Design Optimization and Aerodynamic Performance Analysis of a Small Wind Turbine Blade

Robin Johny K[#1], David Solomon[*2], Suresh C[#3]

[#]Assistant Professor, Department of Aeronautical Engineering, Sri Ramakrishna Engineering College, Affiliated to Anna University-Chennai, NGGO Colony, Coimbatore, Tamil Nadu, India
[#] Additional Director, Head- Knowledge Sharing and Management, National Institute of Wind Energy, Ministry of New and Renewable Energy, Govt of India, Chennai, Tamil Nadu, India
[#]Assistant Professor, School of Aeronautical Sciences, Hindustan University, Chennai, Tamil Nadu, India

Abstract: Harnessing renewable energy is the most important aspect for a country and its economy as non-renewable energy sources such as fossil fuels are being depleted and causing environmental issues. Among the renewable resources, wind energy is abundantly available and harnessing it to produce electricity is done using Wind Turbines. The main objective of this research is to design an optimized small wind turbine (5kW) blade for residential use. This paper solely focuses on the aerodynamic aspects of the wind turbine and ideal conditions are considered for the drive train and electrical generator. AN understanding of Blade Element Momentum (BEM) theory is essential and calculations are carried out for determining the optimized design parameters. The same is calculated through PROPID and the performance characteristics is compared and validated. The design constraint was set for a 5kW wind turbine at a wind speed of 9m/s. Through the analysis of the optimized blade, it is noted that 5kW was developed at a lower wind speed of 8.1 m/s, which is a very promising outcome for regions of low wind speed.

Keywords—*Wind turbine, BEM theory, Aerodynamics, PROPID, Airfoils*

I. INTRODUCTION

One of the most abundantly available renewable energy source is the kinetic energy from the wind, rightfully named the wind energy. Wind is the flow of gases on a large scale. It is an inconsistent form of resource as the wind speeds can vary depending on seasons, time of day and locations. Wind Turbines are devices that can harness the power of the wind to produce electricity. It converts the kinetic energy from the wind into electrical power. The technical description for this type of machine is an airfoil-powered generator.

A. Problem Statement

The underlying problem for the small wind turbine is the unavailability of a stable and efficient rotor design that can extract maximum energy from the wind. Also, at lower heights, wind resource is less in India. So, harnessing the maximum of the available energy is essential. The Wind Power Density (WPD) is a parameter that is used mainly for assessing the Wind Resource available in a potential site. The WPD, measured in Watts per square meter, indicates how much energy is available for conversion by a wind turbine [1].

The National Institute of Wind Energy (NIWE), Chennai, has collected large amount of data from various Wind Monitoring Stations (WMS) in India and published a map Fig. 1, for Wind Resource Assessment (WRA) [2]. India has very limited wind potential at a height of 50m and it would be much less as heights of 10m or 20m, due to the presence of obstacles (buildings, trees) that slow down the wind.

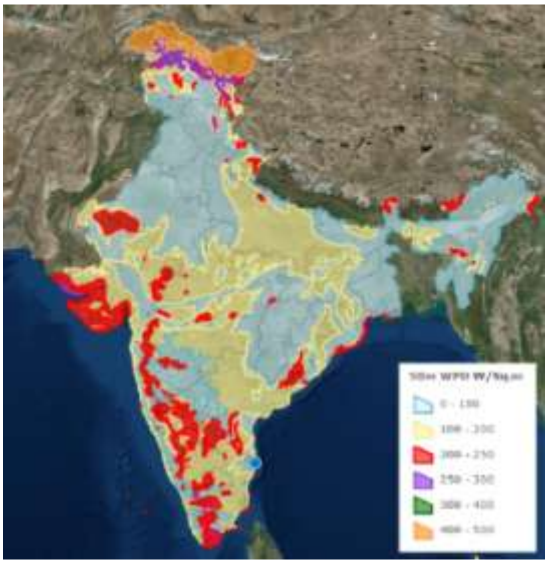


Fig. 1. WPD Map of India at 50m with WMS by WRA Unit

The overall objective of this research will be to design an optimized blade for the small wind turbine to maximize the energy conversion from kinetic energy of the wind to mechanical energy in the rotor. This optimization is done using the Blade Element Momentum (BEM) theory and the aerodynamic performance can be attained. This is then validated through PROPID.

II. THEORY

A. *Principle of Operation:*

Wind Turbine is a machine that can convert wind energy into electrical energy. This is done by converting the kinetic energy of the wind into mechanical energy by the use of a turbine and then a generator is used to convert that mechanical power into electrical power, which can be used directly or stored in batteries. A simple schematic of the principle of operation for a wind turbine is shown in Fig. 2

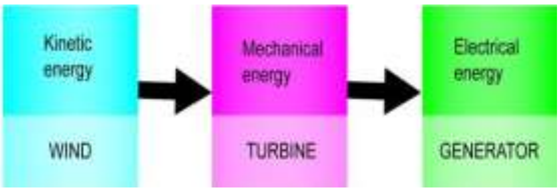


Fig 2. Schematic of the principle of operation of a wind turbine

B. *Rotor Aerodynamics:*

For aerodynamic study, the rotor blade is the preliminary and most important component. The rotor blade is the one that extracts the energy from the wind and converts to mechanical or rotational energy. Aerodynamics plays a major role in the rotor blade design as the cross section of the rotor blade is essentially an airfoil, and the blade rotates using the lift force produced by the blades when air flows across the turbine [3].

The Wind Genie 5000 is a good example of the small wind turbine which is capable of producing a rated power of 5kW. This Wind Turbine is used as the base design model, and it is based on this turbine, that the wind turbine is optimized in this research.

1) *Axial Momentum Theory:*

The Rankine Froude momentum theory predicts the forces acting on a rotor. It helps predicting the ideal efficiency of the rotor. The function of a wind turbine is to convert kinetic energy of moving air into mechanical energy. The final result arrived by this theory is given as:

$$C_p = \frac{P_0}{\frac{1}{2}\rho A V^3} \qquad (1)$$

where,

P_o =Power extracted from the wind or output power (W)

C_p =Coefficient of power

ρ = Density of air, Kgm^{-3}

V = Velocity of air, ms^{-1}

2) *Betz Limit:*

The maximum value of power coefficient in a wind turbine was set by Albert Betz, a German Physicist in 1919. This theory defines an upper limit to the amount of power that can be extracted from the wind and converted into useful power.

$$P_{max} = \frac{16}{27}\left(\frac{1}{2}\rho A V_\infty^3\right) \qquad (2)$$

Therefore, the maximum power that can be extracted is 16/27 times the power in wind (59.3%). The fraction is known as Betz's limit.

