^{-1} was defined for the 2.5 m long blade.

Fatigue of composites for wind turbines: The size of wind turbine rotors has increased in the past decade from 40 m to more than 120 m diameter. The resulting mass of about 18 tons per rotor blade causes high bending moments at the inner part of a blade due to the gravitational loads.

More than 10^8 load cycles will happen in the prospected lifetime of 20 years of a turbine. During this time the rotor blades are exposed to various hostile conditions such as extreme temperatures, humidity, rain, hail impact, snow, ice, solar radiation, lightning and salinity. In order to withstand these external conditions without diminishing the safety a sound knowledge of the fatigue behavior of the material and structural properties is needed. To meet the upcoming requirements the paper of Kensche (2006) highlight some fatigue and lifetime aspects on wind turbine rotor blades made of composite materials. This includes an historical part in connection with glider technology, the presentation of relevant S-N curves not only for the 0° orientated fibers representing the spar cap but also for ±45° lay-ups in shear web and shell, the influence of fiber content and architecture, of environmental effects, a view on lifetime prediction on structural elements as well as on present and future work.

A review was given on fatigue aspects of fiber reinforced plastics used in wind turbine rotor blades, exemplary on the DLR DEBRA 25. This material may serve as information for a safe fatigue design. Special attention should be given, however, in the design and production process of rotor blades to the experience that:

- High fiber contents may lead to a steeper slope of the fatigue curves
- A shear web may be more fatigue-critical than a spar cap
- Stiffness reduction in the leading and the trailing edge may occur when the lay-up is ±45°

The CFRP shows highly interesting properties with respect to stiffness, specific weight and fatigue properties. However, technological problems and the price of the carbon fibers are still hampering reasons for a wider application. The T-bolt and the stud connections are two widely used load introduction principles in modern rotor blade designs. Here it is more the steel itself which is fatigue-endangered than the composite parts. In the area of lifetime prediction development it was shown that it is essential for a sound comparison of different models to apply the same rain flow counting algorithm for each model.

Many items still have to be solved. Currently the EU program OPTIMAT BLADES intends to increase the knowledge on fatigue on composites by investigations in the following areas:

- Complex stress state
- Extreme climate
- Thick laminates and repair
- Condition monitoring

Investigation of fatigue life for a medium scale composite wind turbine blade: A specific fatigue procedure given by Changduk *et al.* (2006) was proposed with the following three steps. Firstly, from the sample load spectrum data during short period operation, the spectrum data were rearranged as layer numbers, wind speeds, cycles per layer, normalized maximum, minimum, cyclic and average loads and stress ratios in time order and then the rearranged data were recorded as cyclic loads per median cyclic load, cycles per layer, cumulative cycles, probability of exceeding and types of cycles, such as Type I, II and III. Secondly, fatigue loads, such as flap wise and chord wise bending moments were calculated by Spera's empirical equations with various engineering data of the studying blade for probability of exceeding. Finally, the allowable fatigue strengths were determined from laboratory fatigue property data for the S-N curve of E-glass/epoxy obtained by

Mandell, empirical coefficients derived by Goodman diagram with the modified stress ratio and the required design life. In prediction of the fatigue life, it was confirmed that the composite wind turbine blade satisfies the design criteria for the 20 years fatigue life because of sufficient safety margins from the fatigue requirement.

A study on stall-delay for HAWT: The boundary layer analysis method is given by Hu *et al.* (2006), the numerical simulation method as well as experimental measurement method is employed to study the fundamental physics of the stall-delay phenomenon in depth. It can be concluded that: Coriolis and centrifugal forces play important roles in 3D stall-delay. At the root area of the blade, where the high angles of attack occur, the effect of the Coriolis and centrifugal forces is strong. Thus, it shows apparent stall-delay phenomenon at the inner part of the blade. With increasing local blade radius r, however, the effect of the Reynolds number on the separation position becomes stronger than that of the Coriolis and centrifugal forces. As a result, at the outboard part of the blade the relationship between the separation points and the radial location shows similar trends in both 2D stationary conditions and 3D rotating condition. For high angle of attack, installed condition, Coriolis and centrifugal forces due to rotation might contribute to this 3D stall-delay. The centrifugal forces induce outflow in regions of separation, which in turn induces a Coriolis force in the chord wise direction that acts as a favorable pressure gradient tending to delay the occurrence of separation to a point further downstream toward the trailing edge. It is shown that rotation has a generally beneficial effect in delaying separation.

