

Design, and Manufacturing of Horizontal Axis Wind Turbine Blade

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ABSTRACT

The whole world is pushing towards clean and green energy and obviously the renewable energy sources are the best alternative for the present world. The wind energy easily available renewable energy source. Many horizontal axis wind turbines are built, installed and running successfully but the design needs to be improved in order to achieve maximum power output and minimum cost of production. A successful design of efficient wind turbine, uses aerodynamic considerations of the blade contour and the material is so selected to ensure the necessary strength and stiffness. In choosing the aerodynamic characteristics of a wind turbine blade, the parameters of the blade contour have to be optimized, thence the loads have to be estimated for the structural adequacy. This paper throws some light on designing the Rotor Blades of the horizontal axis wind turbine so that the turbine gives maximum power output, with maximum efficiency and thereby reducing other power losses. The design of the blade is made for higher strength of the blade and good resistance thrust during high wind speeds consequently increasing the durability of the wind turbine. The cross section of the blade is designed by aerofoil shape using NACA 4 Digit series and NREL'S S-series airfoils.

Keywords: Wind turbine, NACA 4 digit series, NREL'S S-series, aerofoil, CFD and tip speed ratio.

I. INTRODUCTION

Wind energy is the most easily available resource in comparison with other renewable resources. moreover, unlike the solar energy, the utilization could not be affected by the climate and weather. Since the wind is converted to electric energy, the machine can also be called wind generator. Wind turbine is composed of several main parts, such as, rotor, generator, driven chain, control system and so forth. the rotor due to wind rotates at predefined speed, thereby the generator produces electric energy which is regulated by the control system. The maximum kinetic energy from wind, can be sought by the design of effectiveness in blade geometry. During the early stages, the airfoils of helicopters were used for wind turbine blade design, but in present days, many specific airfoils are in use for wind turbine blade design. The theoretical studies restrict researchers to field testing and wind tunnel testing, that requires a big amount of efforts and resources. with advent of computer aided design codes, it paved a path to design and analyze the wind turbine blades in an effective way. thence, computational fluid dynamics (CFD) can be employed for analyzing the aerodynamic performance of wind turbine blades,

II. OBJECTIVES

The fore most objective of this paper is to Design the rotor blades of the horizontal axis wind turbine by taking different airfoils cross sections and changing the design parameters for each design. A total of three designs are to be made of different design parameters and blade contours. The cross-section of these blades is designed by aerofoil profiles employing NACA 4 Digit series and NREL'S S-series airfoils through various twist angles as well as angles of attack in each blade design.

Analysis of these three blade designs is done on Q blade Software which is based upon Blade Element Moment theory or Actuator Disk theory. The outcome of the simulation provides a platform to compare aerodynamic characteristics and aerodynamic design efficiency of the blades. The best design is then selected for further in depth analysis.

III. DESIGN METHODOLOGY OF HORIZONTAL AXIS WIND TURBINE BLADE

The different shapes for wind turbine blades and aircraft wings have been developed by National Advisory Committee for Aeronautics (NACA). The airfoil is the most important and fundamental element in building a

wind turbine blade. Airfoil characteristics can be used to find the performance of the wind turbine, expressed in Lift coefficient (CL) and drag coefficient (CD) of airfoil is the central for designing a wind turbine.

A: NACA four digit series:

The first family of airfoils designed using this approach became known as the NACA Four-Digit Series. In the following way.

The 1st digit: indicates the maximum camber (m) in percentage of the chord (airfoil length),

The 2nd digit: portrays the position of the maximum camber (p) in tenths of chord, and

The 3rd and 4th digits: specify the maximum thickness (t) of the airfoil in percentage of chord. The camber lines were identical to the 4-digit series. The numbering system for these airfoils is defined by: NACA MPXX

Where XX is the max. thickness and t/c is percent chord.

M is the max. value of the mean line in 100ths of chord,

P is the chord wise position of the maximum camber in tenths of the chord.

E.g.: NACA 2412

B: NREL's S-Series airfoils

By using the NREL airfoils, which are specifically designed for HAWTs, the annual energy production loss due to airfoil roughness effects can be curtailed to half relative to previously used aircraft airfoils.. In addition, the airfoils are often scaled to a larger thickness that generally give rise to undesirable performance characteristics. The performance characteristics of the NACA series of airfoils, for instance, deteriorate quite rapidly when airfoil thickness is raised.