C. *Blade Element Momentum Theory (BEM):*

The momentum theory refers to control volume analysis of the forces at the blade based on the conversion of linear an angular momentum. Blade element theory refers to an analysis of forces at a section of the blade, as a function of the blade geometry. Both theories can be combines into what is known as the Blade Element Momentum (BEM) theory. The BEM theory extends the theory of the axial momentum theory incorporating the influence of the rotor blades. In the Blade Element Theory, it is assumed that the forces on a blade element can be calculated in a two-dimensional airfoil characteristics using the angle of attach defined by the incident velocity in the cross-sectional plane of the blade element.

The torque and power as derived from the BEM theory is given as:

$$Q = \frac{1}{2}\rho U_\infty^2 \pi R^3 \lambda \left[\int_0^R \mu^2 \left\{8\acute{a}(1-a)\mu - \frac{W}{U_\infty}\frac{B\left(\frac{c}{R}\right)}{\pi} C_d (1+\acute{a})\right\}\delta\mu\right] \qquad (3)$$

$$P = Q\Omega \qquad (4)$$

where,

Q = Torque(Nm)

U_∞ = Free stream velocity(ms^{-1})

R = Radial length of the blade (m)

λ = Tip speed ratio

μ = Ratio of elementary radius to radial length of the blade

a = Axial interference factor

$\acute{a}$ = Angular interference factor

W = Resultant velocity at the blade (ms^{-1})

B = Number of blades

c = Chord length of the blade profiles (m)

C_d = Coefficient of drag

P = Power (W)

Ω = Angular velocity (rad s^{-1})

III. THEORETICAL CALCULATION

A. *Design Constraints:*

For the preliminary design of the small wind turbine, design constraints are to be set as shown in Table 1.

Parameter	Value	Unit
Power Output	5	kW
Wind Velocity	9	m/s
Rotor Height	20	m
Tip Speed Ratio	6	
Power Coefficient	0.4	

Table I. Design constraints

The objective is to design a 5 kW Small Wind Turbine, and so the Power Output is set at 5 KW. This will be the rated power at a Wind Velocity of 9 m/s, and a Rotor Height or Hub Height of 20 m. Most common wind turbines are 3 bladed as it is the most stable, and hence we assume the number of blades to be 3.From Betz limit, the power coefficient of the wind turbine was calculated to be 0.593 or 59.3%. In practice, modern large wind turbines have achieved C_p of 45 to 50% and small wind turbines have achieved a C_p of 35 to 40%. Here we will consider the power coefficient to be 0.4 for the initial design.

The Tip speed ratio is an important characteristic for any wind turbine. It is the ratio of the speed at which the tip of the rotor blade rotates to the wind velocity. It is given by,

$$\lambda = \frac{\omega R}{V} \quad (5)$$

For small wind turbines, the tip speed ratio varies from 6 to 8. Here we consider a constant tip speed ratio of 6 for preliminary design. Now the Rotor configuration is to be computed, which includes the Rotor Swept Area and the Rotor Radius or Rotor Diameter.

We know from the definition of coefficient of power,

$$C_p = \frac{P_o}{\frac{1}{2}\rho A V^3 \eta_g}$$

$$\therefore A = \frac{P_o}{\frac{1}{2} C_p \rho V^3 \eta_g}$$

$$\eta_g = 0.9 - Generator\ Efficiency$$

$$= \frac{5 * 10^3}{\frac{1}{2} * 0.4 * 1.225 * 9^3 * 0.9}$$

Rotor Swept Area,

$$A = 31.15944\ m^2$$

Rotor radius or blade length,

$$R = 3.149343\ m$$

From the Genie 5000 Wind Turbine, the measurement of the Hub Radius is taken into account for the design.

Hub Radius	0.24	m
Distance from end of the hub to the start of the airfoil profile	0.17	m

Table II. Measured parameters

Blade length (from start of the airfoil profile root to tip)

$$= 3.149343 - (0.24 + 0.17) = 2.739343\ m$$

A schematic of the wind turbine with the preliminary design measurements is given in the Fig. 3

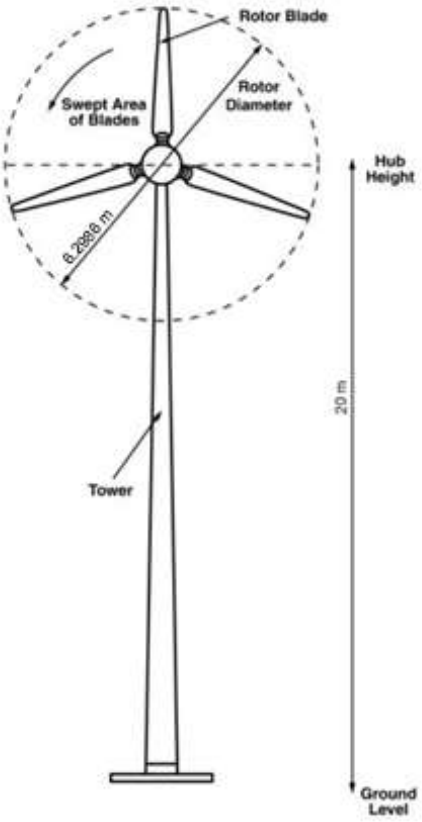


Fig. 3.Schematic of Wind Turbine with Design Constraints

B. Preliminary Blade Design:

The preliminary blade design of the wind turbine is to determine the chord and twist angle radial profiles of the blade based in the design constraints.

*1) **Chord and Twist Angle Distribution:***

The blade is divided into 10 sections or elements. For each element, the chord c_i and twist angle β_i are calculated based on the optimum design and peak performance, such that the efficiency is maximum as design tip speed ratio. By neglecting the effects of tip losses and drag, a set of equations are obtained which give a closed form solution for blade design parameters.$i$represents the element number [5].

$$\lambda_{r,i} = \frac{r_i}{R}\lambda \quad (6)$$

$$\phi_i = \frac{2}{3}\tan^{-1}\left(\frac{1}{\lambda_{r,i}}\right) \qquad (7)$$

$$c_i = \frac{8\pi r}{BC_l}(1-\cos\phi_i) \qquad (8)$$

$$\beta_i = \phi_i - \alpha \qquad (9)$$

where,

λ_r =Elemental tip speed ratio
λ = Tip speed ratio
r = Elemental radius (m)
R = Rotor radius (m)
ϕ = Flow angle (deg)
B = Number of blades
C_l = Design lift co-efficient
β = Twist angle (deg)
α = Angle of attack

For each element, all these parameters are calculated and tabulated.

