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Various Design Aspects of Wind Turbine Blades & a Measure to Analyze these Failures Due to Icing of Blades

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Abstract: *In the last decade, we have heard more and more about the need of renew-able clean energy, but not much has been done. Currently, the wind power energy is the most popular of all of these green technologies. Thousands of wind turbines are being invested and installed everywhere worldwide.Blade is one of the key components in wind turbine, which is needed to be enough stiffness, strength and stability. Loading calculation is significant for the blade strength analysis. In this paper a detailed review provides a complete picture of wind turbine blade loads and shows the dominance of modern turbines almost exclusive use of horizontal axis rotors. The aerodynamic design principles for a modern wind turbine blade are detailed, a review of design loads on wind turbine blades is offered, describing aerodynamic, gravitational, centrifugal, gyroscopic and operational conditions.*

I. Introduction

Power has been extracted from the wind over hundreds of years with historic designs, known as windmills, constructed from wood, cloth and stone for the purpose of pumping water or grinding corn. Historic designs, typically large, heavy and inefficient, were replaced in the 19th century by fossil fuel engines and the implementation of a nationally distributed power network. A greater understanding of aerodynamics and advances in materials, particularly polymers, has led to the return of wind energy extraction in the latter half of the 20th century. Wind power devices are now used to produce electricity, and commonly termed wind turbines.

The orientation of the shaft and rotational axis determines the first classification of the wind turbine. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine or (HAWT). A vertical axis wind turbine (VAWT) has its shaft normal to the ground (Figure 1).

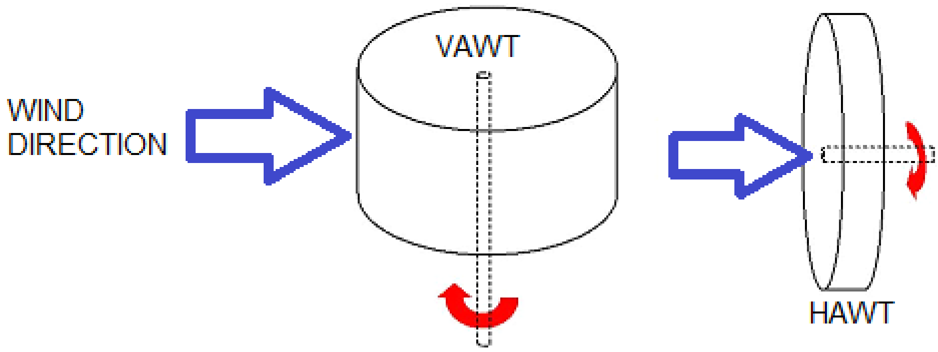

Figure 1. Two configurations for orientation of shaft and rotor

The two configurations have instantly distinguishable rotor designs, each with its own favorable characteristics [1]. The discontinued mainstream development of the VAWT can be attributed to a low tip speed ratio and difficulty in controlling rotor speed. Difficulties in the starting of vertical turbines have also hampered development, believed until recently to be incapable of self-starting [2]. However, the VAWT requires no additional mechanism to face the wind and heavy generator equipment can be mounted on the ground, thus reducing tower loads. Therefore, the VAWT is not completely disregarded for future development. A novel V-shaped VAWT rotor

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design is currently under investigation which exploits these favourable attributes [3]. This design is currently unproven on a megawatt scale, requiring several years of development before it can be considered competitive. In addition to the problems associated with alternative designs, the popularity of the HAWT can be attributed to increased rotor control through pitch and yaw control. The HAWT has therefore emerged as the dominant design configuration, capitalized by all of today's leading large scale turbine manufacturers.

Aerodynamics

Aerodynamic performance is fundamental for efficient rotor design [4]. Aerodynamic lift is the force responsible for the power yield generated by the turbine and it is therefore essential to maximize this force using appropriate design. A resistant drag force which opposes the motion of the blade is also generated by friction which must be minimised.it is then apparent that an aerofoil section with a high lift to drag ratio [Equation (1)], typically greater than 30 [5], be chosen for rotor blade design [4]:

$$\text{Lift to drag ratio} = \frac{\text{coefficientoflift}}{\text{coefficientofdrag}} = \frac{CL}{CD} \qquad (1)$$

Each section of the blade has a differing relative air velocity and structural requirement and therefore should have its aerofoil section tailored accordingly. The differing aerofoil requirements relative to the blade region are apparent when considering airflow velocities and structural loads table 1

Angle of Twist

The lift generated by an aerofoil section is a function of the angle of attack to the inflowing air stream. The inflow angle of the air stream is dependent on the rotational speed and wind speed velocity at a specified radius. The angle of twist required is dependent upon tip speed ratio and desired aerofoil angle of attack