Study of fatigue damage in wind turbine blades: The objective of the present work of Marin *et al.* (2009) is to study the damages detected in the blades of 300 kW wind turbines. These damages, consisting of cracks located in the joining zone of the blade with the root, appeared over short periods of time and systematically in blades in which fatigue loads were more severe. Similar damages appeared also, but over longer periods of time, in blades under more benign fatigue conditions. In any case, these periods were inferior to the design life of the blades (20 years). In this work, the reasons lying behind the damages detected are studied, to be used as a basis for repairing similarly affected blades.

First, a complete inspection of the damaged zone of the blade was carried out, cutting this damaged zone to evaluate the nature of the damage and to observe the inner structure of the zone. The correct correspondence of the structure of the laminates with that established at design as well as the existence of possible defects of manufacture is verified. The results of this visual inspection allow a qualitative estimation of the causes which could originate the appearance of the cracks to be performed.

- Damage appearing in the form of a crack that affected the (non-resistant) superficial laminate, extending over the influence zone of the concentrator and with its likely origin at the corner between the cover and the root
- Damage in the form of a crack that affected the resistant laminate, extending over the zone where there was an abrupt change in the thickness of the laminate
- Delamination, lack of bonding, lack of resin and diverse manufacture defects

Stress concentration and deflection in isotropic, orthotropic and laminated composite plates: The distributions of stresses and deflection in rectangular isotropic, orthotropic and laminated composite plates with central circular hole under transverse static loading have been studied by Mittal and Jain (2008) using finite element method for calculating the properties of material. The aim of author is to analyze the effect of D/A ratio (where D is hole diameter and A is plate width) upon Stress Concentration Factor (SCF) and deflection in isotropic, orthotropic and laminated composite plates under different transverse static loading condition. Analysis has been done for symmetric and anti-symmetric composite laminates. The results are obtained for three different boundary conditions. The variations of SCF and deflection with respect to D/A ratio are presented in graphical form and discussed. The finite element formulation is carried out in the analysis section of the ANSYS package.

OPTIMIZATION TECHNIQUES OF WIND TURBINE ROTOR

The economic optimization of horizontal axis wind turbine: A method for determining the optimum design parameters for horizontal axis wind turbines was developed and tested by Collecutt and Flay (1996). These design parameters were the rotor diameter, rated power and tower height. The optimum values were found to be dependent on site wind regime. The results of the study indicated that it was, however, only the optimization of the relative combination of rotor diameter and rated power with respect to site mean annual wind speed that afforded significant reductions in energy production cost. This optimization confirmed that presently available wind turbines were optimized for mean annual wind speeds in the range 6-8 m sec^{-1} and suggested that for windier sites the energy production cost may be reduced by up to 10% through the optimization of machine rated wind speed to suit such sites.

The majority of wind farm sites around the world having mean annual wind speeds in the range of 8 m sec^{-1}, it would be reasonable to assume that wind turbine manufacturers would have optimized their machines to suit this range of wind speeds. Therefore it seemed plausible that the re-optimization of current technology to suit sites with significantly higher mean annual wind speeds might well yield a reduction in energy production cost at such sites. The effect of the ratio of tower height to rotor diameter was also studied in this paper. This ratio was varied over the range 0.7-2.5. Its effect on the location and magnitude of the minimum was also small and again the potential reductions in energy production cost through optimizing this variable were less than 1%.

There are three important conclusions that may be drawn from these results. Firstly, note that there is little to be gained through optimization for wind speeds around 7 m sec^{-1}. This suggests that the non-optimized machine, which was chosen to represent presently available wind turbines, is in fact well optimized for 7 m sec^{-1} sites, which are typical sites. This comes as no surprise. Secondly, for mean annual wind speeds above about 8 m sec^{-1} there is indeed some reduction possible in energy production cost through optimization. This reduction is in the order of 10% for a 10 m sec^{-1} site, which is significant. Finally, note that it makes little difference whether a machine has both rotor diameter and rated power optimized, or just rated power alone optimized. This is an important finding, as it suggests that the optimization of rated wind speed with respect to mean annual wind speed is the most important player in achieving reductions in energy production cost. Optimization of overall machine size is of little value and fortunately so since the uncertainty in the economy of scale factor makes this optimization terribly unreliable.

