Review on Design of Horizontal Axis Wind Turbine Blades

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Abstract

Review work is done on the horizontal axis wind turbine blade design. This review work presents the design process of the blade including theoretical maximum efficiency, propulsion, and rotor design aspect. HAWT (Horizontal Axis Wind Turbine) blade design, blade loads, practical calculations have also been provided. The main aim of this review work is to put forth the calculations and design process of a HAWT blade. This work shows the overall picture of the design of the wind turbine blade and other aspects of horizontal axis wind turbine rotors. Aerodynamics is one big part to play a certain role in designing this. The aerodynamic factor is responsible for little to big losses in the work energy and efficiency. A clearer understanding has been put into this work about the airfoil and other aspects that affect the overall efficiency of the HAWT and blade designs. The aerodynamic design notions for a modern wind turbine blade have been detailed, along with the blade plan shape/quantity, as well as airfoil selection together with the optimum angle of attack. A detail of the factors is provided in this work, such as design loads on wind turbine blades that describe aerodynamic factors as well as gravitational, centrifugal and operational conditions.

Keywords: **HAWT (Horizontal Axis Wind Turbine), Airfoil, Blade Loads, Angle of Attack, Design Process**

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INTRODUCTION

Background

Energy is essential to human civilization development. With the progress of economics and socialization, there is an expanding demand for renewable energy resources for securing energy supply, such as solar power, wind power, tide and wave power, etc. As a clean renewable resource, wind power plays a more and more important role in modern life. According to the British Wind Energy Association (BWEA), it was estimated that wind power production met 12.2% of electricity demand in the UK around the end of 2011, and the government aims to reach a target of 20% from renewables in 2020.

Wind energy comes from the transformation of the air that is driven by the heat of the sun, which is abundant, clean and renewable. Being the most popular renewable energy resources, wind power exploitation is growing rapidly. At the beginning of 2006, the total installation of wind turbine capacity reached 59,206 MW worldwide. In June 2011, the total installation of 5,560MW was operational in the UK and it is predicted by Renewable UK that in 2012 the annual wind power capacity will increase to 1.2GW. It was also released by the Global Wind Energy Council that in 2011, a total annual increase in wind power industry reached 41GW worldwide, which is corresponding to annual growth of 21% compared from the previous year. It has been estimated that the global capacity could reach no less than 200GW by 2014. From numbers to worth, wind turbine technology is experiencing great expansion. With the evolution of materials, manufacturing expertise, smart control, and rotor aerodynamics, the rotor diameter of a 5MW wind turbine (Repower) have touched 126 meters. A wind turbine translates kinetic energy into mechanical power through a rotor and then converts the mechanical power into electric power through a generator that is linked to the rotor with and without a gearbox. Various types of wind turbines are designed to take advantage of wind power based on the principles of aerodynamics. Depending on the wind turbine rotor orientation, there are two kinds of wind turbines which are, HAWT (horizontal axis wind turbine) as well as VAWT (vertical axis wind turbine). Generally stating, according to wind turbine capacity (size), modern wind turbines could be categorized as small wind turbines (below 50kW), medium-size wind turbine (50kW~250kW) and large wind turbines (above 250kW). When considering installation sites, there are onshore (freestanding or building-mounted) and offshore wind turbines. Based on the operation scheme, wind turbines could be divided into stall-regulated (fixed-pitch) wind turbines and pitch-controlled (variable-pitch) wind turbines. According to the relative flow direction of the wind turbine rotor, horizontal-axis wind turbines are either upwind or downwind turbines. Most modern HAWTs have three blades; however, there are turbines with two blades. For small wind turbines, there are also turbines with 5 or 7 blades. Three-bladed upwind HAWT is the utmost common topology due to higher efficiency, better-balanced performance, and aesthetic appreciation. Nowadays, offshore pitch controlled giant wind turbines have gained a particular emphasis on the wind power industry and research organizations. A lot of advantages are there of small wind turbines as a fixed-pitch wind turbine because it is still the most popular topologies. These advantages are reliability, easily accessible, well-proven and less costly.

