5^{th} International Advanced Technologies Symposium (IATS'09), May 13-15, 2009, Karabuk, Turkey

COMPUTER-AIDED DESIGN AND PERFORMANCE ANALYSIS OF HAWT BLADES

Emrah KULUNK[a, *] and Nadir YILMAZ[b]
[a, *] New Mexico Institute of Mining and Technology, Socorro, USA, E-mail: ekulunk@nmt.edu
[b] New Mexico Institute of Mining and Technology, Socorro, USA, E-mail: nadir@nmt.edu

Abstract

In this paper, a design method based on blade element momentum (BEM) theory is explained for horizontal-axis wind turbine (HAWT) blades. The method is used to optimize the chord and twist distributions of the blades. Applying this method a 100kW HAWT rotor is designed. Also a computer program is written to estimate the aerodynamic performance of the existing HAWT blades and used for the performance analysis of the designed 100kW HAWT rotor.

Keywords: HAWT Design, Blade Element Momentum Theory, Wind Energy, Aerodynamics

Nomenclature

C_P: Power coefficient of wind turbine rotor
C_T: Thrust coefficient of wind turbine rotor
C_{T_r} : Local thrust coef. of each annular rotor section
P: Power output from wind turbine rotor
$\dot{m}$: Air mass flow rate through rotor plane
U_∞: Free stream velocity of wind
U_{rel}: Relative wind velocity
U_R: Uniform wind velocity at rotor plane
A : Area of wind turbine rotor
R : Radius of wind turbine rotor
r : Radial coordinate at rotor plane
r_i : Blade radius for the i^{th} blade element
p' : Pressure drop across rotor plane
H: Bernoulli's constant
T : rotor thrust
Q : rotor torque
F_D: Drag force on an annular blade element
F_L: Lift force on an annular blade element
C_D: Drag coefficient of an airfoil
C_L: Lift coefficient of an airfoil
f : Tip-loss factor
f_i: Tip-loss factor for the i^{th} blade element
N : Number of blade elements
B : Number of blades of a rotor
a : Axial induction factor at rotor plane
a' : Angular induction factor
λ : Tip-speed ratio of rotor
λ_d: Design tip-speed ratio
λ_r: Local tip-speed ratio
$\lambda_{r,i}$: Local tip-speed ratio for the i^{th} blade element
c_i:: Blade chord length for the i^{th} blade element
ρ : Air density
Ω : Angular velocity of wind turbine rotor
α : Angle of attack
θ_i: Pitch angle for the i^{th} blade element
$\varphi_{opt,i}$: Optimum relative wind angle for the i^{th} blade element
σ: Solidity ratio
ν: Kinematic viscosity of air
γ: Glide ratio
Re: Reynolds number
HAWT: Horizontal-axis wind turbine
BEM: Blade element momentum

1. Introduction

The objectives of this study are to develop a method using BEM theory for aerodynamic design of the HAWT blades and performance analysis of the existing blades, also to build a computer program using this method and to design a 100kW HAWT rotor performing the program, finally to determine the aerodynamic characteristics and to create the performance curves of the designed rotor.

The scope of the study is restricted to aerodynamics of HAWTs, blade design procedure for an optimum rotor using BEM theory and performance analysis of the designed rotor.

2. Blade Design Procedure

BEM theory refers to the determination of a wind turbine blade performance by combining the equations of general momentum theory and blade element theory. At the tip of the turbine blade losses are introduced. These can be accounted for in BEM theory by means of a correction factor, f which varies from 0 to 1 and characterizes the reduction in forces along the blade. An approximate method of estimating the effect of tip losses has been given by L. Prandtl and the expression obtained by Prandtl for tip-loss factor is given by the following equation [1]

$$f = \frac{2}{\pi}\cos^{-1}\left\{\exp\left[\frac{-(B/2)\left[1-\left(\frac{r}{R}\right)\right]}{\left(\frac{r}{R}\right)\sin\varphi}\right]\right\} \tag{1}$$

