

Numerical Modelling and Design of Horizontal-Axis Wind Turbine Blade for Low Wind Speed Regimes

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Abstract - In this paper a set of 3 aerofoils of the NWT family designed by National Aerospace Laboratories (NAL) has been modified. The modified aerofoils are NWT 1001, NWT 2004, and NWT 2005. The main purpose of modifying is to shoot the low wind speed regimes hence to get more coefficient of lift and less coefficient of drag. These new modified aerofoils are numerically modeled, and are used to design a blade of 2.5m radius. Since aerofoils play a very important role in blade design and its enhancement in the power production of wind turbine in the low wind speed conditions makes the design unique. The comprehensive study of modified NWT aerofoils and its geometrical optimization are scrutinized to improve the coefficient of performance of the blade with the Reynolds number in the range of 250000. The Dual Evolutionary method is used to optimize the blade. The proposed design is very simple and more suitable for Indian low wind speed regimes.

Keywords- *Modified NWT aerofoils, Blade design, Numerical modeling, Computational fluid dynamics, Optimization.*

1. Introduction

Now a days awareness among the people for increasing amount of greenhouse gases, global warming and rise in the cost of fossil fuels have led to a notion towards investing into low-cost small wind turbines., compact designed, Simple in structure, sturdy and reduced noise levels[2], the horizontal axis small wind turbines are now prominent wind power extracting devices in the suburban, rural and in the widely populated areas where installation of large scale wind turbines would not be accepted due to space constraints and generation of noise. When compared to large wind turbine coefficient of power value of 0.5, the small wind turbine will have a low coefficient of power values of around 0.3. The available wind turbines in India are mostly of imported technology and design. Many a time it feels that their performance characteristics are not well suitable for Indian wind condition. Even though India is one of the leading countries in wind power production, it is very necessary that the technology for wind power production should be based on Indian wind condition. Attention should be specially given to the flow patterns importantly around the stall point and at high angles of attack. This knowledge is essential for the understanding of its starting capability and low speed performance. But in India the

resources about the high angle of aerodynamics is limited, hence the wind turbine designers will be benefited from this experimental study. The mentioned modified blades belong to the stall regulated class of wind turbine. An aboriginal wind turbine blade has been evaluated for angles of attack range from -180° to 180° using low Reynolds number. [1].

It is possible to get the rapid development and comparison with the combined effect of both blade element theory and the blade momentum theory within the balance limit of single or multiple stream tubes in wind industry. Also, the usage of the analysis technique which is of the accuracy in the lower order helps in the initial designing of wind turbine and further analysis can be done by the very improved and trailblazing techniques of CFD. The validation of this improved computational viable method of engineering sciences with the wind tunnel values and the measurements obtained from the field will judge or qualifies their application to perform the analysis of the rotor from a very simplified 2D aerofoils view point.

2. Aerofoil Design and Analysis

Since it is the modified version of the already designed and experimentally analysed aerofoils, hence the blade element method as well as the blade momentum theorem will be applicable. The main purpose of the design of the new modified version is that the increase in the coefficient of lift and the decreasing Amount of the drag coefficient. The algorithms of BEM and blade momentum theorem algorithms are applied to simulate a wind turbine, the required lift and drag coefficients over different angles of attack (AOA) data are obtained from the experiments or through two dimensional flow simulations. The numerical modelling is carried out to compute the flow around subsonic isolated aerofoils. It combines a high-order panel method with a fully coupled viscous/in viscid interaction method.

2.1. Extrapolating Lift and Drag Coefficients to 360° Angle Of Attack

The higher flow angles in the root region is because of the reason that the mean wind velocity remains constant since the rotational

speed is more experienced by the blade tip Unlike airplane wings, wind turbine blades experience stalled operation. To overcome or avoid this angle of attack is kept constant throughout the blade but practically this is not possible so that where the concept of optimal twist came into existence. Hence the blades are inwardly twisted rather than the twist outwardly.