Types of Wind Turbine

The wind has been caused through uneven heating of the earth from the sun making wind a renewable and free source of energy. Wind turbines are an alternate source of energy that harnesses this renewable wind power to make electricity. Since wind turbines run solely on wind, they cause no pollution making them environmentally friendly. The wind turns blades which are connected to a generator; the generator then makes electricity (more on this later). Two main kinds of wind turbines have been presented there, vertical and horizontal axis. A wind turbine made for urban areas was studied as well. The design varies from three types of wind turbines, and different disadvantages and advantages.

Horizontal Axis Wind Turbines

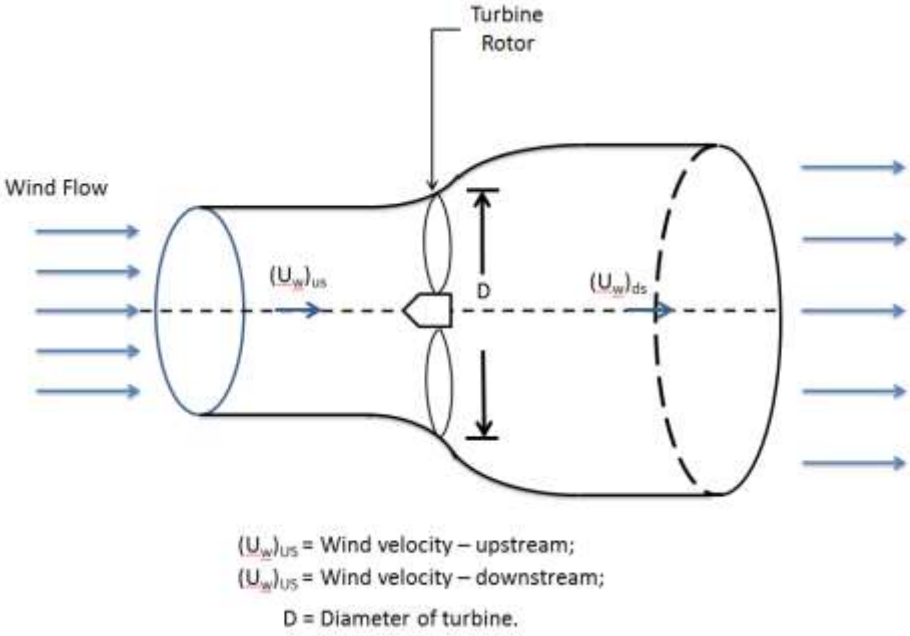
HAWT is the utmost commonly taken in usage kind. All the parts of the turbine (shaft, blades, and generator) are on top of a tall tower, and the blades face the wind front. The shaft is horizontally aligned to the ground. The wind rotates the shaft indirectly as it hits the blades of the turbine and in turn, it rotates the shaft. The shaft has a gear on the end which turns a generator. The generator produces electricity and sends the electricity into the power grid. The wind turbine also consists of some major elements that enhance efficiency. Inside the head (or Nacelle) are wind vane, anemometer, and a controller that notes the direction and speed of the wind. As the direction is changed, a motor (yaw motor) turns the head so the blades always face the wind. The source of power also comes with a feature for safety. At times of extreme winds, the turbine gets a brake that slows down the shaft speed. This is to save any damage to the turbine in the worst conditions.

Vertical Axis Wind Turbines

In vertical axis turbines, the shaft the blades are connected to is vertical to the ground. All of the main components are close to the ground. Also, the wind turbine itself is near the ground, unlike horizontal where everything is on a tower. There are two types of vertical axis wind turbines; lift based and drag based. Lift based designs are generally much more efficient than drag, or ‘paddle’ designs.