The application of this equation for the losses at the blade tips is to provide an approximate correction to the system of equations for predicting rotor performance and blade design. Carrying the tip-loss factor through the calculations, the changes will be as following:

$$dQ = 4f\pi\rho U_\infty \Omega a'(1-a)r^3 dr \tag{2}$$

$$dT = 4f\pi\rho U_\infty^2 a(1-a)r dr \tag{3}$$

$$\frac{a'}{1-a} = \frac{\sigma C_L}{4f\lambda_{r\,sin\varphi}} \tag{4}$$

$$\frac{a'}{1-a'} = \frac{\sigma C_L}{4f cos\varphi} \tag{5}$$

$$C_L = \frac{4f sin\varphi}{\sigma} \frac{(cos\varphi - \lambda_{rsin\varphi})}{(sin\varphi + \lambda_{rcos\varphi})} \tag{6}$$

$$a = \frac{1}{1 + \left[\frac{4f sin^2\varphi}{(\sigma C_L) cos\varphi}\right]} \tag{7}$$

$$a' = \frac{1}{\left[\frac{4f cos\varphi}{(\sigma C_L)} - 1\right]} \tag{8}$$

$$C_P = \frac{8}{\lambda^2} \int_{\lambda_h}^{\lambda} f {\lambda_r}^3 a'(1-a) \left[1 - \frac{C_D}{C_L} tan\beta\right] d\lambda_r \tag{9}$$

The aerodynamic design of optimum rotor blades from a known airfoil type means determining the geometric parameters such as chord length distribution and twist distribution along the blade length for a certain tip-speed ratio at which the power coefficient of the rotor is maximum. For this reason firstly the change of the power coefficient of the rotor with respect to tip-speed ratio should be figured out in order to determine the design tip-speed ratio, λ_d corresponding to which the rotor has a maximum power coefficient. The blade design parameters will then be according to this design tip-speed ratio.

Examining the plots between relative wind angle and local tip-speed ratio for a wide range of glide ratios gives us a unique relationship when the maximum elemental power coefficient is considered. And this relationship can be found to be nearly independent of glide ratio and tip-loss factor. Therefore a general relationship can be obtained between optimum relative wind angle and local tip-speed ratio which will be applicable for any airfoil type.

$$\frac{\partial}{\partial\varphi}\left\{\sin^2\varphi\left(\cos\varphi - \lambda_r \sin\varphi\right)\left(\sin\varphi + \lambda_r \cos\varphi\right)\right\} = 0 \tag{10}$$

Equation 10 reveals after some algebra [2];

$$\varphi_{opt} = \left(2/3\right)\tan^{-1}\left(1/\lambda_r\right) \tag{11}$$

Having found the solution of determining the optimum relative wind angle for a certain local tip-speed ratio, the rest is nothing but to apply the equations from equation 6 to 9, which were derived from the blade-element momentum theory and modified including the tip loss factor, to define the blade shape and to find out the maximum power coefficient for a selected airfoil type.

Dividing the blade length into *N* elements, the local tip-speed ratio for each blade element can then be calculated as

$$\lambda_{r,i} = \lambda\left(r_i/R\right) \tag{12}$$

Then rewriting the equation 11 for each blade element gives

$$\varphi_{opt,i} = \left(2/3\right)\tan^{-1}\left(1/\lambda_{r,i}\right) \tag{13}$$

Also the tip loss correction factor for each element can be calculated as

$$f_i = \frac{2}{\pi} cos^{-1}\left\{exp\left[\frac{-(B/2)\left[1-\left(\frac{r_i}{R}\right)\right]}{\left(\frac{r_i}{R}\right) sin\varphi_{opt,i}}\right]\right\} \tag{14}$$

Chord-length distribution can then be calculated for each blade element by using the equation below [1]

$$c_i = \frac{8\pi r_i F_i \sin\varphi_{opt,i}}{BC_{L,design}} \frac{(\cos\varphi_{opt,i} - \lambda_{r,i}\sin\varphi_{opt,i})}{(\sin\varphi_{opt,i} + \lambda_{r,i}\cos\varphi_{opt,i})} \tag{15}$$

where $C_{L_{design}}$ is chosen such that the glide ratio is minimum at each blade element. The twist distribution can easily be determined by using equation 16.

$$\theta_i = \varphi_{opt,i} - \alpha_{design} \tag{16}$$

where α_{design} is again the design angle of attack at which $C_{L_{design}}$ is obtained.