Parameter	Blade Position (Figure 7)		
	Root	**Mid Span**	**Tip**
Thickness to chord ratio (%) ((^d_c) Figure 2)	>27	27–21	21–15
Structural load bearing requirement	High	Med	Low
Geometrical compatibility	Med	Med	Med
Maximum lift insensitive to leading edge roughness			High
Design lift close to maximum lift off-design		Low	Med
Maximum CL and post stall behavior		Low	High
Low Aerofoil Noise			High

Table 1. The airfoil requirements for blade regions

In contrast the blade tip is likely to be almost normal to the wind. The total angle of twist in a blade maybe reduced simplifying the blade shape to cut manufacturing costs. However, this may force aerofoils to operate at less than optimum angles of attack where lift to drag ratio is reduced. Such simplifications must be well justified considering the overall loss in turbine performance.

Blade Loads

Multiple aerofoil sections and chord lengths, 22 specified stochastic load cases and an angle of twist with numerous blade pitching angles results in a complex engineering scenario. Therefore, the use of computer analysis software such as fluid dynamics (CFD) and finite element (FEA) is now commonplace within the wind turbine industry [6]. Dedicated commercially available software such as LOADS, YawDyn, MOSTAB, GH Bladed, SEACC and AERODYN are utilised to perform calculations based upon blade geometry, tip speed and site conditions [7].

To simplify calculations, it has been suggested that a worst case loading condition be identified for consideration, on which all other loads may be tolerated. The worst case loading scenario is dependent on blade size and method of control. For small turbines without blade pitching, a 50 year storm condition would be considered the limiting case. For larger turbines (D> 70 m), loads resulting from the mass of the blade become critical and should be considered. In practice several load cases are considered with published methods detailing mathematical analysis for each of the IEC load cases.

For modern large scale turbine blades the analysis of a single governing load case is not sufficient for certification. Therefore multiple load cases are analyzed. The most important load cases are dependent on individual designs. Typically priority is given to the following loading conditions:

- Emergency stop. [8]
- Extreme loading during operation. [9]
- Parked 50 year storm conditions. [10]

Under these operational scenarios the main sources of blade loading are listed below: [9]
1. Aerodynamic
2. Gravitational
3. Centrifugal
4. Gyroscopic
5. Operational

The load magnitude will depend on the operational scenario under analysis. If the optimum rotor shape is maintained, then aerodynamic loads are unavoidable and vital to the function of the turbine, considered. As turbines increase in size, the mass of the blade is said to increase proportionately at a cubic rate. The gravitational and centrifugal forces become critical due to blade mass. Gyroscopic loads result from yawing during operation. They are system dependent and generally less intensive than gravitational loads. Operational loads are also system dependent, resulting from pitching, yawing, breaking and generator connection and can be intensive during emergency stop or grid loss scenarios. Gyroscopic and operational loads can be reduced by adjusting system parameters. Blades which can withstand aerodynamic, gravitational and centrifugal loads are generally capable of withstanding these reduced loads. Therefore, gyroscopic and operational loads are not considered within this work.

Aerodynamic Load

Aerodynamic load is generated by lift and drag of the blades aerofoil section (Figure 2), which is dependent on wind velocity (VW), blade velocity (U), surface finish, angle of attack (α) and yaw. The angle of attack is dependent on blade twist and pitch. The aerodynamic lift and drag produced (Figure 2) are resolved into useful thrust (T) in the direction of rotation absorbed by the generator and reaction forces (R). It can be seen that the reaction forces are substantial acting in the flatwise bending plane, and must be tolerated by the blade with limited deformation.

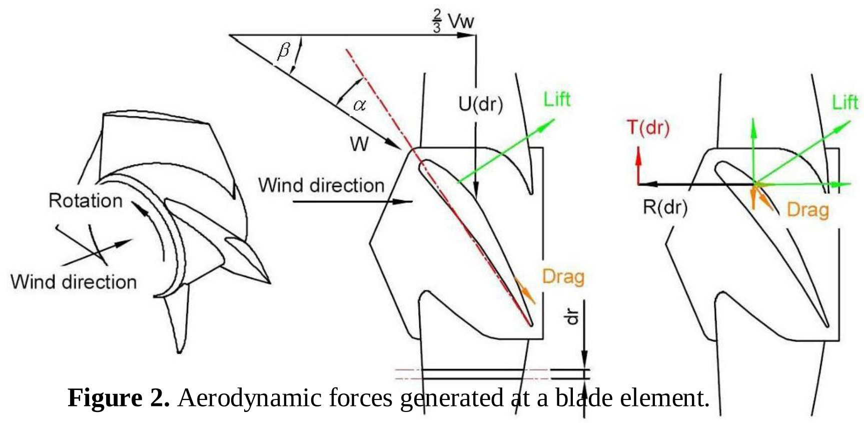

Figure 2. Aerodynamic forces generated at a blade element.