The G R Collecutt, R.G.J. Flay found that an economy of scale in relationships between component cost and component mass (or rated power) was necessary in order to predict an optimum machine size that lay within the range of commonly available wind turbines. Therefore, this approach was unable to uniquely predict an optimum machine size. The results given by Collecutt and Flay (1996) indicate that for a 10 m sec^{-1} site a 10% reduction in energy production cost is achievable through the optimization of the rated wind speed of the machine.

Optimization of a design code: A code for the design of wind-turbine rotor blades against fatigue failure in flap wise bending is considered by Ronold and Christensen (2001). The rotor blades are constructed from fiber-reinforced polyester laminate. The critical location for accumulation of fatigue damage is considered to be at the blade root. The loading consists of a history of bending moment ranges owing to wind exposure and is represented by a model which has been calibrated from load measurements. The capacity is calculated on the basis of a Miner's rule approach to cumulative damage and capitalizes on a conventional S-N curve formulation.

For a particular wind turbine, the distribution of the flap wise bending moment at the blade root for various wind climates (U_{10}, I_T) (10 min mean wind speed, turbulence intensity) at the hub height are obtained from measurements on the wind turbine installed at a particular location. It has been assumed that these conditional load distributions can be used for the same wind turbine installed at other locations. However, at a different location, even though (U_{10}, I_T) at the hub height is the same, the stochastic wind field may be different with different vortices and a different spatial correlation structure. Moreover, a different terrain roughness will give a different vertical wind speed profile. These differences will all contribute to different conditional load distributions when the turbine is installed at a different location than the one at which the conditional load distributions were observed.

For refinement of the code calibration presented in this paper, the effects of transporting conditional load distributions for a wind turbine to locations other than the location of observation should be investigated and accounted for. One way of doing this would be to obtain load measurements on the same wind turbine installed at a number of different representative locations and then analyze the results statistically. The results of this exercise could be interpreted in terms of standard deviations of the statistical moments, which are used as distribution parameters in the conditional load distributions. These standard deviations would be representative for the uncertainty associated with use of the conditional load distributions at any other location than the location of observation. These standard deviations would then have to be included in the reliability analyses whenever a wind turbine in combination with a location other than the location of observation is to be included as a design case in the scope of code. This would have to be done practically by combining them with the standard deviations owing to statistical uncertainty and already included in the analyses presented here, making sure that standard statistical rules for combination of variances are fulfilled as an alternative, design cases should only be formed by combining wind turbines, for which load measurements are available, with those particular locations where the measurements were actually obtained. This would be an attractive alternative if the amount of data would permit; i.e., if a sufficiently wide range of wind turbines have been tested at a sufficiently wide range of locations. Transport of available conditional load distributions to locations other than the actual location of observation would then not be necessary and problems involved with such transport would be avoided

The three locations used for definition of the scope of code represent three different wind climates. These three locations need not necessarily be sufficient to represent all possibilities that can be expected for future locations of wind turbines. The mere presence of an obstruction, such as a house near a prospective wind turbine site, is sufficient to significantly alter the local wind climate and introduce additional turbulence. This implies that a much larger number of typical locations may be required to adequately cover the future demand. A future update of the presented code optimization should therefore also include a greater number of locations and corresponding wind climates in the scope of code. This will be possible when more data from wind-speed measurements become available from a wider selection of typical locations.

Optimization method for wind turbine rotors: This work of Fuglsang and Madsen (1999) presents a recently developed numerical multi-disciplinary optimization method for design of horizontal axis wind turbines. The method allows multiple constraints. The objective was minimum cost of energy, determined by the design giving fatigue and extreme loads and the annual production of energy. Time domain aeroelastic calculations and rainflow counting provided the life time equivalent fatigue loads. A semi-empirical approach was developed for their sensitivities. This resulted in substantial savings in computing time. An optimization of a 1.5 MWstall regulated rotor demonstrated the design method and the results showed that constraints on loads are important for the applicability of the optimization results. Shape optimization of the rotor resulted in maximum strain on more than 80% of the blade span and hence more efficient use of material. The cost of energy was reduced compared to a traditional design with the same swept area. The optimum specific power was found to 460 W m^{-2}, which is lower than that of modern Danish wind turbines. Studies for optimum airfoil characteristics showed that the airfoil sections should have a relative high maximum lift at the entire span including the tip region. An increase in the swept area should therefore involve a complete redesign of the rotor blades and avoid the use of low maximum lift airfoils at the tip, which so far has been widely used to control peak power.