The predictions of separation and transition are of special interest.

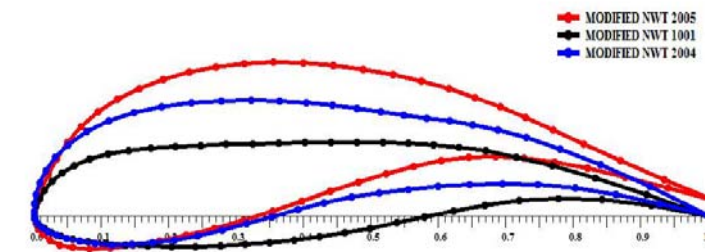


Fig.1: Modified NWT 1001, NWT 2004 and NWT 2005 Aerofoils.

On a condition that the pitch is zero, we have to consider the cases for different and wider range of angle of attack. Beyond stall, it is very difficult to find the behaviour of the aerofoil characteristics even though there is a numerical or experimental methods exists that too including the viscous effects which is nothing but trivial. Due to the high blockage for the high angle of attacks in the wind tunnel measurements, hence the potential flow theory methods will be used which includes the viscous effects by semi empirical models like XFOIL. We have to address this problem by considering the characteristics of the aerofoil which is used for normal operation by extrapolating the values obtainable by using the flat plate theory. This creates a similarity between a flat plate and an aerofoil at high angles of attack and this method is referred as Viterna method. In case of wind turbines, the root region is considerably thick. In order to obtain the extrapolation, we need to apply the method of curve fits to the completely stalled polar curves of a thin plate. We have to then assume that at high AOA an aerofoil behaves very much like a thin plate with a sharp leading edge. There are two different techniques of proceeding with this extrapolation which can be implemented in numerical modelling. Viterna-Corrigan post stall model [8] which is mostly used by the industry helps in the extrapolation of Polar. The model of Montgomerie which is recently developed can also be applied for the above operation.

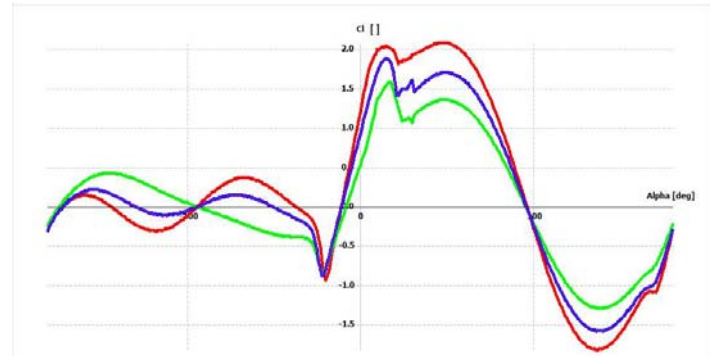


Fig.2: The -180° to 180° polar curve of coefficient of lift v/s A.O.A of modified NWT aerofoils

The shape factor depending upon the momentum thickness and energy equation determines the prediction of separation. (Note that this shape factor has the opposite tendency of the shape factor based on displacement and momentum thicknesses. [2]). There is no such different and relatively reliable limit exists for turbulent boundary layers, It has been assumed that, if the shape factor falls below 1.46 the turbulent boundary layer will separate and will not separate if the shape factor remains above 1.58. one more important assumption is that if the boundary layers are thick the separation will occur at lower shape factors.