The Role of Aerodynamics in Wind Turbine Design

A wind turbine has been a complex system that contains numerous components, involving some electro-mechanical subsystems along with a rotor, transmission system, also a generator, a nacelle, and a tower. The rotor blades are one of the most important components. For transferring wind energy to mechanical power, the design of the blade is done so as an aerodynamic geometry with twist angle and nonlinear chord distributions. The sectioned view of a wind turbine blade is of an airfoil shape (more than one airfoil), which probably generates low drag and high lift forces. The blade shape is a major part as it determines the captured energy, and the loads experienced. The study of the interaction between wind and wind turbines is in actual the aerodynamics of wind turbine which plays a major role in the design and analysis of wind turbines.
Wind turbine aerodynamics is originally from propeller aerodynamics. To introduce wind turbine aerodynamics simply, a “tube” is introduced to explain the flow passing through a rotor in the classical disk theory as shown in Figure 1.



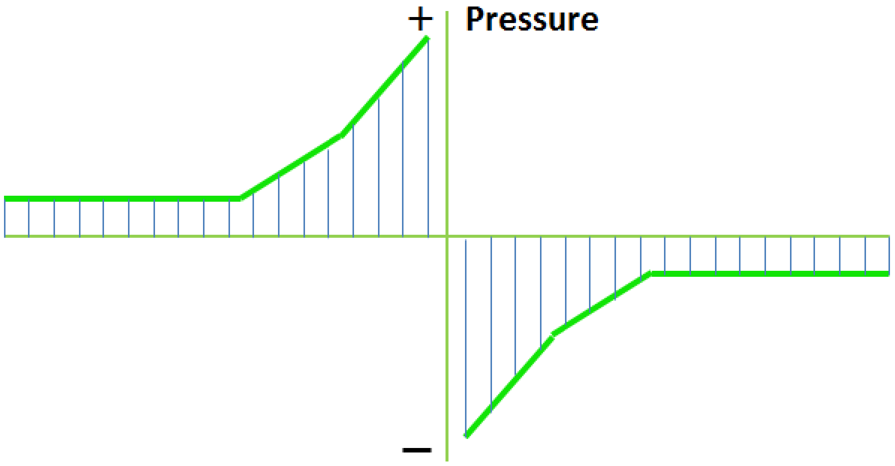


Fig. 1 Rotor Blade and Stream Tube Sketch

http://www.geographynotes.com/energy-management-2/wind-energy/design-of-wind-turbine-rotor-with-diagram-wind-energy-energy-management/4281

LITERATURE REVIEW

(Rehman et al., 2018) [1] gave the overall picture of commonly used techniques, models, tools and approaches to enhance the efficiency of wind turbines. In this review work, specific emphasis is put on approaches that are used to design blades of wind turbines both experimentally and numerically. Methodologies that follow the above approach are active and passive techniques used to increase the power output from wind turbines, reduced cut-in-speed for improved performance of wind turbines, and finally, the research and development work related to finding new and efficient materials for the wind turbines.

(Fernandez-Gamiz et al., 2017) [2] presented the optimal location (position) to improve airfoil aerodynamic performance. Therefore, a dimensional and practical study of a mounted MT on the pressure surface of an airfoil is carried out. This study aims to know the optimal MT dimension and location to ascend airfoil aerodynamic performance and also investigate its effect on the power output of a 5 MW wind turbine. This airfoil got selected as it gets hardly used on a wind turbine, for example, the 5 MW reference wind turbine of the National Renewable Energy Laboratory (NREL). Secondly, computations based on Blade Element Momentum (BEM) have been made to investigate the effect of the MT on the power output of the wind turbine with varying wind speed realizations.

(Pavese et al., 2017) [3] showed that justifying loads on a wind turbine rotor can result in a cost reduction of energy. Sweeping blades creates a structural coupling in amid flap wise torsion and bending, which can be used for load alleviation purposes. A multidisciplinary design optimization (MDO) challenge is framed including the blade sweep as a design variable. A multi-fidelity tactic is used to c antagonize the decisive effects of structural coupling on the educated guess of the loads. During the MDO, extreme and destruction equivalent loads are anticipated using steady-state and frequency-domain–based models, respectively.