The aerodynamic and structural design of rotors for horizontal axis wind turbines (HAWTs) is a multi-disciplinary task, involving conflicting requirements on, for example, maximum performance, minimum loads and minimum noise. The wind turbine operates in very different conditions from normal variation in wind speed to extreme wind occurrences. Optimum efficiency is not obtainable in the entire wind speed range, since power regulation is needed to prevent generator burnout at high wind speeds. Optimum efficiency is limited to a single-design wind speed for stall regulated HAWTs with fixed speed of rotation. The development of suitable optimization methods for geometric shape design of HAWT rotors is therefore a complex task that involves off-design performance and multiple considerations on concept, generator size, regulation and loads.

The design of a 1.5 MWstall regulated rotor was used to demonstrate the capabilities of the design method. He found that:

- Constraints on loads and estimation of cost were important for the applicability of the optimization results
- With traditional airfoil characteristics and blade structure, shape optimization of the rotor reduced cost of energy compared to a rotor of the same size
- The optimum specific power was found to 460 W m^{-2} which is lower than that of modern Danish wind turbines
- Optimum airfoil characteristics showed that the airfoil sections should have a relative high maximum lift on the entire blade including the tip region

Optimization of wind turbine blades: In designing a wind turbine, the goal of Jureczko *et al*., (2005) is to attain the highest possible power output under specified atmospheric conditions. From the technical point of view, this depends on the shape of the blade. The change of the shape of blade is one of the methods to modify stiffness and stability, but it may influence aerodynamic efficiency of wind turbine. Other method to change dynamic and mechanical properties of wind turbine is modifying the composite material, which the blade is made of. The problem of determining the optimal shape of blade and determining the optimal composite material is a complex one, as the mathematical description of aerodynamic load is complex and a number of constraints and objectives have to be satisfied.

The aerodynamic profiles of wind turbine blades have crucial influence on aerodynamic efficiency of wind turbine. However, when blades are longer than 45 m the dynamic behavior of the blade must be also taken into account. Then, the position and shape of spars have to be considered and analyzed. The location of the main spar together with the location of the stiffening ribs will have the biggest influence on the bending modes of the blade. The model of blade is made of shell elements were used in multi-criteria optimization procedure. The blade is to be twisted around the elastic axis. The position of elastic center can be changed by modifying the position of spars and its shape. The solid model of the blade is created in order to obtain required properties of the blade and position of spars.

State of load on the blade: The analysis of the state of load on the wind turbine blade is intended to verify whether the turbine will withstand the action of load within appropriate safety range. Various cases of load on the blade, resulting from the action of various external factors on the turbine, have to be considered. The following types of states of load on a wind turbine blade can be distinguished:

Aerodynamic loads of a wind turbine blade: Mass loads, as the wind turbine blade is slender, the loads associated with its inertia are limited to the loads generated by its weight, which causes sinusoidal loads the frequency of which corresponds to the rotor.

Material of the blade: The considered blade is made of composite materials containing more than one bonded material, each with different structural properties. One of the materials, called the reinforcing phase is embedded in the other material of the matrix phase. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The main advantage of composite materials is the potential.

Composites used for typical engineering applications are advanced fiber or laminated composites, such as fiberglass, glass epoxy, graphite epoxy and boron epoxy. Composites are somewhat more difficult to model than an isotropic material such as iron or steel. The special care must be taken in defining the properties and orientations of the various layers since each layer may have different orthotropic material properties.

Majority of wind turbine blades is made of fiberglass reinforced with polyester or epoxy resin. Construction using wood-epoxy or other materials also can be found. Small turbine blades are made of steel or aluminum, but they are heavier. Lighter and more effective blades decrease material requirements for other wind turbines component making overall costs to be lower. Longer blades require another materials to be applied, usually carbon-based composites. Carbon fiber composites allow to lower blade's mass (from 20 to 18 T at 61.5 m long blade). Carbon-based composites allow also reconstructing older blades made of fiberglass reducing mass and increasing its stiffness. However, use of carbon materials requires increased accuracy and makes manufacturing costs to be higher.