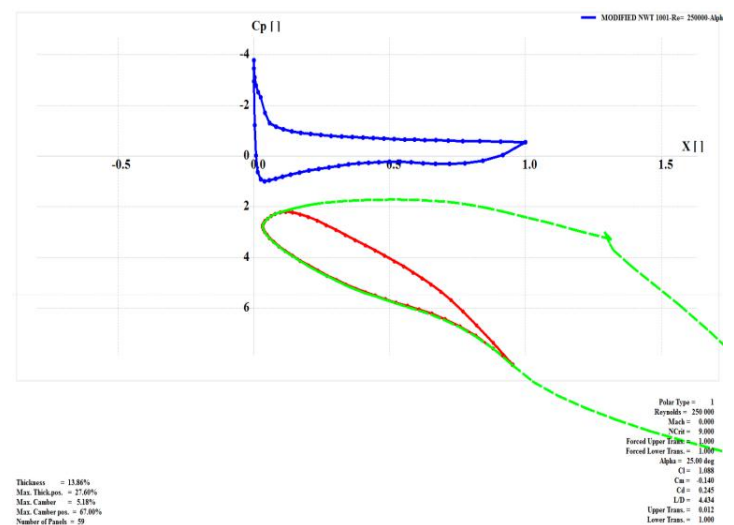


Fig.3: Variation of boundary layer on modified NWT 1001 aerofoil at an angle of 17°

The sudden change in the shape factor rapidly near separation is due to uncertainty which is not a significant disadvantage.

2.2. Boundary-Layer Method

The development of Laminar-Turbulent theorem is basically derived from the momentum and energy equations using integration. The approximate solutions obtained from the laminar boundary-layer method agree very well with exact solutions. The shape-factor laws empirical skin-friction and dissipation are the bases for the turbulent boundary-layer method.

But still the, results must be carefully evaluated with respect to turbulent separation.

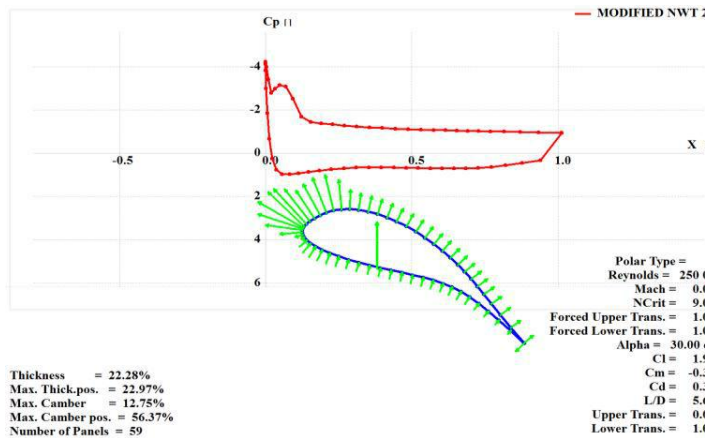


Fig.4: Variation of pressure on the modified NWT 2005 aerofoil at an AOA of 15°

3. Aerodynamics

Numerical simulation uses the aerodynamic model which contains the indications of many variety aerodynamic effects on a horizontal axis wind turbine which is shown below. Wake modelling, static and dynamic aerofoil dynamics, yawed inflow, tower shadow, and atmospheric turbulence effects are the major considerations.

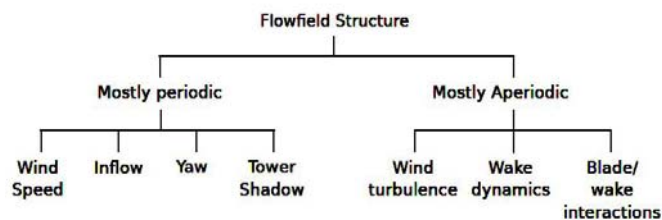


Fig.5: Aerodynamic model of the numerical simulation

3.1. Blade Element Momentum Theory (BEM)

Lot of discussions have been done from several years about the blade element theory and blade momentum theory. Strictly speaking the BEM is based on two important assumptions, that each blade element cuts the rotor discs annular ring section. And said earlier it is the integration of the single annular rotor section of sections of blade to calculate the overall performance. Blade element and momentum theory (BEM) The combination of the blade element theory with a momentum theory allows the calculation of the induction factors a and $a0$, which are necessary to determine the incident velocity W in the

rotor plane. Optimum axial induction factor helps in calculating the maximum coefficient of power. The Betz limit is the maximum coefficient of power [3]. It is observed that airflow possessing higher thrust will result in increase of axial induction factor above the optimum value. The deflection of air from the turbine will be more due to the higher thrust. If the wind turbine is not extracting all the power it symbolizes that the axial induction factor is below the optimal level. As a result the pressure reduces around the turbine, hence allowing most of the air to proceed across the rotor. But it is not ample to adjudge for inadequacy of energy being harvested. It is deduced that the annulus swept by the element is accountable for the change of momentum of the air, which travel through each element of the blade [8].