Partially Optimized Wind Turbine Blade Geometry

Blade Segment	Notation	1	2	3	4	5	6	7	8	9	10	Unit
Relative radius	r/R	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	
Speed ratio	λr	0.3	0.9	1.5	2.1	2.7	3.3	3.9	4.5	5.1	5.7	
Relative Angle	ϕ	48.86717	32.00853	22.46005	16.97556	13.54876	11.23893	9.587596	8.352538	7.395815	6.633751	deg
Twist	β	39.86717	23.00853	13.46005	7.975563	4.548758	2.238933	0.587596	-0.64746	-1.60418	-2.36625	deg
Rel. Chord Length	c/R	0.119448	0.159206	0.13239	0.106463	0.087428	0.073635	0.063384	0.055538	0.049369	0.044404	

Table III. Partially Optimized Wind Turbine Blade Geometry

Blade Twist and Chord Distribution

Segment No	Notation	Unit	1	2	3	4	5	6	7	8	9	10
Rel. Radius	r/R	-	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Radius	r	m	0.157467	0.472401	0.787336	1.10227	1.417204	1.732139	2.047073	2.362007	2.676942	2.991876
Twist	β	deg	39.86717	23.00853	13.46005	7.975563	4.548758	2.238933	0.587596	-0.64746	-1.60418	-2.36625
Chord	c	m	0.376182	0.501395	0.416941	0.335289	0.27534	0.231901	0.199619	0.174909	0.155478	0.139842

Table IV. Blade Twist and Chord Distribution

From the tables 3 and 4, the Chord and Twist distribution along the span of the blade at various sections can be graphically represented as shown in Fig. 4 and Fig. 5

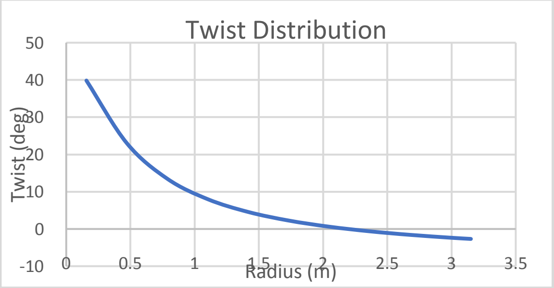


Fig. 4. Twist Distribution

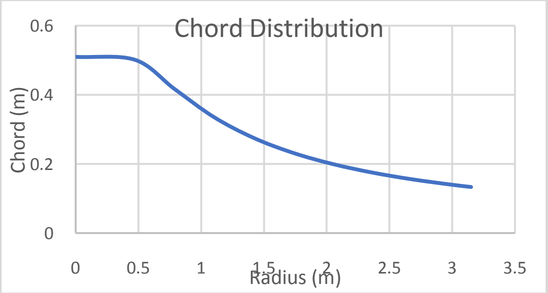


Fig. 5. Chord Distribution

2) Airfoil Selection:

In order to use the relationships derived in the previous section to arrive at the most efficient blade design, the cross-sectional properties of the blade must also be defined. The cross section of the blade is basically an airfoil. There can be one or more airfoil profiles running along the length of the blade for various chord lengths. Most airfoils used in wind design have documented data from a wind tunnel of the coefficients of lift and drag for a range of angles of attack. For aircraft wind design, data is only required for angles of attack up to the first occurrence of a phenomena known as stall, or the angle of attack where lift coefficient is drastically reduced dude to flow separation. Generally, stall occurs in mist airfoils between 15 and 20 degrees, depending on the Reynolds number of the fluid. This data is easily found in many handbooks, but since wind turbines operate at angle of attack up to 90 degrees, lift and grad coefficient data is required for angles if attack past 20 degrees.

The National Renewable Energy Laboratory (NREL) [7] has developed several families of special purpose airfoils for the Horizontal Axis Wind Turbines and especially some for the Small Wind Turbines. The NREL's S-Series airfoils come in both thin and thick families and within each family is a set of two or three different airfoils that are designated 'root', 'primary' ad 'tip'. Each set of three airfoils is defining a single blade with a variable cross section, such that the 'root' airfoil is the cross-section shape at the location of largest chord length, the 'primary' airfoil is the shape at 75% of the radius, and the 'tip' airfoil which occur at 95% of the radius.

Here we require an airfoil that has more coefficient of power over a large range of tip speed ratios. Hence NREL airfoils are used here, even though NACA airfoil has a greater maximum coefficient of power, the NREL airfoil is designed to operate at a higher coefficient of power over a large range of tip speed ratios as shown in the Fig 6.

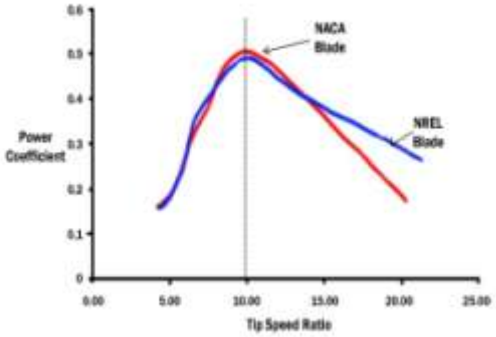
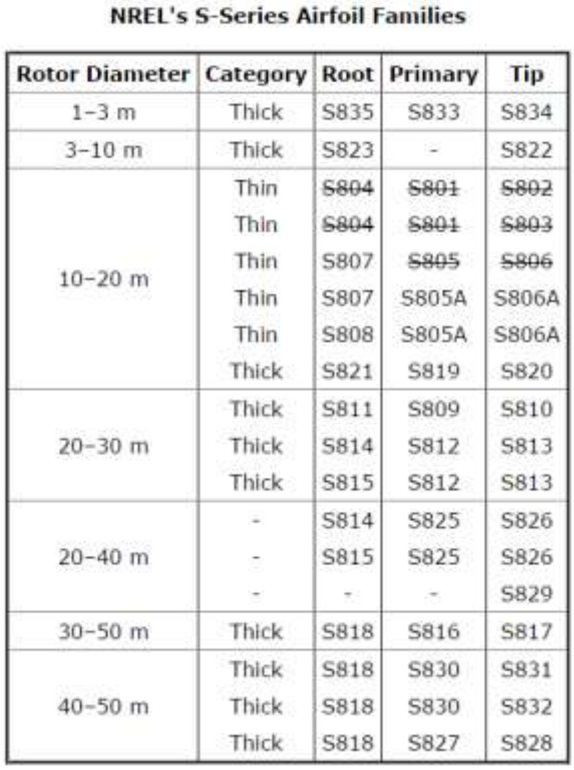


Fig. 6. Power Coefficient vs. Tip Speed Ratio for NACA and NREL Airfoil Profile Blades

The NREL has tested and validated the results for all airfoils that are used in all configurations of wind turbines and provided only the most efficient ones for use. Hence, the airfoil data can be used for further analysis. The S-Series airfoil families are categorized based on the rotor diameter as shown.