r = Radius
W = Relative velocity
U(δr) = Blade velocity at r
V_w = Wind velocity
β = Angle of incidence
α = Angle of attack
$T(\delta r)$ = Thrust at r
$R(\delta r)$ = Reaction at r

For calculation of the blade aerodynamic forces the widely publicized blade element momentum (BEM) theory is applied [9, 11].Working along the blade radius taking small elements (δr), the sum of the aerodynamic forces can be calculated to give the overall blade reaction and thrust loads (Figure 2).

Gravitational and Centrifugal Loads

Gravitational centrifugal forces increase cubically with increasing turbine diameter [12] these forces are mass dependent.Therefore, if the rotor diameter is less than ten meters diameter turbines will have negligible inertial loads, these load are marginal if the rotor diameter is more than 20 meters upward, and these loads are critical if the rotor diameter is 70 meter or above .

The gravitational force is gravitational constant multiplied by mass and its direction is always towards the center of earth an alternate cyclic load is develops due to its direction towards earth's center. The centrifugal force is defined as the square of rotational velocity multiplied by mass and it acts in radial outward direction, so for high tip speed the increased load always desirable.

Structural Load Analysis

Traditionally structure load analyzed by making a model as a cantilever beam with uniformly distributed or equivalent load, then flap wise and edgewise loads are calculated. But now day 3D CAD software are available for structural analysis.

Flapwise Bending

The flap wise bending moment is a result from aerodynamic loads (Figure 2), these loads are calculated using BEM theory. Aerodynamic loads are taken as a critical design load for 50 year storm and other operational conditions [9]. After calculated these, the model is generated as a cantilever beam with uniformly distributed load (Figure 3). By this analysis we know how bending occurs about the chord axis causing compressive and tensile stresses in the blade cross section (Figure 4). For calculation of these stresses the second moment of area of the load bearing material must be calculated [Equation (3)]. Using classical beam bending analysis bending moments can be calculated at any section along the blade [13]. Local deflections and material stresses can then be calculated at any point along the beam using the fundamental beam bending equation [Equation (4)].

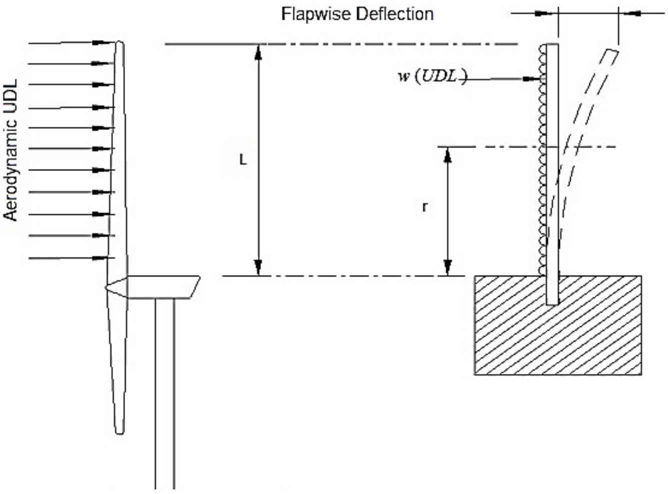

Figure 3. The blade modeled as a cantilever beam with uniformly distributedaerodynamic load.

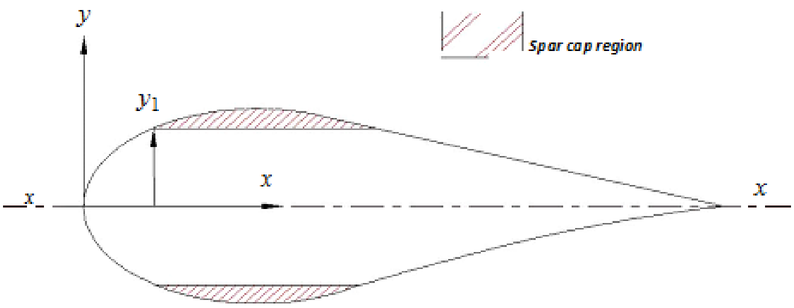

Figure 4. Flapwisebending about the axisxx.