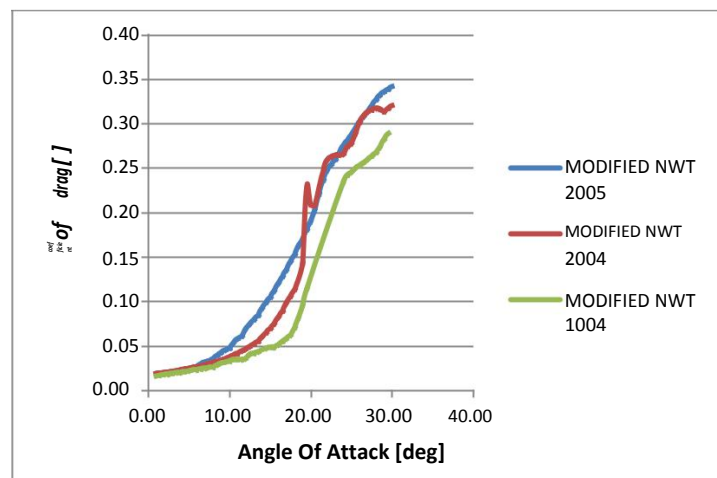


Fig.6: Coefficient of drag v/s angle of attack of modified NWT aerofoils

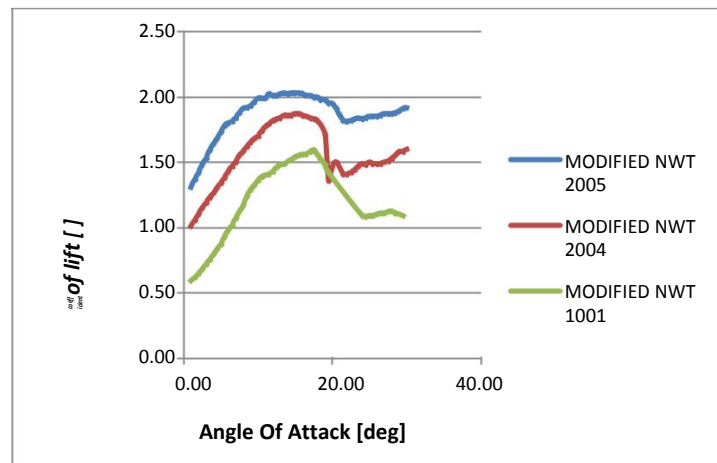


Fig.7: Coefficient of lift v/s angle of attack of modified NWT aerofoils.

