Study of Functional and Airodynamic Design with Blade Parameters of NACA Series (NACA 4412)

R.K. Rathore
Department Of Mechanical Engineering
Christian College of Engineering And Technology,
Bhilai, India

Gagan Sahu
Department Of Mechanical Engineering
Christian College of Engineering And Technology
Bhilai, India

Amit Singh Dhakad
Department Of Mechanical Engineering
Christian College of Engineering And Technology
Bhilai, India

***Abstract*- Wind turbines are the one of the solutions for the today's energy crisis in the world. In India plays a significant role in renewable energy generation as it covers more than 70% of the energy generated by the renewable energy sources. Still we have wind turbine with comparatively less efficiency. For improvement in performance of wind turbine we need to develop some technique for performance prediction of the wind turbine. The development of performance prediction is one of the most important aspects of the design of wind turbines. An established methodology is used to calculate the optimal performance parameters of the horizontal axis wind turbine in provisions of the most vital parameters such as tip speed ratio, blade number, pitch angle and wind speed in this paper. Our estimated Result will show that low pitch is recommended for low wind speed regime. Optimum value of tip speed ratio is found within a range of (5 to 11) within the constraints considered. The cut in speed with the remaining parameters is also studied and their effect on power and torque are explored.**

Keywords: - HAWT (horizontal axis wind turbine), parameters, BEM (blade element moment theory), NACA4412, Functional And Airodynamic Design

I. INTRODUCTION

Wind turbine gains energy from wind by means of its blade thus it makes blade as a key element. It converts kinetic energy of wind in to rotational energy afterwards by the help of generator we convert it in to electricity. Aerodynamic shape optimization is one of the main research fields which are directly related to power production of a wind turbine. The optimum distributions of the pitch angle and the chord length in each section can be acquired with the help of the design parameters, which comprise the measured wind speed, blades number, design angle of attack and design tip speed ratio [2]. Operating at low cut-in wind speeds has been made probable by aerodynamic optimization of the rotor blades which is the mainly significant part of a wind turbine [4, 5]. Aerodynamic optimization of the rotor blades is associated with optimization of the chord and twist distribution, choice of airfoil shape, number of blades, and the tip speed ratio (TSR) [6]. C. J. Bai, et al. [3] presented design of horizontal-axis wind turbine blade and aerodynamic investigation using numerical simulation using BEM theory for S822 aerofoil. BEM theory usually is uses for evaluating the forces on the wind turbine in its design and optimization [7]. Ozge Polat and Ismail H.Tuncer has present parallel genetic algorithm to optimize blade shape at prescribed wind speed, rotor speed, rotor diameter and number of blades of four digit NACA profile of a wind turbine [8].

a. Functional Design

Functional design is carried out by the considering the use of the electrical appliances to meet the need of the household purposes in the rural sectors. The rotor diameter (d) is calculated from the basic Eq. (1) of wind power (P) at rated wind speed (v),

$$\mathrm{P} = \mathrm{C_p}\frac{1}{2}\ \rho\ \eta_{all}\ \left({}^{\pi}\!/_{4}\, d^2\right)\ \mathrm{V}^3$$

For 600 W power output required blade length calculated as 800 mm by considering various efficiencies of the system components.

II. VARIOUS DESIGN PARAMETERS

a. Lift, drag and moment coefficients

In general, there are two forces and one moment that acts upon an aerofoil; pitching moment, lift and drag.

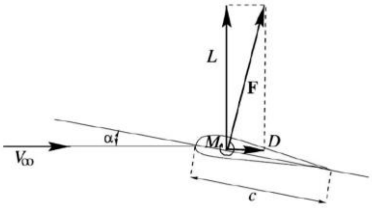

Figure 1. lift and drag on an aerofoil

For an aerofoil lift to drag ratio should be maximized. Lift and drag coefficients C_L and C_D [11] are:

$$\mathrm{C_L} = \frac{F_L}{{}^{1}\!/_{2}\rho V_o{}^2\, c} \tag{1}$$

$$\mathrm{C_D} = \frac{F_D}{{}^{1}\!/_{2}\rho V_o{}^2\, c} \tag{2}$$

Where ρ the density of air and c is is the aerofoil length, known as chord, unit for the lift and drag is N/m (SI units). We need to know pitching moment M to describe the forces completely. Which is found both theoretically and experimentally that, if the aerodynamic force is working at a location ¼ th length of chord from the leading edge on most low speed airfoils, the amount of the aerodynamic pitching moment remains nearly stable with angle of attack? In most aerofoil simulations, the pitching moment centre is set up at ¼ chord length to get an approximate value and the pitching moment coefficient is defined as follows.