Now the parameters such as chord-length and twist distribution along the blade length are known and in this case lift coefficient and angle of attack have to be determined from the known blade geometry parameters. This requires an iterative solution in which for each blade element the axial and angular induction factors are firstly taken as the values which were found for the corresponding designed blade elements and then determined within an acceptable tolerance of the previous guesses of induction factors during iteration.

Applying the design procedure explained a computer program is written to design new blades and to estimate the aerodynamic performance of the existing blades. A detailed flow chart of the program is given in Figure 1.

3. Results

The geometry and configuration of the designed rotor is summarized in Table 1. As it can be seen clearly from Table 1 the rotor employs an NREL S809 airfoil profile at inboard, mid-span and outboard stations of the blades. The S809 profile is also uniquely defined by its coordinates which appear in Table 2 below and also shown graphically in Figure 2.

Lift and Drag coefficients for S809 aerofoil are shown in Figure 3. This plot shows that for low values of angle of attack the aerofoil successfully produces a large amount of lift with little drag. At around α = 16 a phenomenon known as stall occurs where there is a massive increase in drag and a sharp reduction in lift.

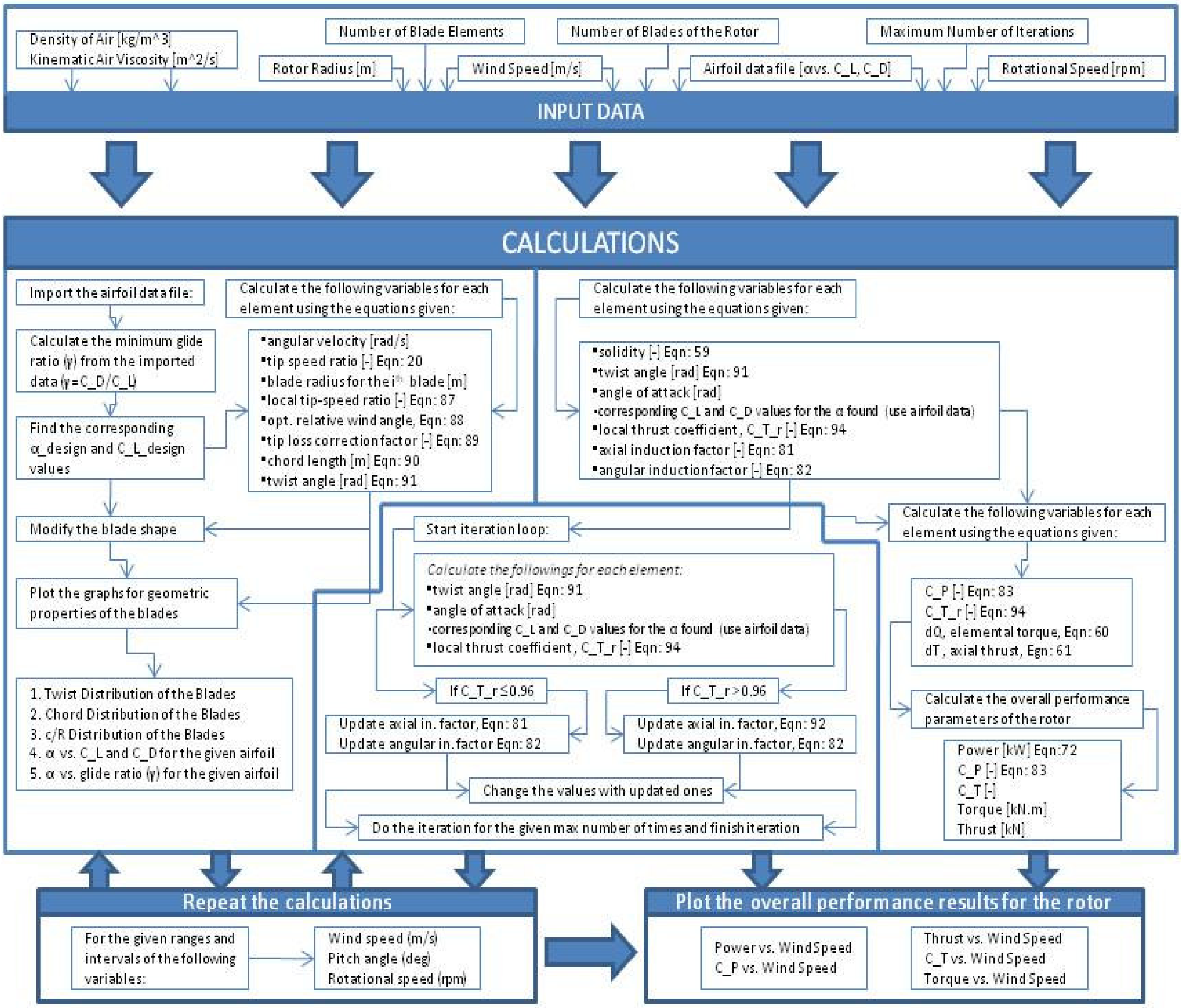

Figure 1. Computer Program Flow Chart

Also the variation of glide ratio of S809 airfoil with different angle of attacks is illustrated in Figure 4. As it is stated before, there is clearly a significant reduction in maximum achievable power as the airfoil drag increases. Since it clearly benefits the blade designer to use or design airfoils with low glide ratio, α and C_L values which corresponds to the minimum glide ratio is chosen as α_{design} and $C_{L,design}$ using the airfoil data file.