IV. DESIGN CALCULATIONS OF THE WIND TURBINE BLADE

The design of one blade i.e. the S-SERIES blade is shown figure 1.. The design of the remaining two blades are similar. Before undergoing calculations, wind tunnel simulation of the chosen airfoils must be done to know the best values of angle of attack. The airfoils selected for first blade are S-818, S-825, and S-826.

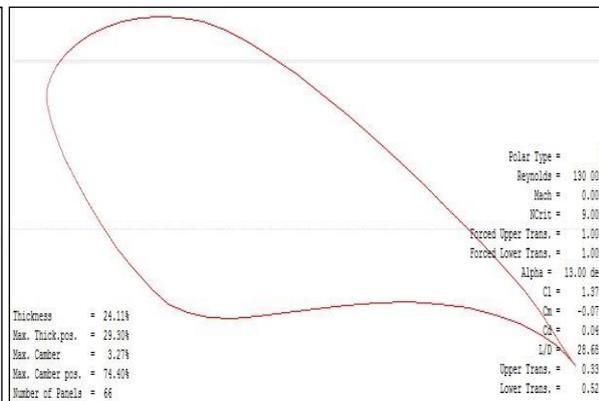
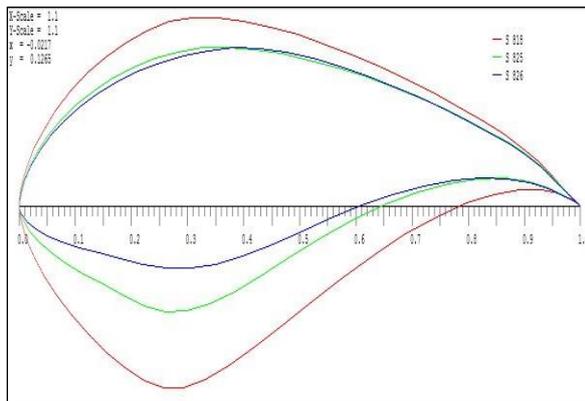


Fig 1: S-818, S-825, S-826 Airfoils

Fig 2: S-818 airfoil at an angle of attack of 13°

A: Wind tunnel simulation results:

The calculations of **S-818**- blade airfoil after wind tunnel simulation, the maximum lift to drag ratio of **28.684** at angle of attack of **13°**. The calculations of **S-825** –blade airfoil after wind tunnel simulation, the maximum lift to drag ratio of **56.690** at angle of attack of **9°**.

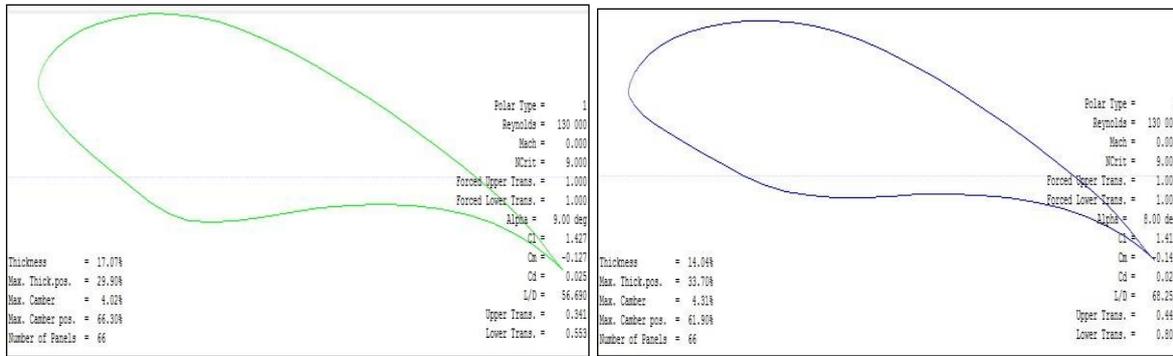


Fig 3 : S-825 airfoil at an angle of attack of 9° Fig 4: S-826 airfoil at an angle of attack of 8°

The calculations of S-826- blade airfoil after wind tunnel simulation, the maximum lift to drag ratio of 68.259 at angle of attack of 8°. The blade length of all blades is considered to be 1 m each. So after knowing the length of the blade, length is split into different sections/stations. At these stations different airfoils are used. The table below shows the total number of stations present and their positions. Also the corresponding airfoils which are used in those stations are shown.