Moment coefficient

$$C_M = \frac{M}{{}^{1}/_{2}\rho {V_o}^2\, c} \qquad (3)$$

b. Tip speed ratio

The tip speed ratio is the ratio of the blade tip speed over wind speed. It is a significant parameter for wind turbine design and its definition is shown in equation 4.

$$\lambda = \omega R/V_0 \qquad (4)$$

ω is the angular velocity of the wind turbine rotor, R is radius of the rotor and V_o is the wind speed. Generally a low speed wind turbine chooses value of tip speed ratio from 1 to 4 and a high speed wind turbine decided its range from 5 to 9.

As a preliminary design concept, the best value of tip speed ratios for a high speed turbine is about 7 [11], which ensure that the wind turbine can run at near maximum power coefficient. The relationship between rotational speed and tip speed ratio is shown in Equation 5.

$$\lambda = \frac{2\,\pi n r}{60\,V_o} \qquad (5)$$

Where n is the rotational speed of the rotor, r is the rotor radius and V_0 is the wind speed. For instance, if tip speed ratio is 8, the rotor radius is 9m and speed of wind is 10m/s, then the revolving pace of the rotor should be 85 rpm using Equation 6.

$$n = \frac{60\lambda V_o}{2\pi r} \qquad (6)$$

Thus, an inverse relationship between the rotational speed and the blade span is presented in this equation. Due to the same tip speed ratio, a blade with a big span has a low rotational speed. What's more, taking into account of the structural design of blades, elevated rotational speed needs a highly considerable structure, which outlay too greatly to build and induces huge noise.

c. Betz limit

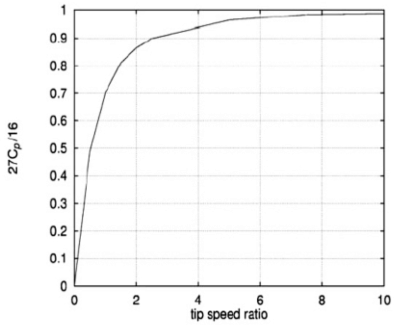

Figure 2. The efficiency of an optimum turbine with rotation

The efficiency is defined as the ratio between power coefficient *Cp* and the Betz limit, Betz = 16/27 ≈ 0.593. This value was concluded by **Albert Betz** who was a German physicist in 1919, 0.593 is the upper limit of power efficiency of a wind turbine which changes the kinetic energy to mechanical energy, So efficiency $\eta = \frac{C_p}{{}^{16}/_{17}} = \frac{C_p \times 17}{16}$. Seeing from Figure 2, the power loss is big for a low tip speed ratio wind turbine. A running wind turbine can only accomplish 85% efficiency when the tip speed ratio is 2. The system will become more and more efficient if the tip speed ratio is higher. When the tip speed ratio reaches to 6, the efficiency is approximate 96%. It indicates that wind turbines with high tip speed ratio can extract more kinetic energy from wind by comparing with low tip speed ratio wind turbines.

d. Blade element momentum theory (BEM)

With this theory, it is possible to calculate the steady loads and also the thrust and power for different settings of wind speed, rotational speed and pitch angle. As shown in Figure 3, for illustration purpose, the blade is assumed to be divided into N sections or elements and the following assumptions are made:

1. Every element is independent; a variation in one element will not affect other elements.
2. The force from the blades is determined individually by the lift and drag of the airfoil shape of the blades.

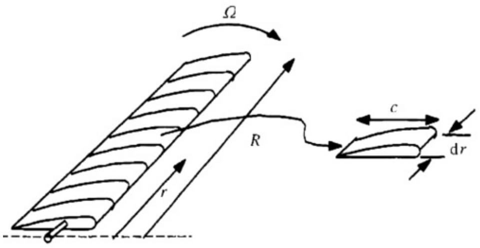

Figure 3. Schematic of blade elements; c, aerofoil chord length; d_r, radial length of element; r, rotor radius; Ω, angular velocity of rotor

In order to get good results when using BEM method, it is necessary to apply two important corrections below. [11]

The first is called Prandtl's tip loss factor, which corrects the assumption of an infinite number of blades. The second correction is called Glauert's correction and is an empirical relation between the thrust coefficient $\mathbf{C_T}$ and the axial induction factor a when value is greater than approximately 0.3.

e. Aerofoil Behaviour

Before introducing the aerofoil behaviour, Mach number and Reynolds number need to be explained. Mach number is a proportion of speed of an object with sound and it is defined as:

$$M_a = v_s / u_c \qquad (7)$$

Where M_a is mach number, v_s is object speed and u_c is sound speed. Subsonic is defined as $M_a \leq 1$, transonic is defined as $M_a = 1$, supersonic is defined as $M_a \geq 1$ and hypersonic is defined as $M_a \geq 1$. The Reynolds number is a non-dimensional value and it is a ratio of inertial force to viscous force is defined as:

$$\mathrm{Re} = \frac{{}^{\rho v^2}\!/_{L}}{{}^{\mu V}\!/_{L^2}} = \frac{\rho V L}{\mu} \qquad (8)$$