(Rocha et al., 2016) [4] presented a standardization study of the k-ω SST turbulence model for gauge wind turbines. To achieve this, two distinct sets of blades were designed, constructed, experimented and simulated. The first set directed the NACA 0012 and the second the NACA 4412 airfoil. The numerical exploration was taken using the CFD (computational fluid dynamics) code Open FOAM and the turbulence model was calibrated testing numerous values for the β*(turbulence modeling constant), counting its canonical value, 0.09. The numerical calibration (the main impact of this paper), stretched previous results, which stated that discrete β*(turbulence modeling constant) values could calibrate the k-ω SST turbulence model for small wind turbines, mostly intended for the drag effects.

(Hu, Choi and Cho, 2016) [5] explained reliability-based design optimization (RBDO) of a 5-MW wind turbine blade for designing dependable as well as cost-effective wind turbine blades. A different dynamic wind load uncertainty model has been created using 249 groups of wind data to contemplate wind load distinction over a huge spatiotemporal extent. The probability of fatigue failure throughout a 20-year service life is assessed using the uncertainty model in the RBDO process and is decreased to meet anticipated target reliability. In the meantime, the price of composite materials used in the blade is minimalized by improving the composite laminate thicknesses of the blade.

(Premkumar et al., 2015) [6] gave a thorough review of the existing state-of-art for wind turbine blade design, counting theoretical utmost efficiency, propulsion, hands-on efficiency, HAWT blade design, as well as blade loads. The evaluation provides an entire picture of wind turbine blade design along with the displays the supremacy of modern turbines nearly exclusive practice of horizontal axis rotors. The aerodynamic design notions for a modern wind turbine blade are described, including blade plan shape/amount, airfoil choice and optimal angles of attack.

(Han et al., 2015) [7] made an effort by designing single-stage horizontal axis wind turbine with a shroud and lobed ejector aimed at the efficient utilization of substandard wind energy by taking into concern the influence of the shroud and lobed ejector. The functioning of the proposed wind turbine was assessed using the commercial software CFX. Simulation outcomes specified that the wind energy utilization efficiency of the proposed wind turbine amplified to 66-73% at low wind speeds stretching from 2 to 6 m/s. It was understood that the complex vortices in the flow field exterior the wind turbine comprised stream-wise vortices, normal vortices following the lobes, and three large scale vortex rings.

(Elfarra, Sezer-Uzol and Akmandor Sinan, 2015) [8] considered the foremost objectives of this report were to aerodynamically design and improve a winglet for a wind turbine blade by operating computational fluid dynamics (CFD) and to inspect its consequence on the power production. To validate and as a baseline rotor, the National Renewable Energy Laboratory Phase VI wind turbine rotor blade is exercised. The Reynolds-averaged Navier–Stokes equations are solved, and k–e Launder–Sharma turbulence model was used. The numerical outcomes have shown considerable conformity with the investigational data. The genetic algorithm was used as the optimization technique with the help of artificial neural web to reduce the computational cost.

(Capuzzi, Pirrera and Weaver, 2014) [9], presented the use of a recent blade as the baseline for an aerodynamic analysis for maximizing the turbine's yielded power in part 1. These outcomes are then spent to detect ideal aeroelastic behavior. In Part II, they make use of material and structural bend-twist couplings in the key spar to bring appropriate differential blade twist, segment by segment, while bending flap-wise.

(Capuzzi, Pirrera and Weaver, 2014) [10] analyzed the essential elastically-induced twist from a structural viewpoint and acclimatized accordingly in part II. Additionally, a blade notion that realizes the desired adaptive behavior is projected and the surge of power harvested is evaluated by an interim structural design.

(Eke and Onyewudiala, 2010) [12] presented a design gizmo for augmenting wind turbine blades. The design model is based on an aerodynamic/aero-elastic code that includes the structural dynamics of the blades and the Blade Element Momentum (BEM) theory. To model the key aero-elastic behavior of an actual wind turbine, the code employs 11 elementary degrees of freedom corresponding to 11 elastic structural equations. In the BEM theory, a refined tip loss correction model is exercised. The purpose of the optimization model is to minimalize the price of energy which is computed from the annual energy production and the expense of the rotor.