Table 1: Design Dimensions of S-818 Series Blade.

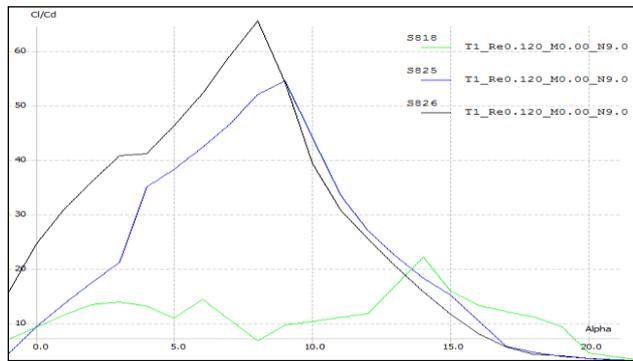


Fig 5: Cl/Cd vs. Angle of Attack of S-818 , S-825 & S-826 Blade Length = 1m= 1000 mm.

S. NO	POSITION(mm)	AIRFOILS USED
1	0	CIRCLE
2	45	CIRCLE
3	75	S-818
4	175	S-818
5	275	S-818
6	375	S-818
7	475	S-825
8	575	S-825
9	675	S-825
10	775	S-825
11	875	S-826
12	975	S-826
13	1000	S-826

V. DESIGN CONSIDERATION

A: The blade which is designed for TSR = 8 and rated wind velocity is at 12m/s So, $V_w = 12m/s$, $TSR = 8$ and $TSR = \Omega R / V_w$ Therefore the $R = 1.025 m$ and the results are $\Omega = TSR * V_w / R = 8 * 12 / 1.025 = 93.84 rad/sec$.

B: Calculation of twist angles Twisted blades = less drag = more energy can be converted to work so higher efficiency.

3rd Station:

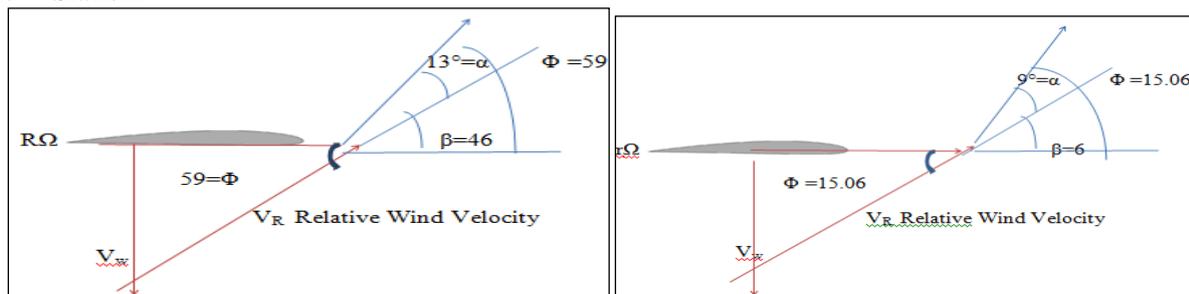


Fig 6: Twist Angle of 3rd Station (S-818 Airfoil) Fig 7: Twist Angle of 7th Station (S-825 Airfoil) Where, r = blade 1st section height 75mm, Ω = angular velocity of rotor in rpm.

V_w = velocity of wind in miles/sec, α = angle of attack, β = twist angle Φ = angle of incidence, R = rotor radius in m.

$r\Omega = .075 * 93.84 = 7.038 \text{ m/s}$

C:Hypothesis:

$(V_R)^2 = (V_w)^2 + (r\Omega)^2$ $(V_R)^2 = (12)^2 + (7.038)^2$ and $V_R = 13.91 \text{ m/sec}$

D:Angle of incidence:

$\Phi = \text{Tan}^{-1} (V_w/r\Omega) = \text{Tan}^{-1} (12/7.038)$, $\Phi = 59$

Angle of attack $\alpha = 13^\circ$

$\beta = 59^\circ - 13^\circ = 46^\circ$, Therefore twist angle $\beta = 46^\circ$

The Twist angle of blades can be explained by velocity triangles. In this work the blade is divided in four sections and each section can be explained by velocity triangles, with an angle of attack 6° .