$$I_{xx} = \iint (y-y_1)^2 \, dx \, dy \quad (2)$$

$$M = -\frac{1}{2} w (l - r)2 \quad (3)$$

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{E}{R} \quad (4)$$

When calculating the second moment of area [Equation (2)] it is apparent that increasing the distance from the central axis of bending gives a cubic increase. When substituted into the beam bending equation [Equation (4)], it can be seen that a squared decrease in material stress can be obtained by simply moving load bearing material away from the central plane of bending. It is therefore efficient to place load bearing material in the spar cap region of the blade at extreme positions from the central plane of bending (x) (Figure 4). This signifies why thick section aerofoils are structurally preferred, despite their aerodynamic deficiencies. This increase in structural efficiency can be used to minimize the use of structural materials and allow significant weight reductions[14]. The conflict between slender aerofoils for aerodynamic efficiency and thicker aerofoils for structural integrity is therefore apparent. Bending moments [Equation (3)] and therefore stress [Equation (4)] can be seen to increase towards the rotor hub. This signifies why aerofoil sections tend to increase in thickness towards the hub to maintain structural integrity.

Edgewise Bending

The bending moment caused by blade mass and gravity is known as edgewise bending. Therefore we consider these loads negligible for smaller blades with negligible blade mass. Simple scaling laws dictate a cubic rise in blade mass with increasing turbine size. Therefore for increasing turbine sizes in excess of 70 m diameter, this loading case is said to be increasingly critical. The bending moment is at its maximum when the blade reaches the horizontal position. In this case the blade may once again be modeled as a cantilever beam (Figures 5 and 6). [15]

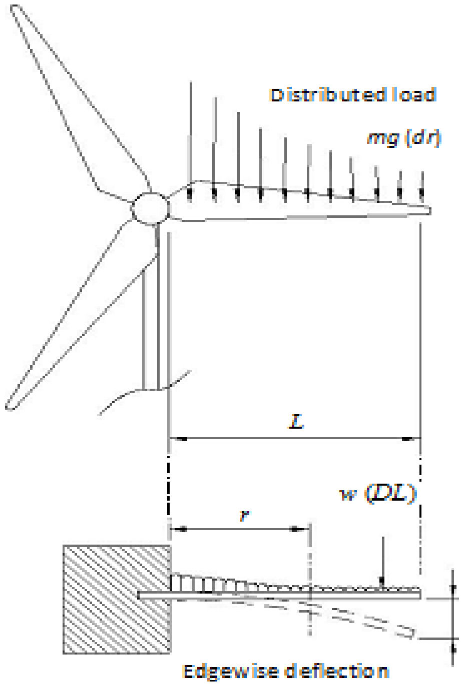

Figure 5. Gravitational load modelled as a cantilever beam.

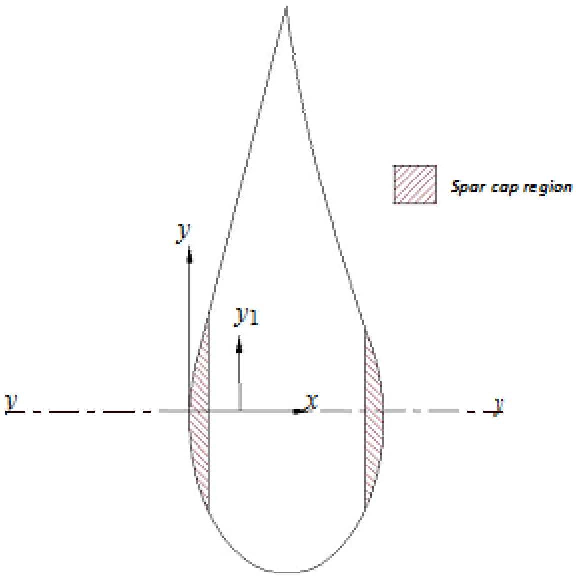

Figure 6. Edgewise bending aboutyy.

Structural Blade Regions

The modern blade can be divided into three main areas classified by aerodynamic and structural function (Figure 7):

The blade root. The transition between the circular mount and the first aerofoil profile—thissection carries the highest loads. Its low relative wind velocity is due to the relatively small rotor radius.

The low wind velocity leads to reduced aerodynamic lift leading to large chord lengths. Therefore the blade profile becomes excessively large at the rotor hub. The problem of low lift is compounded by the need to use excessively thick aerofoil sections to improve structural integrity at this load intensive region. Therefore the root region of the blade will typically consist of thick aerofoil profiles with low aerodynamic efficiency.