(Negm and Maalawi, 2000) [14] defined numerous optimization models for the design of a standard wind turbine tower structure. The principal tower body is counted to be built from unvarying segments where the applicable design variables are selected to be the cross-sectional area, the radius of gyration and the height of the respective segment. The nacelle/rotor blend is regarded as a firm non-rotating mass fastened at the top of the tower. Five optimization strategies are established and tried. The final one regarding the decline of vibration level by the direct intensification of the system natural frequencies works very fine and has shown tremendous results for both tower unaided and the united tower/rotor model.

(Malhotra et al., 2012) [15] defined as the blades are one of the greatest critical components of a wind turbine, illustrative samples must be experimentally verified to confirm that the real performance of the blades is consistent with their specifications. In specific, it must be validated that the blade can endure both the ultimate loads and the fatigue loads to which the blade is anticipated to be subjected throughout its design service life. In general, there are fundamentally two types of blade testing: static testing as well as fatigue (or dynamic) testing. This work comprises a summary review of various utility-scale wind turbine blade testing ways and the initial design study of a fresh concept for tri-axial testing of large wind turbine blades.

(Jureczko, Pawlak and Mężyk, 2005) [16] focused to achieve the highest conceivable power output under definite atmospheric conditions while designing a wind turbine. From the technical opinion, this depends on the profile of the blade. The alteration of the shape of a blade is one of the approaches to modulate stiffness and stability, but it may affect the aerodynamic efficiency of the wind turbine. Another approach to alter the dynamic and mechanical properties of the wind turbine is altering the composite material, which the blade is formed of. The challenge of determining the optimal shape of a blade and deciding the optimal composite material is an intricate one, as the mathematical description of the aerodynamic load is complicated and several constraints and purposes have to be fulfilled.

(Johansen et al., 2009) [17] described the design of a three-bladed wind turbine rotor where the major focus has been uppermost possible mechanical power coefficient, C_P, at a single operational condition. Structural, along with off-design, issues are not pondered, leading to an entirely theoretical design for examining maximum aerodynamic efficiency. The rotor is designed supposing constant induction for the utmost of the blade span, but nearby the tip region, an invariable load is assumed in its place. The rotor design is attained using an actuator disc model and is then verified using both a free-wake lifting line approach and a full three-dimensional Navier–Stokes solver.

(Hirahara et al., 2005) [18] showed tests of the energy amount produced, turbine speed, power coefficient, and torque of the turbine were conveyed for a wide range of unrestricted stream velocity. The flow around the wind turbine and the impact of the turbulence were scrutinized with a particle image velocimetry. The experimentally attained power coefficient was 0.4 in the highest and 0.36 in the rated running condition, correspondingly. The tip speed ratio conforming to the optimum driving condition was 2.7.

(Det Norske Veritas, 2010) [19] provided principles, technical conditions, and direction for the design and manufacture of wind turbine blades. This standard aims to deliver the design and manufacturing requirements for wind turbine blades subject to DNV certification. A recommendation for designers, manufacturers, operatives, and controllers of wind turbines.

(Chen, Agarwal and Louis, 2013) [20] showed that FX, DU, and NACA 64 series airfoils are thick airfoils extensively used for wind turbine blade purposes. They have numerous advantages in getting the intrinsic conditions for wind turbines in terms of design point, off-design capabilities, and structural properties. This paper utilizes a multi-objective genetic algorithm for shape optimization of FX, DU, and NACA 64 series airfoils to achieve two objectives, namely, the generation of both maximum lift and maximum lift-to-drag ratio.

METHODOLOGY

Horizontal axis wind turbine goes from a process of steps for designing. Without having prior knowledge of these steps and requires the technical aspect of these things, it might get so fuzzy and complicated. A regular wind turbine design process is explained in Fig. 2, where the aspects involved in the design process and their relationship are depicted. The design process is composed of three main models which are an aerodynamic model, a structure model and an economics model (cost model). These three models form the mainframe of wind turbine design. Among the three models, the aerodynamic model is the most fundamental one which determines the power extracted and the loads underwent. As a result, the AEP, the Cost of Energy (CoE) and the lifetime of a wind turbine are all affected by the aerodynamic model used. In a word, the aerodynamic model has great importance on the design of wind turbine rotor blades and other components and subsystems. An accurate aerodynamic model is the first consideration in the wind turbine design process.