E:7th Station:

$r\Omega = 0.475 * 93.84 = 44.574$

F:Hypothesis:

$(V_R)^2 = (V_w)^2 + (r\Omega)^2$ $(V_R)^2 = (12)^2 + (44.574)^2$

$V_R = 46.16 \text{ m/sec}$

G:Angle of incidence :(Φ)

$\Phi = \text{Tan}^{-1} (V_w/r\Omega) = \text{Tan}^{-1} (12/44.574)$

$\Phi = 15.06^\circ$ Angle of attack $\alpha = 9^\circ$ $\beta = 15.06^\circ - 9^\circ = 6^\circ$

Therefore twist angle $\beta = 6^\circ$

G1:11th Station:

G2:Hypothesis:

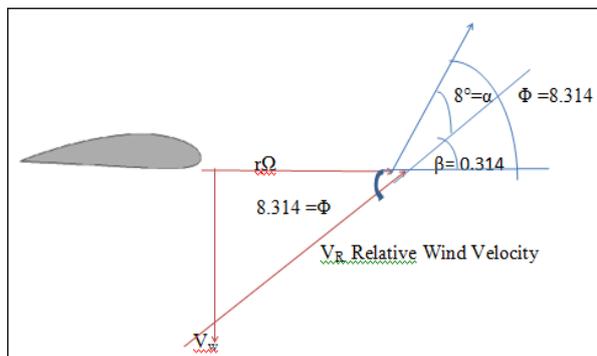
$(V_R)^2 = (V_w)^2 + (r\Omega)^2$, $(V_R)^2 = (12)^2 + (82.11)^2$, $V_R = 82.98 \text{ m/s}$

G.2.1:Angle of incidence :(Φ) $\Phi = \text{Tan}^{-1} (V_w/r\Omega) = \text{Tan}^{-1} (12/82.11)$, $\Phi = 8.314$

G.2.2:Angle of attack $\alpha = 8^\circ$, $\beta = 8.3314^\circ - 8^\circ = 0.314^\circ$, Therefore twist angle $\beta = 0.314^\circ$

$r\Omega = 0.875 * 93.84 = 82.11 \text{ m/s}$ So in the similar way twist angles of other stations are also calculated.

Fig 8:Twist Angle of 11th Station (S-826 Airfoil



2: Final Design Dimensions of S-818 Series Blade.

SERIAL NO	POSITION(mm)	TWIST ANGLE	CHORD LENGTH H(mm)	AIRFOILS USED
1	0	0	50	CIRCLE
2	45	0	50	CIRCLE
3	75	46	62	S-818
4	175	24	74	S-818
5	275	11.5	75	S-818
6	375	7	68	S-818
7	475	6	61	S-825
8	575	4.15	54	S-825
9	675	3.25	47	S-825
10	775	1.25	40	S-825
11	875	0.314	33	S-826
12	975	0.05	27	S-826
13	1000	0	25	S-826

It is very difficult to compute the chord length of the blade by conventional relations and formulas. The conventional formulas give unexpected results and unrealistic chord lengths, therefore, the chord lengths have to be estimated. The design data chart has been used to approximate the values of chord length for the 1000 mm length blade. In the above chart C/R is the ratio of chord length to the total length of the blade and r/R is the ratio of position to the total length of the blade. Thus all the necessary design parameters and data are calculated. So this S-818 series blade becomes the first blade design. And the remaining 2 designs are NACA 44 Series blade design and NREL'S-808 Series blade design respectively.

Table 3: Design Data Chart of Original Wind Turbine

Element	r/R	Twist °	C/R	Airfoil	Position (m)	Airfoil
1	0.075	42	0.0614	S818	0.000 m	S826
2	0.125	32	0.06826		0.075 m	S826
3	0.175	23	0.07452		0.150 m	S825
4	0.225	15	0.07782		0.225 m	S825
5	0.275	11.5	0.07543		0.300 m	S825
6	0.325	8.2	0.07188		0.375 m	S825
7	0.375	7	0.06832		0.450 m	S825
8	0.425	6	0.06479		0.525 m	S825
9	0.475	5	0.06126	S825	0.600 m	S825
10	0.525	4	0.05771		0.675 m	S825
11	0.575	4.15	0.05415		0.750 m	S818
12	0.625	3.85	0.05062		0.825 m	S818
13	0.675	3.25	0.04707		0.900 m	S818
14	0.725	2.75	0.0436		0.975 m	S818
15	0.775	1.25	0.04024	S826	0.075 m	S818
16	0.825	0.75	0.03704		0.045 m	S818
17	0.875	0.55	0.03385		0.000 m	S818
18	0.925	0.85	0.03066			Circular Foil
19	0.975	0.05	0.02747			Circular Foil

Fig 9: Preview of S-818 Series Blade Design.