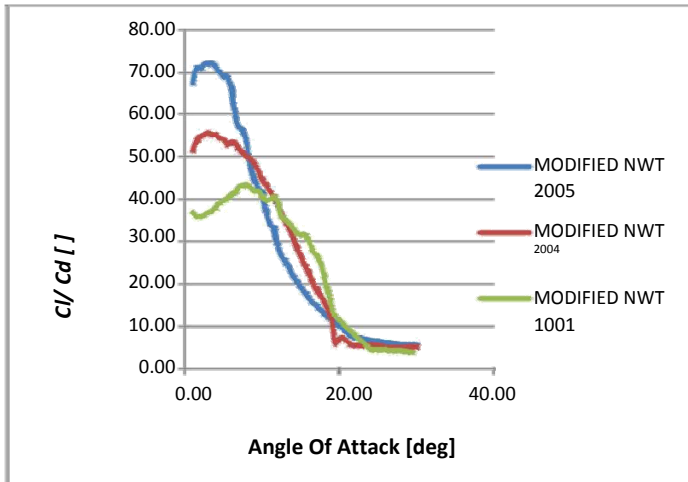


Fig.8: Cl/Cd v/s angle of attack of modified NWT aerofoils

4. Blade Design and Optimization

The lift and drag forces and also the pitching moment are determined for each element, when the blade is divided into number of blade elements. The local blade element coordinate system come into existence when the computation of the two dimensional local blade element formulation. Thus the accumulation of the all velocities of each element is expressed in the same local coordinate system. And hence the resulting velocity W along with the total resulting inflow angle of attack is found out. The main advantage of the polar tables comes here by using each lift coefficient C_l , drag coefficient C_d , and moment coefficient C_m the final elemental forces can be calculated[4]. Then the integration is performed over the forces of each blade of the rotor. Next step involves updating the dynamic directions of the blade through the involvement of structural model and in the next time step progress is made on wind turbine structure. These activities result in the change of the local element velocities thereby again producing a change in blade element aerodynamics.

4.1. Optimal Chord Length

Chord length is one of the important parameter in the blade design and the optimal chord length is the main parameter in the blade optimization. For optimal chord calculation Betz equation and Schmidt equation is the basic later this equation is modified by Burton and woods. This design of blade is based on the wood equation. It is given as follows [3]

$$c = (16 \cdot 3.142) / (9 \cdot N \cdot \lambda \cdot \lambda_r \cdot C_l) \quad (1)$$

Local tip speed ratio

$$\lambda_r = (\lambda \cdot r) / R \quad (2)$$

Since the maximum coefficient of lift is known for each aerofoil and blade radius is known hence it is very easy to calculate the blade chord. Without the knowledge of this it is very difficult to stack the aerofoils in the blade.

	Pos (m)	Chord (m)	Twist	Foil	Polar	
1	0.00	0.15	0.00	Circular Foil	CD = 1.2	360 Polar
2	0.14	0.15	0.00	Circular Foil	CD = 1.2	360 Polar
3	0.25	0.24	60.60	MODIFIED NWT 1001	T1_Re0.250_M0.00_N9.0 360 M (2)	
4	0.50	0.12	42.46	MODIFIED NWT 1001	T1_Re0.250_M0.00_N9.0 360 M (2)	
5	0.75	0.06	32.61	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
6	1.00	0.05	28.39	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
7	1.25	0.04	25.78	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
8	1.50	0.03	24.02	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
9	1.75	0.03	22.75	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
10	2.00	0.02	21.79	MODIFIED NWT 2005	T1_Re0.250_M0.00_N9.0 360 M (3)	
11	2.25	0.02	21.04	MODIFIED NWT 2004	T1_Re0.250_M0.00_N9.0 360 M	
12	2.50	0.02	20.44	MODIFIED NWT 2004	T1_Re0.250_M0.00_N9.0 360 M	

Fig.9: Snippet of table of position of aerofoil and optimal chord and twist value of blade

4.2. Optimal Twist

Since the HAWT is a lift based machine, it is a known fact that as the lift increases the drag also will increase so to reduce the drag the twist come into existence .the twist goes on decreasing from root to tip. The root will have the maximum twist. The optimal twist used for this blade is based on the woods twist equation even though there are several other formulas are available. First we calculate the inflow angle then with that we go on to find the actual twist [3]

Inflow angle

$$\tan \phi = 2 / (3 \cdot \lambda_r) \quad (3)$$

Blade twist

$$\theta_p = \phi + \alpha \quad (4)$$

4.3. Optimisation

The main intention of designing of the wind turbine is to extract maximum power from the wind. Once the operational tip speed ratio and aerofoil have been chosen, the optimal twist and optimal chord equation helps to decide the twist and chord ignoring tip losses. Hence the maximum efficiency is the only parameter to be optimised. The quick starting of the small blade is also an important criterion for the designing. Despite of the fact that there are many number of optimisation methods are available for designing of blade as are available in MATLAB functions [3].