NREL's S-Series Airfoil Families

Rotor Diameter	Category	Root	Primary	Tip
1-3 m	Thick	S835	S833	S834
3-10 m	Thick	S823	-	S822
10-20 m	Thin	~~S804~~	~~S801~~	~~S802~~
	Thin	~~S804~~	~~S801~~	~~S803~~
	Thin	S807	~~S805~~	~~S806~~
	Thin	S807	S805A	S806A
	Thin	S808	S805A	S806A
	Thick	S821	S819	S820
20-30 m	Thick	S811	S809	S810
	Thick	S814	S812	S813
	Thick	S815	S812	S813
20-40 m	-	S814	S825	S826
	-	S815	S825	S826
	-	-	-	S829
30-50 m	Thick	S818	S816	S817
40-50 m	Thick	S818	S830	S831
	Thick	S818	S830	S832
	Thick	S818	S827	S828

Table V. NREL's Airfoil Families

Our rotor lies in the 1-3m diameter category and hence we choose the airfoils S823 for the Root section and S822 for the Tip section. The airfoil data is taken from the NREL documents and is validated to be accurate with XFLR.

i) NREL S822:

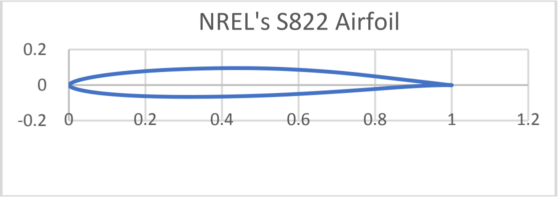


Fig. 7. Airfoil Profile of NREL s822

NREL's S822 Airfoil				
x/c	**y/c**		**x/c**	**y/c**
1	0		0.000443	-0.002413
0.996089	0.000642		0.001282	-0.004385
0.985048	0.003157		0.005329	-0.010118
0.968133	0.007602		0.015376	-0.01868
0.946046	0.013324		0.030216	-0.02717
0.918825	0.020084		0.049559	-0.0352
0.887037	0.028045		0.073374	-0.04256
0.851444	0.037037		0.101374	-0.04906
0.812782	0.046731		0.133441	-0.05458
0.771742	0.056677		0.169219	-0.05903
0.728946	0.066315		0.208482	-0.06236
0.684771	0.074819		0.250797	-0.06455
0.638946	0.081988		0.295834	-0.06559
0.591971	0.087923		0.343087	-0.0655
0.544321	0.092477		0.392138	-0.06434
0.496467	0.095295		0.44242	-0.06214
0.44832	0.096342		0.493444	-0.05897
0.400324	0.095949		0.544594	-0.05483
0.353012	0.094259		0.595407	-0.0496
0.306932	0.091363		0.645795	-0.04346
0.262594	0.087322		0.695149	-0.03687
0.220471	0.082211		0.742856	-0.03007
0.181021	0.076101		0.788279	-0.02303
0.144635	0.069084		0.831428	-0.01608
0.111706	0.061261		0.871626	-0.01
0.082528	0.052754		0.907952	-0.00522
0.057423	0.043713		0.93944	-0.00195
0.036592	0.034302		0.96515	-0.00014
0.02031	0.024706		0.984246	0.000448
0.008599	0.015142		0.996022	0.000259
0.00176	0.006074		1	0
0.000651	0.003396			
0.000138	0.001358			
0.000023	-0.000542			
0.000294	-0.001935			

Table VI. NREL s822 Airfoil Coordinates

ii) NREL S823:

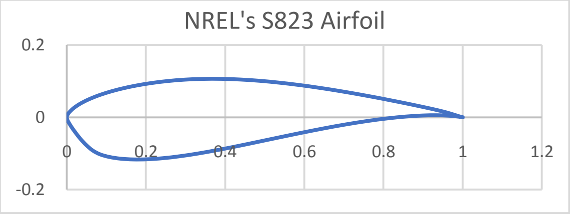


Fig. 8. Airfoil profile of NREL s823

NREL's S823 Airfoil				
x/c	**y/c**		**x/c**	**y/c**
1	0		0.000174	-0.00193
0.996182	0.001021		0.0008	-0.00484
0.985647	0.004487		0.002374	-0.00939
0.969834	0.009935		0.010193	-0.02397
0.949208	0.016186		0.021425	-0.0414
0.923311	0.02286		0.03433	-0.05938
0.892433	0.030245		0.049121	-0.07669
0.857144	0.038305		0.065425	-0.09171
0.818037	0.046896		0.084347	-0.10251
0.775723	0.05581		0.108058	-0.10978
0.73081	0.064793		0.136074	-0.11443
0.68389	0.073566		0.168058	-0.11652
0.635537	0.081835		0.203782	-0.11604
0.586291	0.089312		0.243045	-0.11306
0.536666	0.095725		0.285642	-0.10769
0.487145	0.100825		0.331343	-0.10014
0.438182	0.104394		0.379872	-0.09068
0.390202	0.106236		0.430894	-0.07971
0.343554	0.106115		0.483993	-0.06767
0.298349	0.104071		0.538656	-0.05509
0.25503	0.100219		0.594258	-0.04251
0.213826	0.094667		0.650057	-0.03052
0.17515	0.087661		0.70519	-0.01965
0.139404	0.079378		0.758682	-0.01038
0.106993	0.069983		0.809471	-0.00307
0.078238	0.059647		0.856439	0.002045
0.053489	0.048562		0.89846	0.004922
0.032973	0.036935		0.934449	0.005687
0.017013	0.025059		0.963294	0.004594
0.005871	0.013252		0.9839	0.00254
0.001538	0.006021		0.996032	0.000732
0.000533	0.003322		1	0
0.000235	0.00216			
0.000026	0.000734			

Table VII. NREL s823 Airfoil Coordinates

From the NREL database, the properties of the airfoils are also defined as shown in Appendix C. The coefficient of lift, drag along with their respective angle of attack are also given for varying Reynolds number.

	Tip	**Root**
Airfoil	S822	S823
Thickness	0.16c	0.21c
Design Re	6.00E+05	4.00E+05
$C_{l,max}$	1	1.2

Table VIII. Airfoil Parameters

IV. NUMERICAL CALCULATION

A. Rotor Performance Analysis:

The wind turbine rotor power is contributed from each individual blade element of the three blades, and therefore the calculation is based on each blade element's performance analysis [9]. The performance parameters of each blade element are calculated through an iterative process, which is summarized below:

1. Assume an initial value for the axial induction factor a(=0.3), and angular induction factor $\acute{a}$(=0)

2. Calculate the relative flow angle,

$$\varphi_{i,j} = \tan^{-1}\left(\frac{1 - a_{i,j}}{(1 + \acute{a}_{i,j})\lambda_{r,i}}\right) \qquad (10)$$

Subscripts, $i = i^{th}$ *element of the blade*
j = *number of iterations*

3. Calculate the local solidity ratio given by,

$$\acute{\sigma}_i = \frac{Bc_i}{2\pi r_i} \qquad (11)$$

4. Calculate the local angle of attack of the ith blade element:

$$\alpha_{i.j} = \varphi_{i,j} - \beta_i \qquad (12)$$

For this angle of attack, the coefficient of lift and drag values are taken from the airfoil data provided.