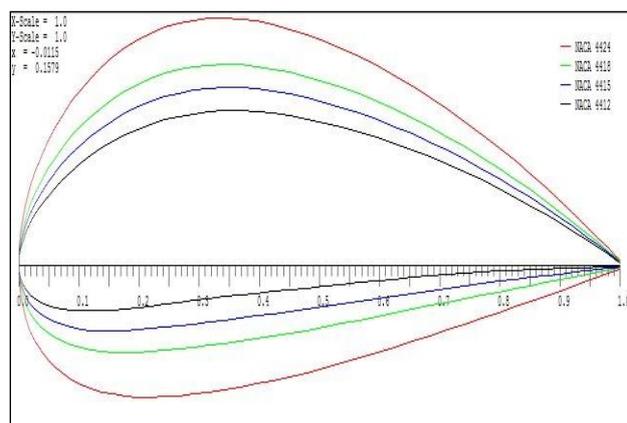
Similar calculation process can be used for knowing the design parameters and data of remaining 2 designs which are NACA 44 Series and S-808 Series blade.

H: The estimating the design parameters and data

1. The Length of the blade is fixed at 1000 mm. The selected airfoils for the blade design are undergone virtual wind tunnel simulation and testing.
2. From the results obtained from the wind tunnel simulation the best Angle of Attack (AoA) is chosen for each airfoil. The best Angle of Attack is the angle at which that particular airfoil gives maximum lift to drag ratio.
3. Twist angle is calculated based on the best Angle of attack by using the relations which are present.
4. Finally the Chord length is approximated by using standard design data charts of original wind turbines working currently.
5. For the remaining 2 blade designs, NACA 44 Series and S-808 Series the same process is followed for calculation of design parameters.

VI. NACA 44 SERIES AIRFOIL BLADE DESIGN

Table 3: Dimensions Of NACA 44 Series Blade



SERIAL NO	POSITION(m)	TWIST ANGLE	CHORD LENG TH(m)	AIRFOILS USED
1	0	0	100	CIRCLE
2	50	0	100	CIRCLE
3	150	32.44	140	NACA 4424
4	250	18.04	180	NACA 4424
5	350	11	160	NACA 4418
6	450	7	140	NACA 4418
7	550	4	120	NACA 4415
8	650	2	100	NACA 4415
9	750	0.67	80	NACA 4415
10	850	0.4	60	NACA 4412
11	900	0.2	50	NACA 4412
12	1000	0	10	NACA 4412