Table 1 Properties of the Designed Blades

Property	Value
Blade Length (m)	8.5451
Hub Radius (m)	0.8915
Tip Radius (m)	9.4366
Total Blade Twist Angle	6.82 deg
Operational Pitch Setting	-1.0 deg
Tested Rotational Speed	70.00 rpm
Blade Coning Angle	7.00 deg
Root (inboard) Airfoil	S809
Mid-span Airfoil	S809
Tip (outboard) Airfoil	S809
Maximum Chord (m)	1.0400
Maximum Chord Station (m)	3.5387
Tip Chord (m)	0.3326
Root Chord (m)	0.7583
Number of Blades	3
Rotor Radius (m)	9.4366
Hub Radius (m)	0.5415
Pre-cone Angle (deg)	6.0
Shaft Tilt Angle (deg)	0.0
Hub Height (m)	34.9154

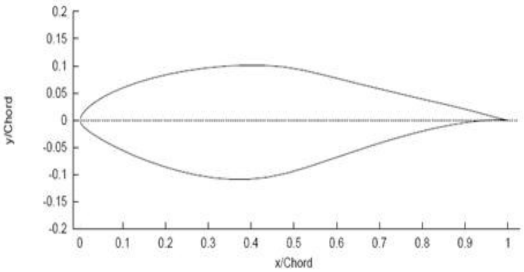

Figure 2. S809 Aerofoil [3]

Table 2 Coordinates of the S809 Airfoil [2]

Upper Surface		Lower Surface	
x/c	y/c	x/c	y/c
0.00037	0.00275	0.0014	-0.00498
0.00575	0.01166	0.00933	-0.01272
0.01626	0.02133	0.02321	-0.02162
0.03158	0.03136	0.04223	-0.03144
0.05147	0.04143	0.06579	-0.04199
0.07568	0.05132	0.09325	-0.05301
0.10390	0.06082	0.12397	-0.06408
0.13580	0.06972	0.15752	-0.07467
0.17103	0.07786	0.19362	-0.08447
0.20920	0.08505	0.23175	-0.09326
0.24987	0.09113	0.27129	-0.10060
0.29259	0.09594	0.31188	-0.10589
0.33689	0.09933	0.35328	-0.10866
0.38223	0.10109	0.39541	-0.10842
0.42809	0.10101	0.43832	-0.10484
0.47384	0.09843	0.48234	-0.09756
0.52005	0.09237	0.52837	-0.08697
0.56801	0.08356	0.57663	-0.07442
0.61747	0.07379	0.62649	-0.06112
0.66718	0.06403	0.67710	-0.04792
0.71606	0.05462	0.72752	-0.03558
0.76314	0.04578	0.77668	-0.02466
0.80756	0.03761	0.82348	-0.01559
0.84854	0.03017	0.86677	-0.00859
0.88537	0.02335	0.90545	-0.00370
0.91763	0.01694	0.93852	-0.00075
0.94523	0.01101	0.96509	0.00054
0.96799	0.00600	0.98446	0.00065
0.98528	0.00245	0.99612	0.00024
0.99623	0.00054	1	0
1	0		