5. Calculate the Prandtl's Tip Loss factor and Glauert correction factor [10],

$$F_{i,j} = \left(\frac{2}{\pi}\right)\cos^{-1}\left[exp\left(-\left(\frac{\left(\frac{B}{2}\right)\left(1-\left(\frac{r_i}{R}\right)\right)}{\left(\frac{r_i}{R}\right)\sin\varphi_{i,j}}\right)\right)\right] \qquad (13)$$

$$K_{i,j} = \frac{4F_{i,j}\sin^2\varphi_{i,j}}{\acute{\sigma}_i(C_l sin\varphi - C_d cos\varphi)} \qquad (14)$$

6. Then update the axial induction factor a and angular induction factor $\acute{a}$ for the next iteration,

If the initial axial induction factor is less than 0.2, we use $a_{i,j,2}$, else $a_{i,j,1}$

$$a_{i,j,1} = \frac{1}{(K_{i,j} + 1)} \quad (15)$$

$$a_{i,j,2} = \frac{1}{2}\left[2 + K_{i,j}\left(1 - (2a_c)\right) - \sqrt{\left\{\left(K_{i,j}\left(1 - (2a_c)\right) + 2\right)^2 + \left(4\left(K_{i,j}{a_c}^2 - 1\right)\right)\right\}}\right] \quad (16)$$

$$\acute{a}_{i,j+1} = \frac{1}{(4F_{i,j}\sin\varphi_{i,j} * \cos\varphi_{i,j}) * \acute{\sigma}_i(C_l cos\varphi + C_d sin\varphi - 1)} \quad (17)$$

The iteration process is carried out as shown in Appendix A, until the axial induction converges or is within tolerance limits.

7. The tangential and axial forces are calculated using,

$$F_x = \frac{1}{2}\rho W^2 c C_x r \ (18)$$

$$F_y = \frac{1}{2}\rho W^2 c C_y r \ (19)$$

9. Now power will be given by,

$$P = \Omega B \int_0^R F_x dr \ (20)$$

Total Power extracted,

$$\boldsymbol{P = 5.6\ kW}$$

B. PROPID Validation:

The design constraints used for the numerical calculation can be used in the PROPID [12] tool to predict the torque and power developed by the wind turbine.

PROPID is based on codes and the numerical values assigned to each variable.

The input parameters are:

Normalized chord and twist distribution:

Normalized Chord, $CH = \frac{Chordlength}{RotorRadius}$

CH	TW
0.119448	39.86717
0.159206	23.00853
0.13239	13.46005
0.106463	7.975563
0.087428	4.548758
0.073635	2.238933
0.063384	0.587596
0.055538	-0.64746
0.049369	-1.60418
0.044404	-2.36625

Table IX. Normalized Chord and Twist Distribution

Normalized hub cut-out $HUB = \frac{HubRadius}{RotorRadius} = \frac{0.24}{2.9877} = 0.08$

Normalized hub height $HH = \frac{HubHeight}{RotorRadius} = \frac{20}{2.9877} = 6.694$

Number of blades $BN = 3$

Airfoil used along the blade length:
NREL S823 and NREL S822
Blade RPM = 172.574
Wind Speed = 9 m/s

The data for airfoil is directly fed from separate files, which contain the airfoil characteristics into the PROPID analysis. After the parameters and values are assigned in the coding page as shown in Appendix B, the code is run through command prompt. The run page is shown in Fig. 9.

```
* PROPID                                         *
* --------------------------------------------- *
* A Multipoint Inverse Design Method for        *
* Horizontal Axis Wind Turbines                 *
* Version 5.3 Jan 2010                          *
* Michael S. Selig, Nikhil Raj,                 *
* Philippe Giguere                              *
* University of Illinois at Urbana-Champaign *
**********************************************

**********************************************
* Running input file: propid.in ->          wt01a.in

**********************************************

Reading polar data file (pdata.f): s823.pd
Reading polar data file (pdata.f): s823.pd
Reading polar data file (pdata.f): s822.pd
Reading polar data file (pdata.f): s822.pd

Performing 2D sweep analysis.
-> Done performing 2D sweep analysis.

**********************************************
* Output
* ---------------------------------------------
* rotor p vs v          --> ftn048.dat
* rotor cp vs x         --> ftn045.dat
* rotor thrust vs wind speed --> ftn051.dat
**********************************************
```

Fig. 9. PROPID run page-command prompt

IV. RESULT

A. Performance Characteristics:

The Power curve is given by the Rotor Power vs Wind Speed graph. At a speed of 20 mph (9 m/s), the power is higher than the rated power of 5 kW, as the blade design has been optimized. The Power curve is shown in Fig 10. This power curve is incomplete as the cut-out conditions are not specified into the design yet. This power curve is only for the amount of power that can be produced by the optimized wind turbine for various wind speeds and is the main aerodynamic requirement for the small wind turbine.

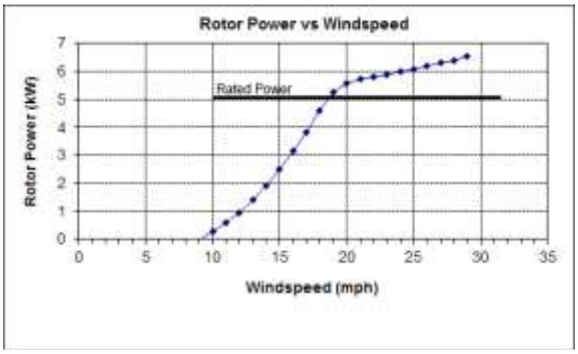


Fig. 10. Power Curve

In the power curve, the produced power seems to increase as the wind speed increases. This is because the power produced is a function of the cube of the wind speed. The rated power is set at 5kW and hence, the power production will be limited to 5kW as shown.

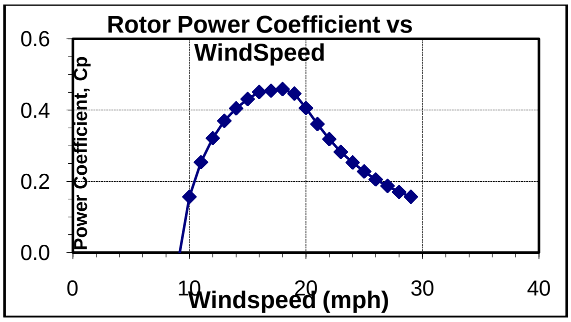


Fig. 11. Power Coefficient vs. Wind Speed

In Fig. 11, it is seen that the power coefficient increases with increasing wind speed and reaches a limit value of 0.46 at a wind speed of 18 mph (8 m/s). Wind speed is never constant and hence the power coefficient always varies, which affects the power production of the turbine. To counter this, various active control models are used on large wind turbine. Since this is a small wind turbine and for residential use, including more parts is not viable.