The mid span. Aerodynamically significant—the lift to drag ratio will be maximized. Therefore utilising the thinnest possible aerofoil section that structural considerations will allow.

The tip. Aerodynamically critical—the lift to drag ratio will be maximized. Therefore slender airfoils and specially designed tip geometries have been used to reduce noise and losses. Such tip geometries are as yet unproven in the field but in any case they are still used by some manufacturers [1].

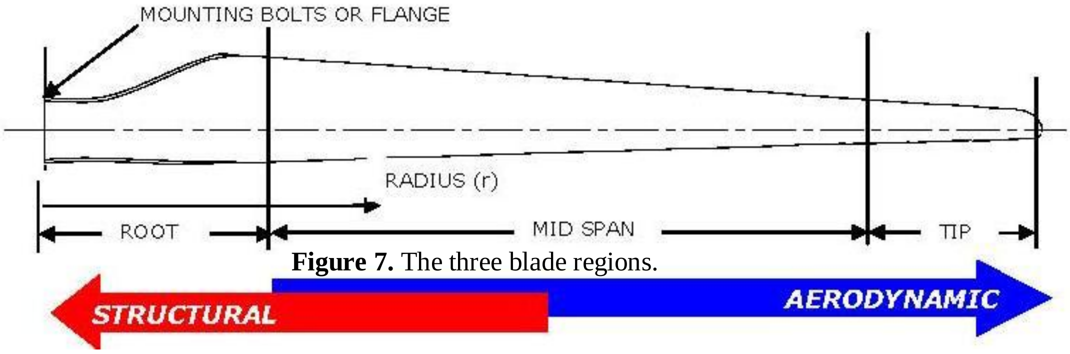

Figure 7. The three blade regions.

These are the loads developed in wind turbine blades. Also in snowy areas there is a problem of icing of wind turbine blades. Due to icing of blades, failure of blades takes place, but there is no method developed to measure & account this failure.In reference to these loads, there is a need for measurement and accounting of various loads acting on blade's surface. In relation to this there is a need for load monitoringof rotor blades and for this purpose suitable techniques are under development. One of thepromising methods to measure and analyze the blade loads continuously is by use of metalfoil strain gauges. Figure 8 shows arrangement of 3 strain gauges on each blade. It also followed by straingauge conditioning and transmitting system and data reception system.

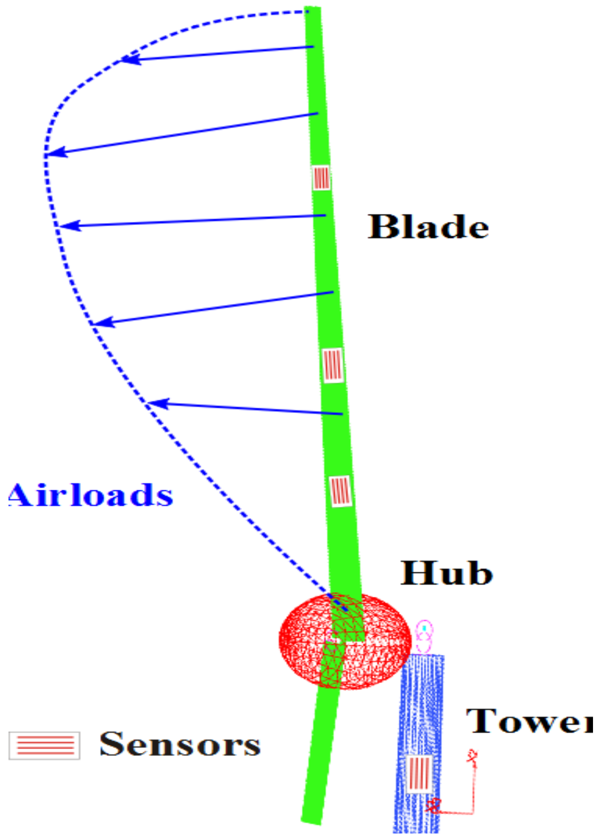

Figure 8. Sensor arrangement on blades

II. Conclusions

This provides a review of various designing considerations and factor affecting the wind turbine blades. A theoretical study on blade design has revealed that an efficient blade shape is defined by aerodynamic load calculations based on available input and output parameters. The optimum efficient shape is complex consisting of airfoil sections of increasing width, thickness and twist angle towards the hub. The general shape and processes are constrained by physical laws and are unlikely to change. However, airfoil lift and drag performance will help to draw the exact angles of twist and lengths of chords for optimal aerodynamics. All these aspects force to develop an effective Dynamic Load/ Strain Measurement System for the wind turbine blades.

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