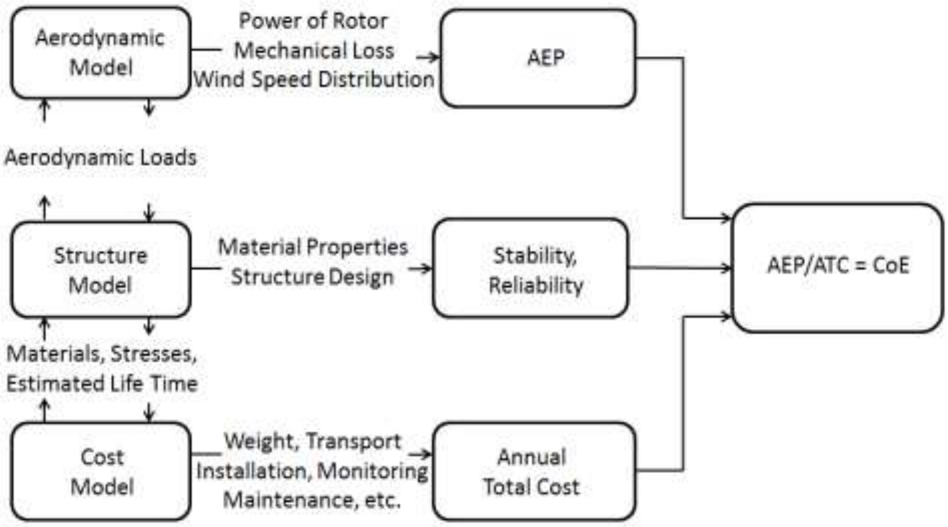


Fig. 2 Design Process of Wind Turbine

Difference Forces acting

1. Axial Thrust - It works in the similar direction as that of the flowing wind course.
2. Circumferential Force - It works in the path of wheel rotation that delivers the torque.
3. Force on Turbine Rotor - A turbine takes out wind energy, causing the variance in the momentum of air streams amongst the upstream and down-stream sides as shown in Fig. 3.