VI. CONCLUSION

The BEM theory, along with Prandtl and Glauert correction factors is utilized and an optimized blade is designed based on the theoretical and numerical calculations. This is also verified using the PROPID code, which also works based on the afore mentioned theories. Generally, the power curve, being the ultimate performance parameter of a wind turbine, is required to contain a cut-in speed, cut-out speed and its corresponding power. Here, since only the aerodynamic properties are analysed (i.e., the conversion of kinetic energy from the wind to rotational energy alone is considered), the power curve shows the cut-in speed, where the turbine would start generating power, and the power continues to increase as the wind speed increases, due to the fact that power varies in a cubic fashion to the wind speed. In reality, a generator would produce only the rated power. Initially, the small wind turbine blade was to be designed for a power output of 5kW at a wind speed of 9 m/s (20.1324 mph). With the optimization of the blade, the rated power was achieved at a wind velocity of 8.1 m/s (18 mph).

ACKNOWLEDGMENT

I express my thanks to God all mighty and my family for their never-ending support in all my endeavours. I wish to express my heartfelt gratitude to Dr. Dilip A. Shah, Head of the Department, School of Aeronautical Sciences, Hindustan University, Chennai, for much of his valuable support and encouragement in carrying out this work. I am especially thankful to Dr. K. Ramajeyathilagam, Senior Professor, School of Aeronautical Sciences, Hindustan University, for arranging my research work to be carried out at the National Institute of Wind Energy, Chennai. I would like to express my gratitude to Dr. G. Gomathinayagan, Director General, National Institute of Wind Energy, for allowing me to work on this research at NIWE. I would like to thank Mr. Praveen Kumar P. K., Project Engineer, NIWE and other NIWE personnel for their continuous support in this work. Last but not the least, I am deeply indebted to my parents who have been a great support while I worked day and night for the research to make it a success.

REFERENCES

[1] Ministry of New and Renewable Energy (MNRE), *Developmental Impacts and Sustainable Governance Aspects of Renewable Energy Projects*, (September 2013)

[2] National Institute of Wind Energy, www.niwe.res.in

[3] Siraj Ahmed, *Wind Energy: Theory and Practice*, Second Edition, ISBN-978-81-203-4490-7, (June 2013)

[4] Han Cao, *Aerodynamic Analysis of Small Horizontal Axis Wind Turbine Blades by Using 2D and 3D CFD Modelling*, Research (May 2011)

[5] Xiongwei Liu, Lin Wang, Xinzi Tang, *Optimized linearization of chord and tit angle profiles for fixed pitch fixed speed wind turbine blades*, Article in Renewable Energy, (September 2013)

[6] Mohammadreza Mohammadi, Alireza Mohammadi, *Optimization of Small Scale Wind Turbine Blades for Low Speed Conditions*, Journal of Clean Energy

[7] National Renewable Energy Laboratory, https://wind.nrel.gov/airfoils/

[8] David Hartwanger, Dr. Andrej Horvat, *Dimensional Modelling of a Wind Turbine Using CFD*, NAFEMS UK Conference June 2008, Engineering Simulation: Effective Use and Best Practice

[9] John McCosker, Emesto Gutierrez-Miravete, *Report on Design and Optimization of a Small Wind Turbine*, December 2012

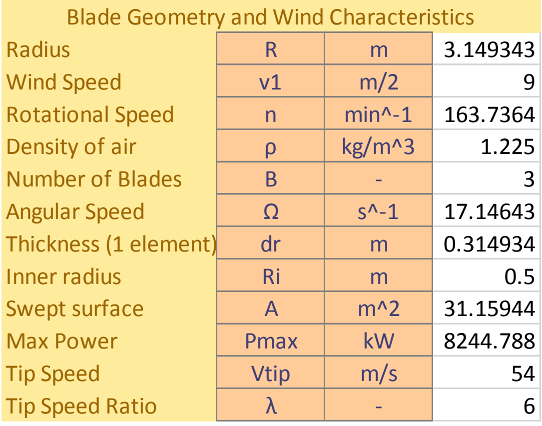
[10] Glauert, H., *The Analysis of Experimental Results in Windmill Brake and Vortex Ring States of an Airscrew*, Reports and Memoranda, No. 1026 AE. 222, 1926

[11] Veronica Cabanillas Sanchez, *Report on Blade Performance Analysis and Design Improvement of a Small Wind Turbine for Rural Areas*, Purdue University, August 2013

[12] Michael S. Selig, *Aerodynamic Design Software for Horizontal Axis Wind Turbines*, January 6, 2012

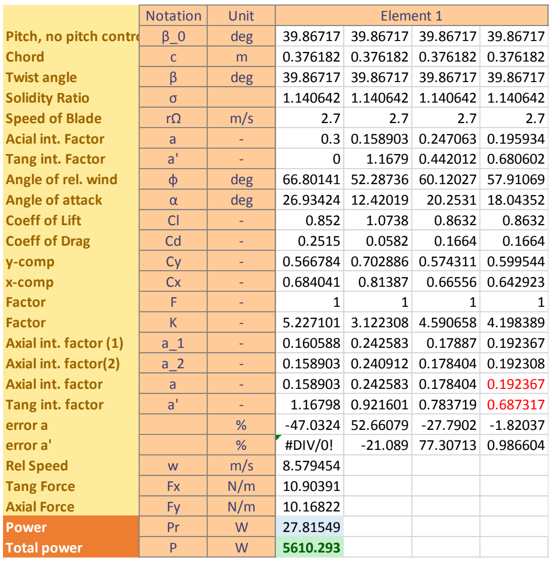
APPENDIX A

SPREADSHEET NUMERICAL CALCULATIONS



Blade Geometry and Wind Characteristics			
Radius	R	m	3.149343
Wind Speed	v1	m/2	9
Rotational Speed	n	min^-1	163.7364
Density of air	ρ	kg/m^3	1.225
Number of Blades	B	-	3
Angular Speed	Ω	s^-1	17.14643
Thickness (1 element)	dr	m	0.314934
Inner radius	Ri	m	0.5
Swept surface	A	m^2	31.15944
Max Power	Pmax	kW	8244.788
Tip Speed	Vtip	m/s	54
Tip Speed Ratio	λ	-	6

Table X. Blade Geometry and Wind Characteristics



	Notation	Unit	Element 1			
Pitch, no pitch contr	β_0	deg	39.86717	39.86717	39.86717	39.86717
Chord	c	m	0.376182	0.376182	0.376182	0.376182
Twist angle	β	deg	39.86717	39.86717	39.86717	39.86717
Solidity Ratio	σ		1.140642	1.140642	1.140642	1.140642
Speed of Blade	rΩ	m/s	2.7	2.7	2.7	2.7
Acial int. Factor	a	-	0.3	0.158903	0.247063	0.195934
Tang int. Factor	a'	-	0	1.1679	0.442012	0.680602
Angle of rel. wind	ϕ	deg	66.80141	52.28736	60.12027	57.91069
Angle of attack	α	deg	26.93424	12.42019	20.2531	18.04352
Coeff of Lift	Cl	-	0.852	1.0738	0.8632	0.8632
Coeff of Drag	Cd	-	0.2515	0.0582	0.1664	0.1664
y-comp	Cy	-	0.566784	0.702886	0.574311	0.599544
x-comp	Cx	-	0.684041	0.81387	0.66556	0.642923
Factor	F	-	1	1	1	1
Factor	K	-	5.227101	3.122308	4.590658	4.198389
Axial int. factor (1)	a_1	-	0.160588	0.242583	0.17887	0.192367
Axial int. factor(2)	a_2	-	0.158903	0.240912	0.178404	0.192308
Axial int. factor	a	-	0.158903	0.242583	0.178404	0.192367
Tang int. factor	a'	-	1.16798	0.921601	0.783719	0.687317
error a		%	-47.0324	52.66079	-27.7902	-1.82037
error a'		%	#DIV/0!	-21.089	77.30713	0.986604
Rel Speed	w	m/s	8.579454			
Tang Force	Fx	N/m	10.90391			
Axial Force	Fy	N/m	10.16822			
Power	Pr	W	27.81549			
Total power	P	W	5610.293			