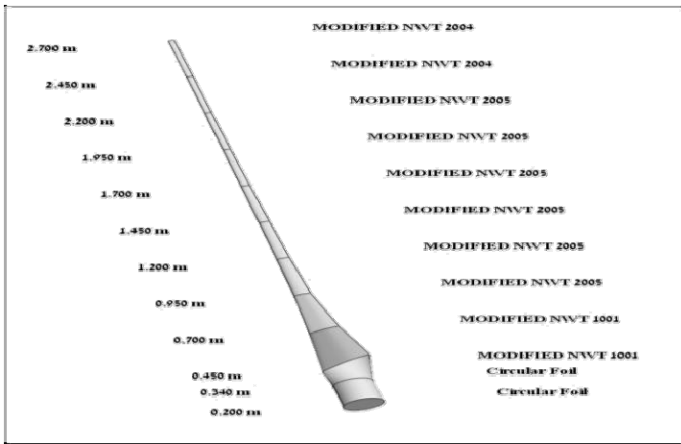


Fig.10: Blade design using modified NWT aerofoils

Evolutionary strategy is the mimic process of natural selection to reach at optimum results by developing a population over a noteworthy number of generations. In the present situation the twist and chord are considered as the genes and it is then optimised using the dual evolutionary method.

5. Standard Simulation

Numerical modelling gives the results of an exemplary simulation of a wind turbine blade, which is equipped with active elements. It is more meant to be a description of how to approach the set up and use of a simulation with numerical model rather than a complete scientific investigation. The behaviour of the aero elastic model and the sensibility to changes of specific key input parameters should be known [4]. A final test case is derived which will then be used for a simulation using one and more than one active flow control elements. It also gives a real time simulation but for a very limited time may be that of 10 sec.

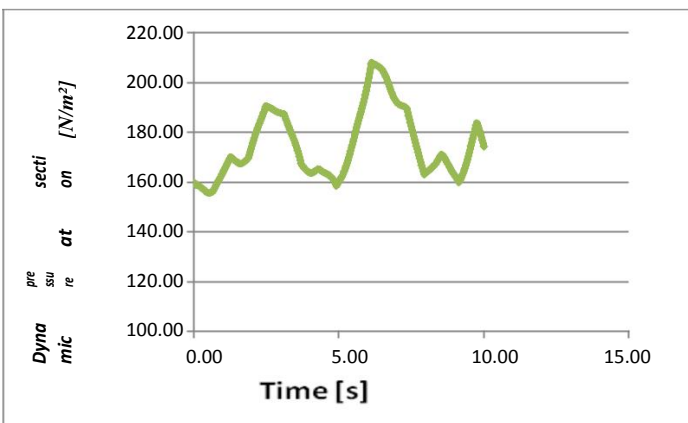


Fig.11: real time simulation of blade in numerical analysis for 10sec

5.1. Dynamic Stall Effects

The utilization of active elements changes the aerodynamic behaviour of the aerofoil. This can result in non-validity of semi-empirical derived dynamic stall model. It is quite relevant to avoid any stall related phenomena for the active simulation. So it is necessary to pitch the blade lower angles of attack to achieve the desired results. From the above action, we warrant that the outer region of the blade (where the active elements will be positioned [4]) will function in the attached flow region during the entire simulation. The following graph illustrates the AOA distribution over the blade at an explicit instant of time.