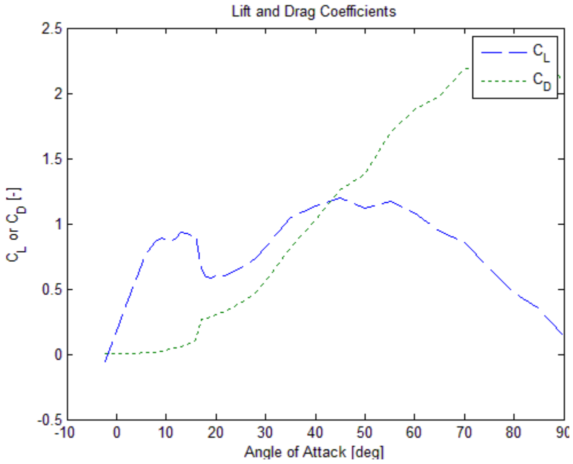

Figure 3. Lift and Drag Coefficients for S809 Aerofoil

Table 3 contains the local twist distribution and chord distribution schedules for the designed rotor blades. Also the twist and chord distribution schedules are presented graphically in Figure 5 and 6 respectively.

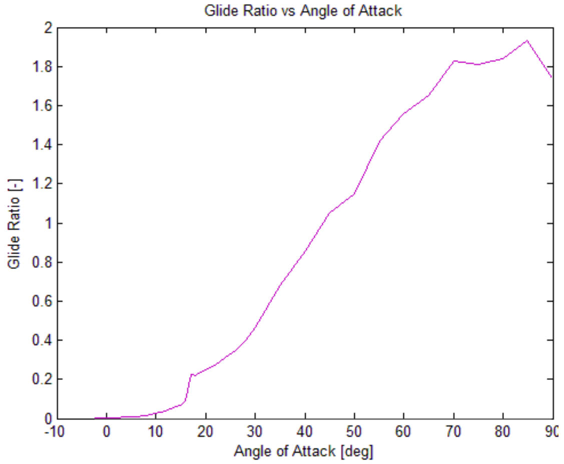

Figure 4. Glide Ratio vs. α for S809 Aerofoil

Table 3 Geometric properties of the designed blades

r/R	Station [m]	twist [deg]	chord [m]	c/R
0.100	0.892	22.264	0.758	0.080
0.156	1.180	14.510	0.802	0.085
0.213	1.769	11.103	0.888	0.094
0.269	2.359	9.663	0.962	0.102
0.325	2.949	7.920	1.012	0.107
0.381	3.539	6.474	1.040	0.110
0.438	4.129	5.451	1.028	0.109
0.494	4.718	4.697	0.956	0.101
0.550	5.308	4.121	0.882	0.094
0.606	5.898	3.668	0.809	0.086
0.663	6.488	3.302	0.750	0.080
0.719	7.077	3.001	0.682	0.072
0.775	7.667	2.750	0.619	0.066
0.831	8.257	2.538	0.535	0.057