Fig 10: NACA 4424,4414,4415,4412 Airfoils

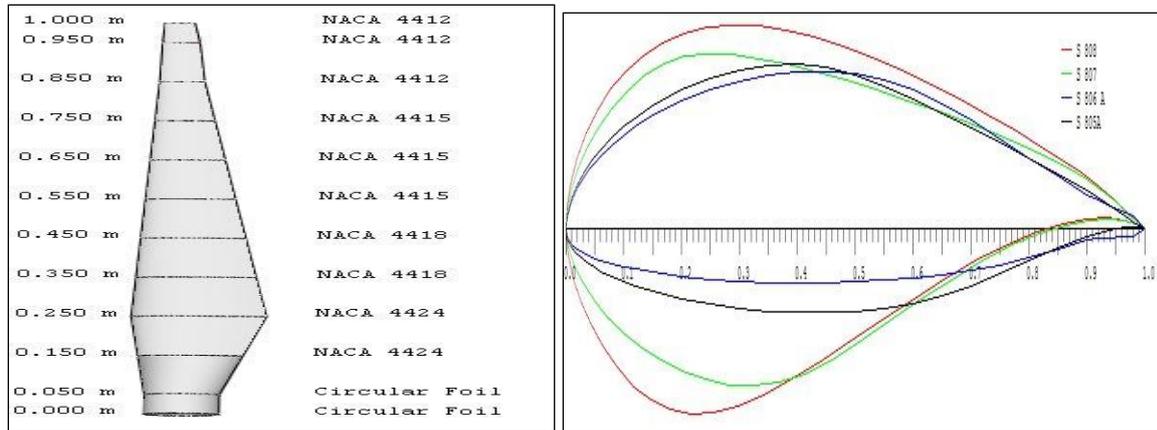


Fig 12: Preview NACA 44 Series Airfoil Blade Design Fig 13: S-808,807, 806A, 805A Airfoils

All the calculated values of the design dimensions of the NACA 44 Series blade are exhibited in the Table 3 and Figure 12. This blade is designed and modeled based on the above parameters and data only.

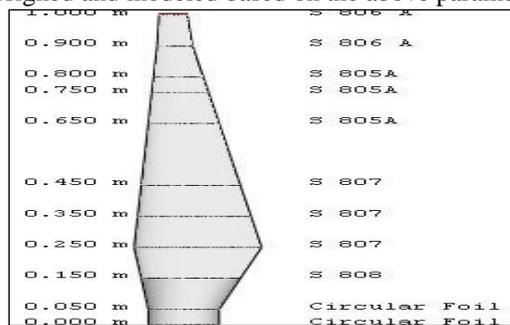


Fig 14: Preview of S-808 Series Airfoil Blade Design

All the calculated values of the design dimensions of the S-808 Series blade are exhibited in the Table 3 and Figure 13. This blade is designed and modeled based on the above parameters and data.

Having calculated all the design parameters and design data, the blade can be easily modeled using SolidWorks Software.

Modeling of all the 3 blade designs is done on SolidWorks software and after that static CFD analysis is done on these models.

VII. MODELING OF HORIZONTAL AXIS WIND TURBINE BLADES

A: Modeling of blade design in SolidWorks:

The entire blade design is modeled in SolidWorks Software. The three blades created from one blade model shown in figure 16.

B: Final design of 3 blades after modeling

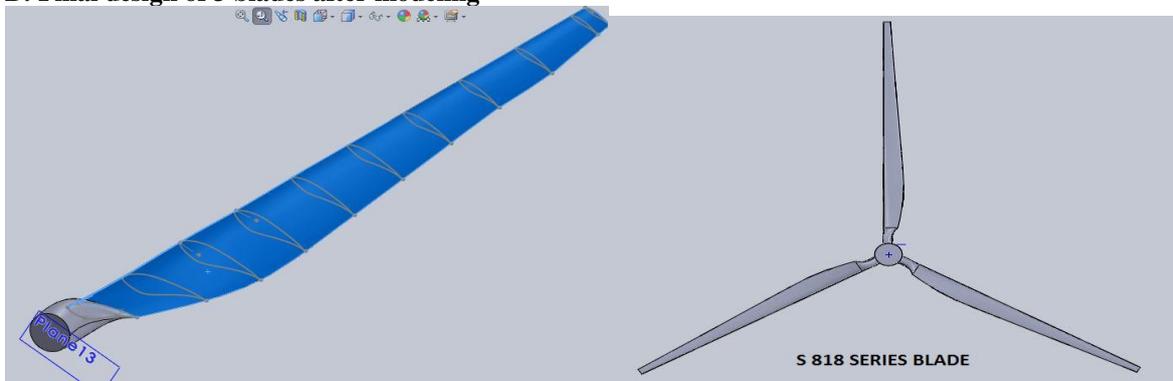


Fig 15: Lofting of Airfoils to make Blade Surface:

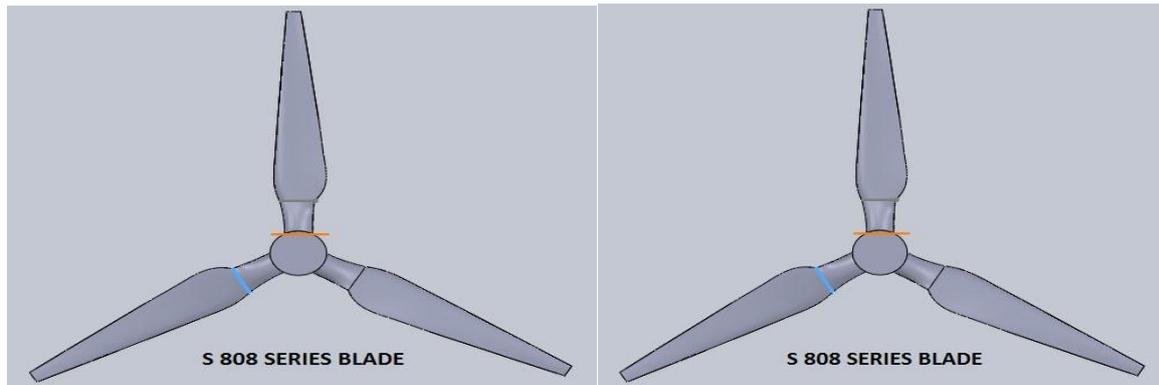


Fig 16: S-818 Series, NACA Series and S-808 Series blades after modeling

C: Primary analysis of the blade

The primary analysis of the above 3 blade designs is carried out on Q blade software. The Q blade software works on the principle of Blade Element Momentum (BEM) theory or disk actuator theory, a mathematical model of an ideal actuator disc, with the blade element theory, which describes the local events taking place at the actual blade. The blade is discretized into a finite number of blade elements. Two sections bound an element to sweep the rotor plane on a circular path. The blade cross sections are defined by their radial position, profile, chord, twist and length. With the momentum theory, the relative wind speed for every section can be computed. This permits the computation of the angle of attack and the derivation of the CL and CD of the respective profile out of a table. With these coefficients and the area of an element the normal and tangential force components, thus the thrust and torque of an element are computed. The element's contributions can then be added up to yield the final thrust and torque of the whole rotor.

The input values for analysis are Tip Speed Ratio TSR=7, Wind velocity =12 m/s, Loss Factor = 0.3 Fixed pitch angle of 4°

D: Lift to drag ratio:

The maximum lift to drag ratio at tip is 47 and at middle is 37.5 of NACA series blade

The maximum lift to drag ratio at tip is 38 and at middle is 24 of S-808 series blade

The maximum lift to drag ratio at tip is 60 and at middle is 49 of S-818 series blade.

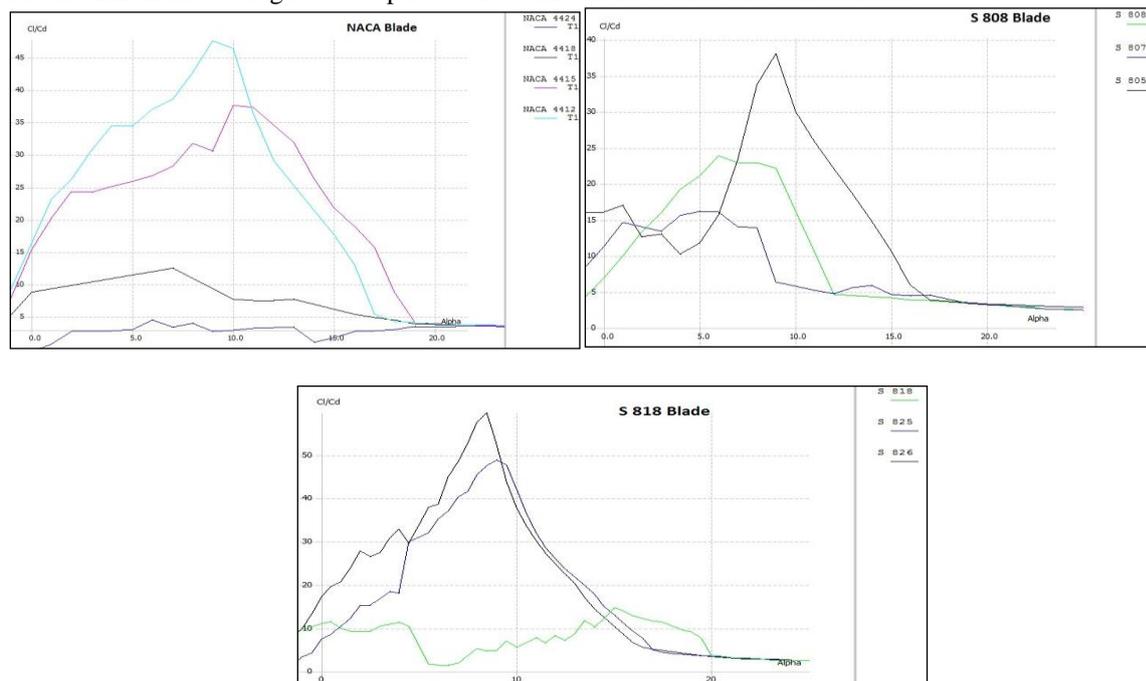


Fig 17: Lift to Drag Ratio vs. angle of attack graphs of 3 blades.