Table XI. Iterative calculation of 1st blade element

APPENDIX B

PROPID CODE

```
# File: wt01a.in
# Analysis case
# Stall Regulated Turbine modeled loosely after the AOC 15/50
# Basic input
MODE 1.0          # wind turbine
INCV 0.0          # wind turbine mode
LTIP 1.0          # use tip loss model
LHUB 1.0          # use hub loss model
IBR 1.0           # use brake state model
ISTL 1.0          # use viterna stall model
USEAP  1.0        # use swirl suppression
WEXP 0.0          # boundary layer wind exponent
NS_NSEC 10.0  1.0  # number of blade elements/number of sectors
IS1   1.0         # first segment used in analysis
IS2  10.0         # last segment used in analysis
BE_DATA 1         # printout blade element data
SH 0.0            # shaft tilt effects
RHO 0.0023769     # air density (slug/ft^3)
# Geometry
HUB 0.08          # normalized hub cutout
HH 6.694          # normalized hub height
BN 3              # blade number
CONE 6.0          # cone angle of rotor (deg)
RD 9.802          # radius (ft)
CH_TW             # Normalized chord and twist distribution
0.119448      39.86717
   0.159206      23.00853
   0.13239       13.46005
   0.106463       7.975563
   0.087428       4.548758
   0.073635       2.238933
   0.063384       0.587596
   0.055538      -0.64746
   0.049369      -1.60418
   0.044404      -2.36625
# No stall models used
# CORRIGAN_EXPN 1
# Corrigan inputs are present but not used since stall model is off
AIRFOIL_MODE    4
4
s823.pd
.21  15.6  3  1.600  6
s823.pd
.21  15.6  3  1.600  6
s822.pd
.16  15.2  3  1.180  6
s822.pd
.16  15.2  3  1.100  6
# airfoil family 1 with 4 airfoils
# r/R-location and airfoil index
AIRFOIL_FAMILY    4
     .0000   1
     .3000   2
     .7500   3
    1.0000   4
# use the first airfoil family (the one above)
USE_AIRFOIL_FAMILY   1
# Enforce tip loss model to always be on
TIPON
# Use the Prandtl tip loss model,
# not the original modified model.
TIPMODE  2
# Design point: 172 rpm, 0deg pitch, 20.13 mph
DP  1  172.574  0  20.13  2
# Initiate design (does some required preliminary work before analysis)
IDES
# Determine the rotor power, Cp, and thrust curves (2D_SWEEP)
#
# use pitch setting from design point (DP) 1
PITCH_DP 1
# use rpm from design point (DP) 1
RPM_DP 1
# sweep the wind from 5 to 50 mph in increments of 1 mph
WIND_SWEEP  5  50  1  2
# perform the sweep
2D_SWEEP
# write out data to files
# 40 - power curve (kW) vs wind speed (mph)
# 45 - Cp vs TSR
# 51 - rotor thrust curve
WRITE_FILES  40 45 51
# Compute the gross annual energy production
# Output the data to file: gaep.dat
#
# Initial avg wind speed - 14 mph
# Final   avg wind speed - 18 mph
# Step                 -  2 mph
# Cutout                - 45 mph
#
# 100% efficiency
GAEP  14 18 2 45
#
# 15 mph only, 85% efficiency
# GAEP  15 15 1 45 .85
# Obtain aero distributions along the blade (1D_SWEEP)
#
PITCH_DP 1
RPM_DP 1
WIND_SWEEP 5 30 5 2
1D_SWEEP
# write out
# 75 - blade l/d  dist
# 76 - blade Re   dist
# 80 - blade alfa dist
# 85 - blade cl   dist
```

```
# 90 - blade a    dist
WRITE_FILES 75 76 80 85 90
# Write out
# 95 - chord dist (ft-ft)
# 99 - alfa  dist (ft-deg)
WRITE_FILES 95 99
# Write out the rotor design parameters to file ftn021.dat
DUMP_PROPID
```

APPENDIX C
AIRFOIL DATA

NREL S823														
Re	200000		Re	300000		Re	400000		Re	500000		Re	600000	
AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd
-4	-0.051	0.016	-4	-0.049	0.0142	-4	-0.048	0.0131	-4	-0.047	0.0123	-4	-0.047	0.0118
-3	0.057	0.0154	-3	0.059	0.0137	-3	0.061	0.0126	-3	0.062	0.0119	-3	0.062	0.0113
-2	0.166	0.015	-2	0.168	0.0133	-2	0.169	0.0123	-2	0.17	0.0115	-2	0.171	0.011
-1	0.274	0.0148	-1	0.276	0.0131	-1	0.278	0.0121	-1	0.279	0.0113	-1	0.279	0.0108
0.0	0.3810	0.0147	0.0	0.3840	0.0130	0.0	0.3860	0.0120	0.0	0.3870	0.0113	0	0.388	0.0107
1.0	0.4880	0.0148	1.0	0.4920	0.0131	1.0	0.4930	0.0121	1.0	0.4950	0.0114	1.0	0.4960	0.0109
2.0	0.5940	0.0150	2.0	0.5980	0.0133	2.0	0.6010	0.0123	2.0	0.6020	0.0116	2.0	0.6030	0.0110
3.0	0.7000	0.0154	3.0	0.7040	0.0136	3.0	0.7070	0.0126	3.0	0.7090	0.0118	3.0	0.7110	0.0113
4.0	0.8040	0.0159	4.0	0.8100	0.0141	4.0	0.8130	0.0129	4.0	0.8150	0.0122	4.0	0.8170	0.0116
5.0	0.9090	0.0167	5.0	0.9150	0.0148	5.0	0.9180	0.0136	5.0	0.9210	0.0128	5.0	0.9230	0.0122
6.0	1.0090	0.0178	6.0	1.0190	0.0157	6.0	1.0230	0.0145	6.0	1.0250	0.0136	6.0	1.0270	0.0130
7.0	1.1050	0.0195	7.0	1.1190	0.0172	7.0	1.1250	0.0159	7.0	1.1280	0.0149	7.0	1.1300	0.0142
8.0	1.1280	0.0255	8.0	1.1680	0.0232	8.0	1.1960	0.0218	8.0	1.2050	0.0207	8.0	1.2090	0.0199
9.0	1.0548	0.0331	9.0	1.1810	0.0270	9.0	1.2060	0.0255	9.0	1.2260	0.0244	9.0	1.2420	0.0235
10.0	0.9816	0.0408	10.0	1.1039	0.0351	10.0	1.1263	0.0336	10.0	1.1442	0.0325	10.0	1.2750	0.0261
11.0	0.9631	0.0531	11.0	1.0789	0.0474	11.0	1.1001	0.0459	11.0	1.1170	0.0448	11.0	1.2408	0.0385
12.0	0.9446	0.0654	12.0	1.0538	0.0597	12.0	1.0738	0.0582	12.0	1.0898	0.0572	12.0	1.2065	0.0508
13.0	0.9262	0.0777	13.0	1.0288	0.0721	13.0	1.0476	0.0706	13.0	1.0626	0.0695	13.0	1.1723	0.0632
16.0	0.8708	0.1146	16.0	0.9537	0.1090	16.0	0.9688	0.1076	16.0	0.9810	0.1065	16.0	1.0695	0.1003
20.0	0.7976	0.1732	20.0	0.8530	0.1678	20.0	0.8632	0.1664	20.0	0.8713	0.1653	20.0	0.9304	0.1593
25.0	0.8043	0.2581	25.0	0.8490	0.2528	25.0	0.8572	0.2515	25.0	0.8638	0.2504	25.0	0.9115	0.2446
27.5	0.8088	0.3146	27.5	0.8464	0.3095	27.5	0.8532	0.3082	27.5	0.8588	0.3072	27.5	0.8989	0.3015