0.888	8.847	2.356	0.458	0.049
1.000	9.437	2.199	0.333	0.035

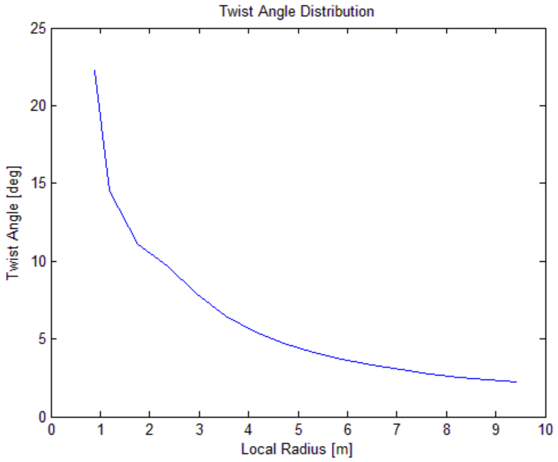

Figure 5. Twist Angle Distribution of the Designed Blades

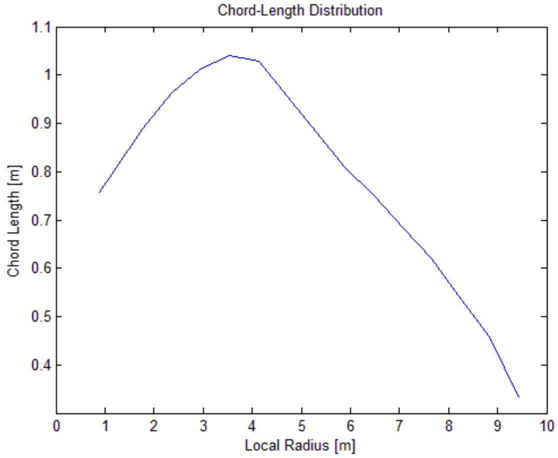

Figure 6. Chord-Length Distribution of the designed blades

The change of the performance parameters of the designed rotor such as power C_P, bending moment, thrust with respect to the wind speed is given in Figure 7, Figure 8, Figure 9 and Figure 10 respectively. As it can be seen from the figures the analysis has been repeated for different values of the pitch angle at the rotational speed of 70 rpm.