III. AERODYNAMIC DESIGN

All the parameters which are related to the Aerodynamic such as the Chord Length(C), Relative angle (Φ), Local Radius (r), Angle of attack (α), Reynolds Number (Re), Coefficient of lift (CL), Coefficient of drag (CD) (Corresponding to the Re), Solidity (σ), Axial Induction Factor (a), Radial Induction Factor (a') and Coefficient of power (Cp) by using the Blade Element Momentum Theory [9, 11, 14]. Blade is divided in ten elements. The relative angle is calculated by equation (9) as

$$\phi = \tan^{-1} {}^{2}\!/_{3\lambda_r} \qquad (9)$$

The chord length at each station is calculated from equation (10) as

$$C = {}^{16\,\pi}\Big/_{9N\frac{\lambda\sqrt{4}}{9} + \left[\lambda_r + 21\,(9\,\lambda_r)\right]^2} \qquad (10)$$

Reynolds Number is given by Eq. (11),

$$\mathrm{Re} = \nu \times \lambda_r \times {}^{C}\!/_{1.5 \times 10^{-5}} \qquad (11)$$

Coefficient of Lift and Coefficient of Drag are taken from the chart and by using interpolation for corresponding Reynolds Number and angle of attack calculated the values of the same. The solidity is calculated by equation (12) as

$$\sigma = {}^{B \times C}\!/_{2\,\pi r} \qquad (12)$$

The axial induction factor (a) and radial induction factor (a') are given by Eq. (13) and Eq. (14) as:-

$$a = {}^{1}\Big/_{1 + \frac{1+4F\sin^2\phi}{\sigma C_L \cos\phi}} \qquad (13)$$

$$a' = {}^{1}\Big/_{\frac{4F\cos\phi}{\sigma C_L}} - 1 \qquad (14)$$

After calculating the axial and radial induction factor, relative or blade in-flow angle is again calculated from equation (15),

$$\tan\phi = 1 - {}^{a}\!/_{(1+a')\lambda_r} \qquad (15)$$

Then, through multiple iterations calculates Axial and Radial Induction Factors, blade inflow angle for the greater accuracy and to get small change in the angle of attack. It is further used to calculate the Coefficient of Power (*Cp*) by Eq. (16)

$$\mathrm{Cp} = \frac{8}{\lambda}\left[\frac{F\sin^2(\cos\phi\,(\cos\phi - \lambda_r \sin\phi)\,(\sin\phi + \lambda_r\cos\phi\ )}{\left(1 - \frac{C_D}{C_L}\cot\phi\right)\lambda_r{}^2}\right] \qquad (16)$$

Following these steps, through multiple iterations aerodynamic parameters can determined.

IV. OPTIMIZATION OF THE WIND TURBINE

The optimization with the objective of enhancement of power performance and low speed starting behaviour is carried out. For Optimization we have used the Betz- Joukowsky Limit Theory. Reynolds number and solidity are calculated by Eq.4 and Eq.5. The axial force coefficient (*Ca*) and tangential force coefficient (*C'a*) are given by equation (17) and equation (18)

$$C_a = C_L \cos\phi + C_D \sin\phi \qquad (17)$$

$$C_a' = C_L \sin\phi - C_D \cos\phi \qquad (18)$$

For Tip Loss Correction, two intermediate factors Y_1 and Y_2 are given by Eq. (19) and Eq. (20),

$$Y1 = {}^{4F\sin^2\phi}\!/_{\sigma C_a} \qquad (19)$$

$$Y2 = {}^{4F\sin\phi\cos\phi}\Big/_{\sigma C_a{}'} \qquad (20)$$

Axial and Radial Induction Factors are determined by Eq. (21) and Eq. (22)

$$a = {}^{2 + Y_1 - \sqrt{\left[4\,Y_1(1-F) + Y_1{}^2\right]}}\Big/_{2\,(1+FY_1)} \qquad 21$$

$$a = {}^{1}\Big/_{\frac{2\,(1-aF)Y_2}{(1-a)}} - 1 \qquad 22$$

Relative angle is given by Eq. (9) and twist angle of blade element is given from equation (23) as

$$\theta_P = \phi - a \qquad (23)$$

The coefficient of power is given by Eq. (16). Blade optimization is achieved through multiple iterations.

V. DISCUSSION

In this paper we have discussed various design parameters of the aerofoil which is used to analytically obtain parametrical data for any horizontal axis wind turbine which will be used to simulate the wind turbine blade aerofoil NACA 4412 for output generation. By means of suitable algorithm we will optimize the blade parameter which will give us a modified aerofoil shape; then again analysis will be carried out on the obtained aerofoil. expected outcome is modified blade profile will give more value of power coefficient which will give us higher value of efficiency in terms of power carried out by the blades of wind turbine.

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