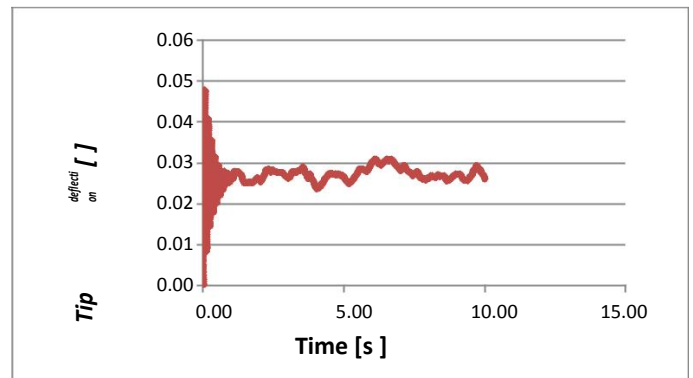


Fig.12: Influence of the dynamic stall model on the blade tip deflection over time

We can deduce from the graph that the blade outer regions operate under stalled conditions, as the AOA already surpasses the level for the static stall angle of attack. The effect of the dynamic stall phenomenon is visualized from the graph, which includes the blade deflection over the simulation time. It is noticed that the maximum aerodynamic forces which ensue are higher. Consequently the influence of dynamic stall leads to higher blade deflections. When maximum lift takes place there occurs a rapid lift break-in which results in generating higher slopes of the blade deflection curve.

6. Results and Discussion

The modified NWT aerofoils show more coefficient of lift and less drag coefficient when compared with the original NWT aerofoils. The lift coefficient values and the drag coefficients obtained from the numerical modelling and CFD are almost equivalent. The power obtained from the numerically modelled blade will be around 5kW at a rotation speed of 180 rpm in the wind speed of 11 m/s. The critical Reynolds number of 250000 is used for the analysis. The trailing edge of the modified NWT 2005 aerofoil is slightly bend to increase the lift coefficient in the angle of attack of 10° to 20° which is our region of interest. The power coefficient is about 0.47 for the tip speed ratio of 7

obtained by keeping the Reynolds number in the range below the critical Reynolds number. As the NWT aerofoils are designed for the Indian scenario hence the modified aerofoil with more lift can be further used for the blade manufacturing and its dynamic characteristics can be evaluated in field measurements.