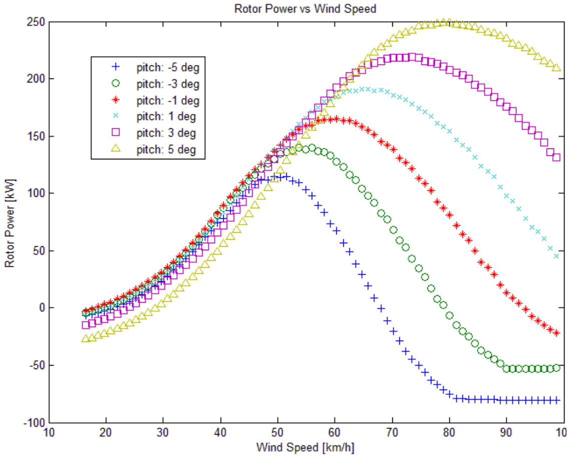

Figure 7. Power vs. Wind Speed for the Designed Rotor

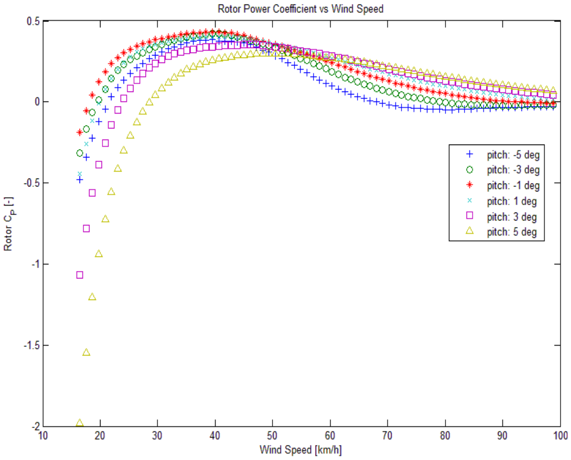

Figure 8. C_P vs. Wind Speed for the Designed Rotor

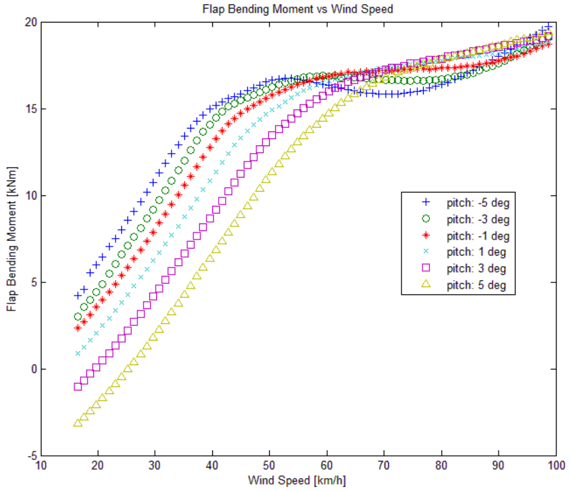

Figure 9. Bending Moment vs. Wind Speed for the Designed Rotor

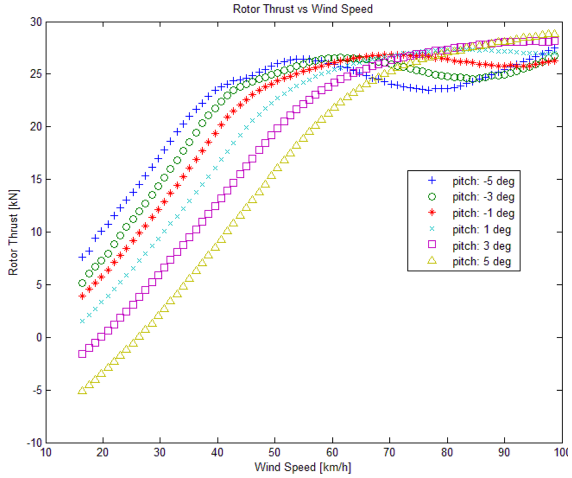

Figure 10. Thrust vs. Wind Speed for the Designed Rotor

Also the 3-D views of the designed blades and rotor are given in the Figure 11, 12, 13 and Figure 14, 15 respectively. The dimensions and the geometric properties with the configuration of the rotor are given in Table 1 and Table 3.

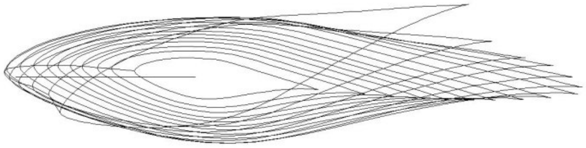

Figure 11. Views of Blade Elements from Root towards Tip

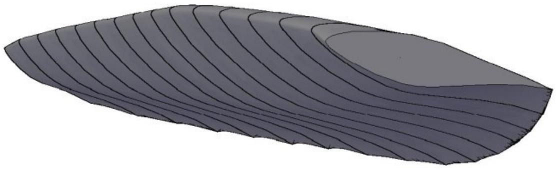

Figure 12. 3D View of the Designed Blade

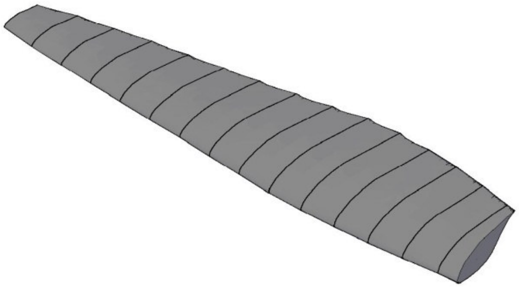

Figure 13. 3D view of the designed blade

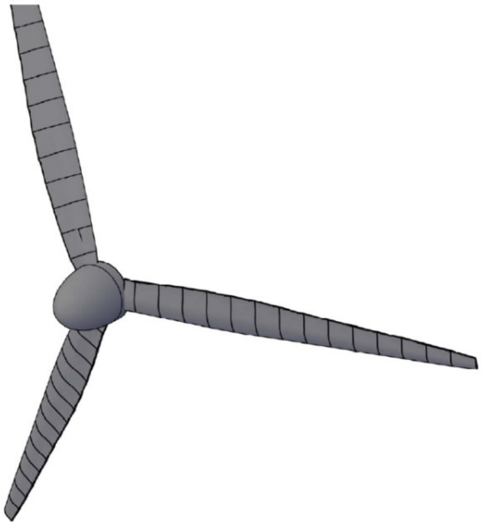

Figure 14. 3D View of the Designed Rotor

Figure 15. Side View of the Designed Rotor

REFERENCES

[1] Burton, T. and Sharpe, D., Wind Energy Handbook. John Wiley & Sons Ltd, Chichester, 2006.

[2] Hau, E., Wind Turbines: Fundamentals, Technologies, Application, Economics. Krailling, Springer, 2006.

[3] Bertagnolio, F., Niels Sorensen, N., Johansen, J. Fuglsang, P., Wind Turbine Airfoil Catalogue. Riso National Laboratory, Roskilde, 2001.