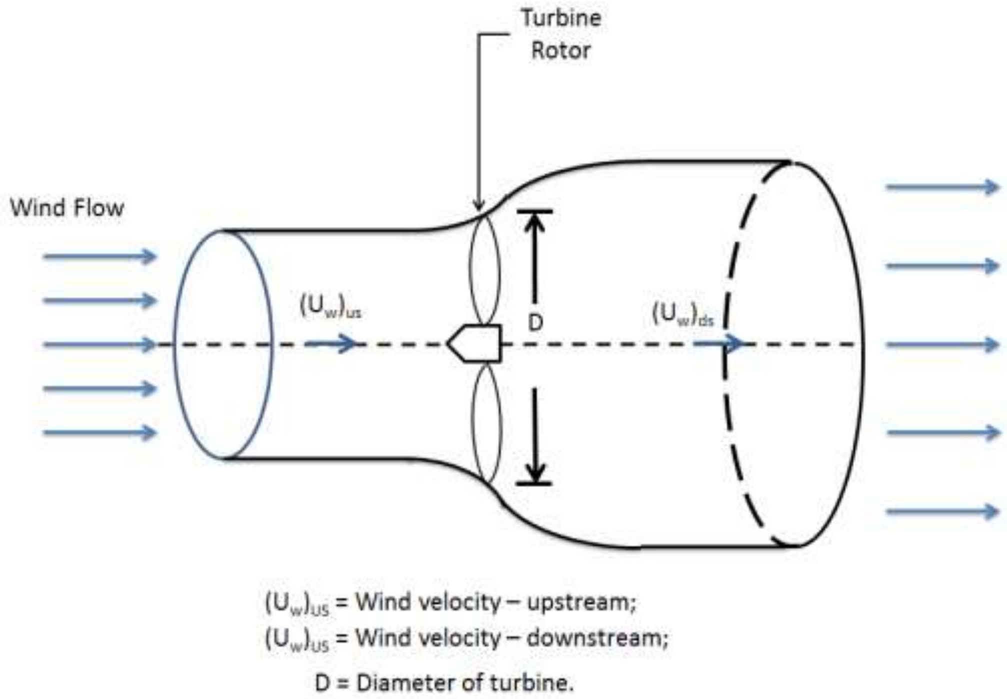


Fig. 3 Force on Turbine Rotor

Actual Force,

$$F_x = \rho A_{bl}(U_u)_{bl}[(U_u)_{us} - (U_u)_{ds}]$$

$$= F_x + \rho A_{bl} \frac{[(U_u)_{us} + (U_u)_{ds}]}{2} [(U_u)_{us} - (U_u)_{ds}]$$

Or

$$F_x = \frac{1}{2} \rho \frac{\pi}{4} D^4 \left[(U_u)_{us}{}^2 - (U_u)_{ds}{}^2 \right] \tag{1}$$

$$F_x = \rho \frac{\pi}{8} D^2 \left[(U_u)_{us}{}^2 - (U_u)_{ds}{}^2 \right] \tag{2}$$

For maximum output

$$(U_u)_{bl} = \frac{1}{3} (U_u)_{us} \tag{3}$$

$$F_{x(max)} = \rho \frac{\pi}{8} D^2 \left[(U_u)_{us}{}^2 - \frac{1}{9} (U_u)_{ds}{}^2 \right]$$

$$F_{x(max)} = \rho \frac{\pi}{9} D^2 (U_u)_{us}{}^2 \tag{4}$$

Eqn. (4) specifies that for designing a wind energy generator (WEG) a big axial force can be attained by using huge diameter turbines. The higher limit of the diameter demands to be optimized by corresponding structural design with the economy.

Blade Plan Quantity and Shape

The perfect plan form of a HAWT rotor blade is well-defined using the BEM method by computing the chord length conferring to Betz limit, local air velocities and airfoil lift. Several theories occur for computing the optimum chord length which fluctuates in complexity, with the plainest theory built on the Betz optimization. For blades with tip speed ratios of six to nine operating airfoil sections by negligible drag and tip losses, Betz's momentum theory gives a decent approximation. In occurrences of low tip speeds, high drag airfoil sections along with blade sections all around the hub, this approach could be considered imprecise. In such instances, wake and drag losses must be accounted for. The Betz method delivers the fundamental shape of the modern wind turbine blade. Though, in exercise more advanced approaches of optimization are frequently used.

$$C_{opt} = \frac{2\pi r}{n} \frac{8}{9C_L} \frac{U_{wd}}{\lambda V_r} \tag{5}$$

Where

$$V_r = \sqrt{V_w^2 + U^2}$$

r = radius (m)
n = Blade quantity
C = Lift coefficient
λ = Speed ratio of Local tip
V_r = Local resultant velocity of air (m/s)
U = wind speed (m/s)
U_{wd} = Design wind speed (m/s)
C_{opt} = Optimum chord length