The developed numerical model of the wind turbine blade and the computer program package for performing multi criteria discrete–continuous optimization of wind turbine blades are of general nature. Various blade models can be created by means of an ANSYS parametric file; thicknesses and main dimensions of the model blade can be varied.

A model for yawing dynamic optimization: A novel design optimization model for placing frequencies of a wind turbine tower/nacelle/rotor structure in free yawing motion is developed and discussed by Maalawi (2007). The main aim is to avoid large amplitudes caused by the yawing-induced vibrations in the case of horizontal axis wind turbines or rotational motion of the blades about the tower axis in case of vertical-axis wind turbines. This can be a major cause of fatigue failure and might severely damage the whole tower/nacelle/rotor structure. The mathematical formulation considers a single pole tower configuration having thin-walled circular cross section with constant taper along the tower height. The nacelle/rotor combination is modeled as a rigid mass elastically supported at the top of the tower by the torsion spring of the yawing mechanism. Adequate scaling and non-dimensionalization of the various parameters and variables are given in order to make the model valid for a variety of wind turbine configurations and types of the material of construction. The resulting governing differential equation of motion is solved analytically by transforming it into a standard form of Bessel's equation, which leads to the necessary exact solutions for the frequencies and mode shapes. Several cases of study are examined for different values of the yawing stiffness and inertia parameters by considering both conditions of locked and unlocked yawing mechanism. Useful design charts are developed for placing the frequencies at their needed target values with no penalty of increasing the total structural weight of the system. In all, the developed model guarantees full separation of the system frequencies from the critical exciting yawing frequencies by proper choice of the optimization design parameters.

Efficient model for placing frequencies of a combined wind turbine tower/nacelle/rotor structure in free yawing motion has been presented and discussed. The mathematical procedure implemented, combined with exact Bessel's function solutions, resulted in a beneficial tool that can be used for finding the optimal frequency design of a real world wind turbine of any size, configuration and material of construction. The model provides exact solutions to the vibration frequencies and mode shapes, against which the efficiency of approximate methods, such as the finite element method, may be judged. Design variables include the tower tapering ratio, wall thickness and mean radius of the tower cross section. Useful design charts for placing the frequencies at their desired (target) values has been developed for a prescribed total structural weight and known nacelle/rotor inertia and torsion stiffness of the yawing mechanism. The fundamental frequencies can be shifted sufficiently from the range which resonates with the excitation yawing frequencies. There are other factors that ought to be considered in future investigations. For example, the system response due to sudden yaw motion, which may cause severe bending and shearing stresses within the blades and tower structures, should be analyzed and examined. Another natural extension of this work is to optimize the performance of a wind machine by simultaneously minimizing vibration level and structural weight using a multi-criteria optimization technique.

CONCLUSIONS

Wind turbine technology has demonstrated the potential for contributing to the energy needs of the world. If the sites with acceptable wind characteristics were fully utilized, they could contribute up to about 10% of the nation's electrical energy needs. The limitation is based on utility system stability issues rather than available site locations. As in all energy investment decisions, the ultimate penetration level will be driven by the cost of energy that is produced. In turn, this is decided by the initial cost of the wind energy plant and the annual cost for maintenance and operation. Wind turbines should be optimized, by taking swept area into consideration, in terms of the local area conditions to capture power as maximum as possible. The output power of a wind turbine is directly related to the wind speed as well as to the swept area of its blades. The larger the diameter of its blades, the more power can be extracted from the wind. The power produced by the wind turbine increases from zero at the threshold wind speed (cut in speed) (usually around 5 m sec^{-1} but varies with site) to the maximum at the rated wind speed. Above the rated wind speed, (15 to 25 m sec^{-1}) the wind turbine continues to produce the same rated power but at lower efficiency until shut down is initiated if the wind speed becomes dangerously high, i.e., above 25 to 30 m sec^{-1} (gale force). The exact specifications for energy capture by the turbine depend on the distribution of wind speed over the year at the individual site.

Many factors have to be considered during manufacturing or installation of wind turbines, i.e., (turbine swept area, air density, wind speed and power coefficient as a function of pitch angle and blade tip speed).

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