Table XII. Airfoil Characteristics of NREL S823 for Reynolds Number of 2E+05 to 6E+05

NREL S822														
Re	400000		Re	500000		Re	600000		Re	700000		Re	800000	
AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd	AOA	Cl	Cd
-3	-0.042	0.0087	-3	-0.041	0.0081	-3	-0.04	0.0076	-3	-0.039	0.0072	-3	-0.037	0.0071
-2	0.062	0.0082	-2	0.065	0.0076	-2	0.068	0.0072	-2	0.07	0.007	-2	0.071	0.0068
-1	0.17	0.0081	-1	0.174	0.0076	-1	0.176	0.0072	-1	0.178	0.0069	-1	0.179	0.0067
0.0	0.2780	0.0083	0.0	0.2810	0.0077	0.0	0.2840	0.0073	0	0.286	0.007	0	0.287	0.0068
1.0	0.3840	0.0085	1.0	0.3880	0.0079	1.0	0.3910	0.0075	1.0	0.3930	0.0072	1.0	0.3940	0.0070
2.0	0.4900	0.0088	2.0	0.4940	0.0082	2.0	0.4970	0.0077	2.0	0.4990	0.0074	2.0	0.5010	0.0072
3.0	0.5930	0.0091	3.0	0.5990	0.0084	3.0	0.6020	0.0080	3.0	0.6050	0.0076	3.0	0.6070	0.0074
4.0	0.6940	0.0095	4.0	0.7030	0.0088	4.0	0.7070	0.0083	4.0	0.7100	0.0079	4.0	0.7120	0.0076
5.0	0.7930	0.0099	5.0	0.8030	0.0091	5.0	0.8110	0.0087	5.0	0.8150	0.0083	5.0	0.8170	0.0081
6.0	0.8890	0.0104	6.0	0.9040	0.0097	6.0	0.9110	0.0092	6.0	0.9160	0.0089	6.0	0.9200	0.0086
7.0	0.9490	0.0182	7.0	0.9570	0.0174	7.0	0.9640	0.0167	7.0	0.9690	0.0162	7.0	0.9740	0.0158
8.0	0.8925	0.0254	8.0	1.0370	0.0195	8.0	1.0440	0.0189	8.0	1.0500	0.0183	8.0	1.0550	0.0178
9.0	0.8360	0.0327	9.0	0.9732	0.0272	9.0	0.9795	0.0266	9.0	0.9849	0.0260	9.0	0.9894	0.0255
10.0	0.7795	0.0399	10.0	0.9094	0.0348	10.0	0.9150	0.0342	10.0	0.9197	0.0336	10.0	0.9237	0.0331
11.0	0.7719	0.0522	11.0	0.8949	0.0471	11.0	0.9001	0.0466	11.0	0.9046	0.0460	11.0	0.9084	0.0455
12.0	0.7643	0.0645	12.0	0.8803	0.0595	12.0	0.8852	0.0589	12.0	0.8895	0.0583	12.0	0.8930	0.0578
13.0	0.7567	0.0768	13.0	0.8657	0.0718	13.0	0.8703	0.0712	13.0	0.8743	0.0706	13.0	0.8776	0.0701
14.5	0.7453	0.0953	14.5	0.8438	0.0903	14.5	0.8480	0.0897	14.5	0.8516	0.0891	14.5	0.8546	0.0886
15.5	0.7377	0.1076	15.5	0.8292	0.1026	15.5	0.8331	0.1021	15.5	0.8365	0.1015	15.5	0.8393	0.1010
16.5	0.7301	0.1199	16.5	0.8146	0.1150	16.5	0.8182	0.1144	16.5	0.8213	0.1138	16.5	0.8239	0.1133
17.5	0.7225	0.1322	17.5	0.8000	0.1273	17.5	0.8033	0.1267	17.5	0.8062	0.1261	17.5	0.8085	0.1257
18.0	0.7187	0.1383	18.0	0.7927	0.1335	18.0	0.7959	0.1329	18.0	0.7986	0.1323	18.0	0.8009	0.1318
19.0	0.7111	0.1507	19.0	0.7781	0.1458	19.0	0.7810	0.1452	19.0	0.7835	0.1446	19.0	0.7855	0.1442
20.0	0.7062	0.1724	20.0	0.7650	0.1676	20.0	0.7675	0.1670	20.0	0.7697	0.1664	20.0	0.7715	0.1660
21.0	0.7089	0.1818	21.0	0.7664	0.1770	21.0	0.7689	0.1764	21.0	0.7710	0.1759	21.0	0.7728	0.1754
22.0	0.7143	0.2007	22.0	0.7693	0.1959	22.0	0.7717	0.1953	22.0	0.7737	0.1948	22.0	0.7754	0.1943
25.0	0.7305	0.2572	25.0	0.7780	0.2526	25.0	0.7800	0.2520	25.0	0.7817	0.2515	25.0	0.7832	0.2510
27.5	0.7467	0.3138	27.5	0.7866	0.3093	27.5	0.7883	0.3087	27.5	0.7898	0.3082	27.5	0.7910	0.3078

Table XIII. Airfoil Characteristics of NREL S822 for Reynolds Number of 2E+05 to 6E+05