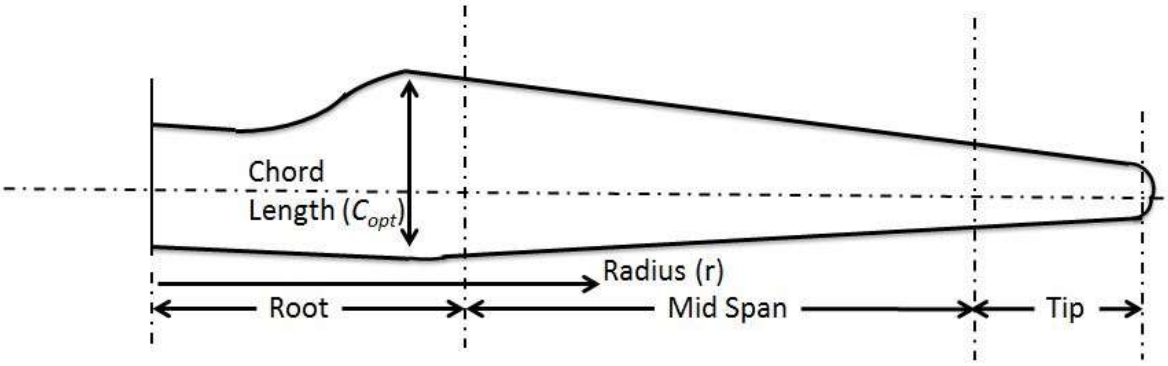


Fig. 4 A Standard Blade Plan and Region Classification

Supposing that a realistic lift coefficient is upheld, utilizing a blade optimization approach produces blade plans mainly dependent on the design tip speed ratio and quantity of blades. Low tip speed ratios produce a rotor with an elevated ratio of solidity, which is the proportion of the blade area to the swept rotor area. It is beneficial to decrease the area of solidity as it advances to a lessening in material usage and therefore production budgets. Though, problems are related to high tip speeds.

Aerodynamics

Aerodynamic performance is fundamental for efficient rotor design. Aerodynamic lift is the thrust responsible for the power yield produced by the turbine and it is so essential to amplify this force using appropriate design. A strong drag force that opposes the motion of the blade is also produced by friction which must be lessened. It is then apparent that an airfoil section with a high lift to drag ratio [Equation (6)], typically greater than 30, be chosen for rotor blade design.

$$Lift\ to\ Drag\ Ratio = \frac{Coefficient\ of\ lift}{Coefficient\ of\ drag} = \frac{C_L}{C_D} \tag{6}$$

The co-efficient aimed at the lift and drag of airfoils is hard to predict mathematically, even though freely available software, for instance, XFOIL model results correctly with the exclusion of post-stall, extreme angles of attack and airfoil thickness conditions. Traditionally airfoils are verified experimentally with tables associating lift and drag at given angles of attack and Reynolds numbers. In history, wind turbine airfoil designs have been rented from aircraft technologies with similar Reynolds numbers and section thicknesses suitable for conditions at the blade tip. However, special considerations should be made aimed at the design of wind turbine specific airfoil profiles due to the differences in operating conditions and mechanical loads.

The angle of attack is the angle of the oncoming flow relative to the chord line, and all figures for CL and CD are quoted relative to this angle. The use of a single airfoil for the entire blade length would result in inefficient design. Each segment of the blade has a varying relative air velocity and structural prerequisite and so should have its airfoil section tailored correspondingly. At the origin, the blade sections have an enormous minimum thickness which is vital for the thorough loads carried causing in thick profiles. Advancing the tip blades merger into thinner sections with decreased load, greater linear velocity, and more and more critical aerodynamic performance. The differing airfoil requirements relative to the blade region are apparent when considering airflow velocities and structural loads (Table 1).

Table 1. Blade Position on different Parameters

Parameter	Blade Position		
	Root	Mid Span	Tip
Thickness to chord ratio (%)	>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 Airroil Noise			High

The sensitivity of blades to dirtying, off-design conditions counting stall and thick cross-sections for structural reasons are the main driving thrusts for the growth of wind turbine particular airfoil profiles. The use of up-to-date materials with high-class mechanical properties may permit for thinner structural sections with an amplified lift to drag ratios at root sections. Thinner sections also bid a chance to surge efficiency through sinking drag. Elevated lift coefficients of thinner airfoil sections will in turn advance to condensed chord lengths decreasing material usage.

CONCLUSIONS

This review paper explains various aspects of designing of Horizontal Axis Wind Turbine Blade. The necessary calculations and terminologies that have been put in this paper explain the whole of the horizontal axis wind turbine. A clearer understanding is given about the technical and other aspects of the blade of the horizontal axis wind turbine. The literature review explains a variety of aspects and different research works over the relevant topics of horizontal wind turbine blade design. In different directions, this exploration has been done through different literary works of recent times. Through this review work, designing of the blade of the horizontal axis wind turbine has been made to take it to further steps.

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