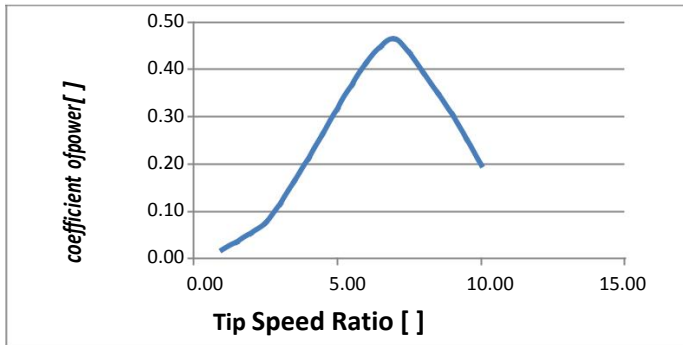


Fig.13: Coefficient of power v/s tip speed ratio of the designed blade

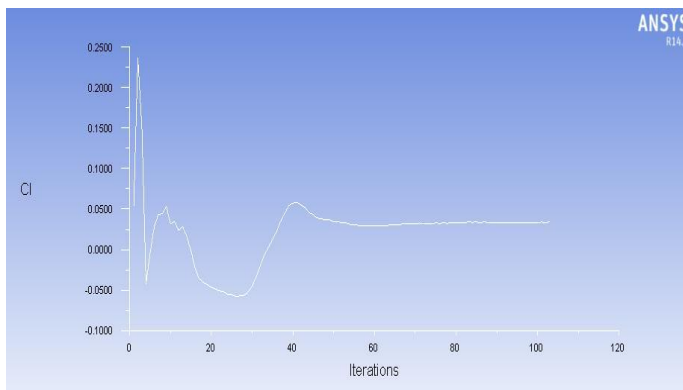


Fig.14: Coefficient of lift of modified NWT 2005 in FLUENT

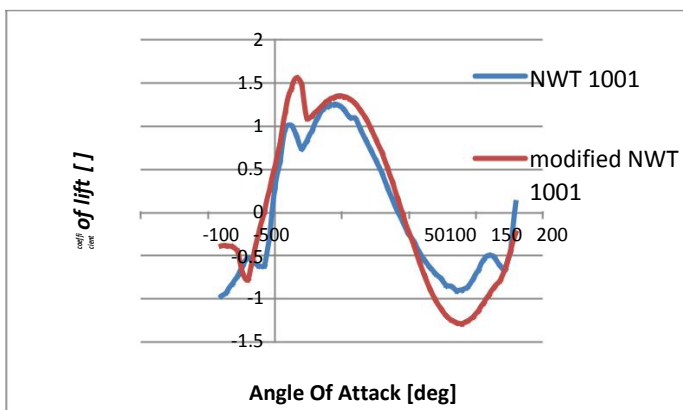


Fig.15: Comparisons of existing NWT 1001 aerofoil and modified NWT 1001 coefficient of lift.

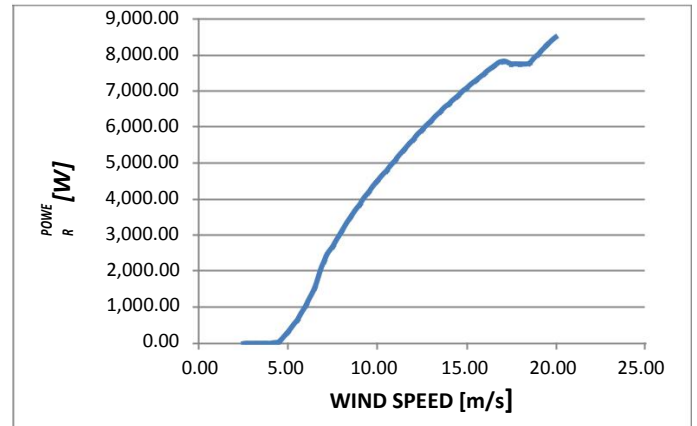


Fig.16: Power curve of the modified NWT blade

7. Conclusion and Scope of Work

CFD calculation can precisely calculate the flow around the aerofoil is the important conclusion. The numerical modelling can clearly predict the point where stall begins. The lift and drag coefficients values obtained in comparison with the numerical modelling and the CFD are approximate and also it discloses that the dominance of the viscous effects of numerical model. Ultimately both methods contribute to the optimization of the wind turbine blade design. Even though the designing and analysis can be done, but there is no much provision for the structural analysis like stress and strain details. There can be further study of AFC in the blade can be incorporated. In regards to the control of the turbine it is essential to look for a more advanced control strategy than the simple PID controller. The PID controller has to be modified and/or the controller tuning has to be improved in order to simulate multiple flaps on a blade. The additional noise, which created by the actuators has to be investigated. The whole array of the deferent wind turbine conditions of operation and load cases has to be explored.

Nomenclatures

Abbreviations

- CFD Computational Fluid Dynamics
- AFP Active Flow Control
- PID Proportional-Integral-Derivative controller
- BEM Blade Element Momentum
- NWT National Wind Turbine
- HAWT Horizontal Axis Wind Turbine

Symbols

- α = Angle of attack
- c = Chord length
- Cl = Co-efficient of lift

C_d = Co-efficient of drag
 P = power output
 C_p = co-efficient of performance
 W = Wind velocity
 λ = Tip speed ratio
 λr = Local tip speed ratio
 τ_p = Twist angle
 R = Radius of the rotor
 a = Axial induction factor
 a_0 = Radial induction factor
 ϕ = Inflow angle
 N = Number of blade
 r = Radial position of aerofoils in blade
 Ω = Blade angular velocity
 U_∞ = Far wake wind velocity

Author Profile

Amlan Das has obtained his B.Tech degree in Mechanical Engineering in 2011 and M.Tech degree in Advanced Thermal Power and Energy Systems in 2015. His keen interests are in Renewable Energy, Manufacturing Science and Production Technology. He has briefly involved himself in research work at National Institute of Wind Energy, Chennai, India.



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