VIII.POWER DEVELOPED BY THE TURBINE

The power developed by NACA series blade is 552.6 Watts; S808 series blade is 310.8 Watts and S818 series blade is 715 Watts as shown in figure 18,19 and 20.

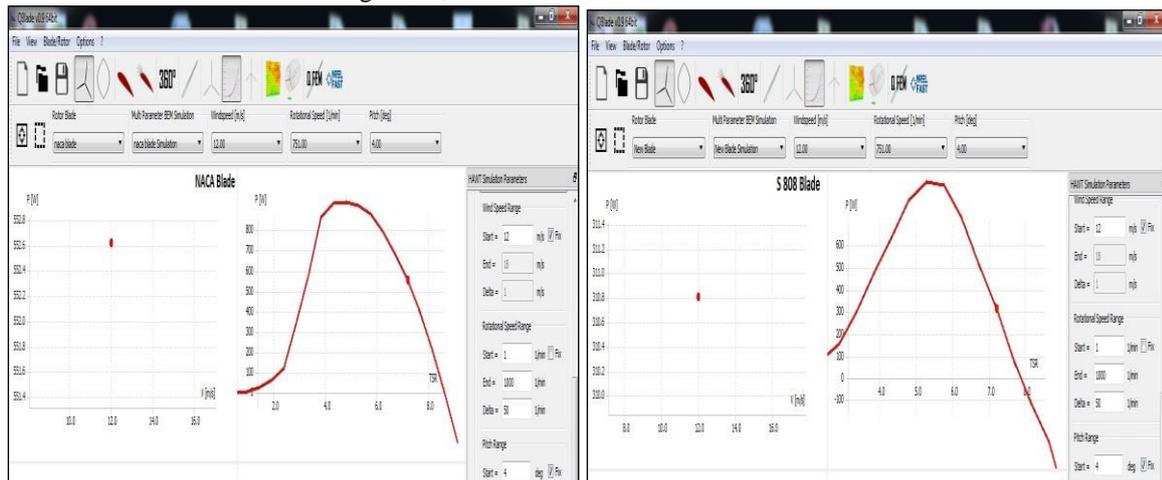


Fig 18: Power developed by the NACA series blade Fig 19: Power developed by the S-808 series blade

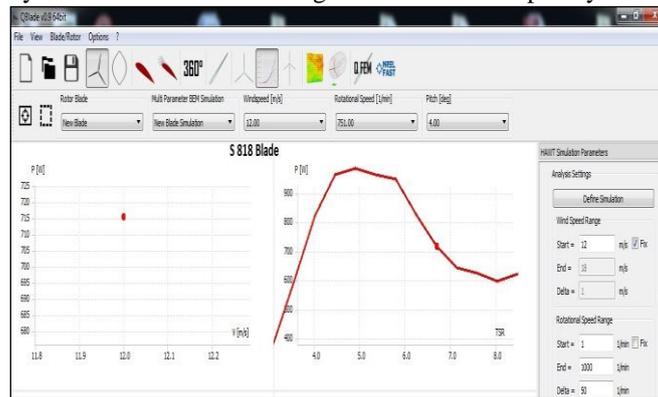


Fig 20: Power developed by the S-818 series blade

IX.TORQUE AND BENDING MOMENT

- A:The Torque generated by the wind at 12m/s in NACA Series blade is 5 Nm
- B:The Torque generated by the wind at 12m/s in S-808 Series blade is 4 Nm
- C:The Torque generated by the wind at 12m/s in S-818 Series blade is 6.4 Nm
- D:The Bending Moment of NACA series blade at 12 m/s wind speed is 68 Nm
- E:The Bending Moment of S-808 series blade at 12 m/s wind speed is 55 Nm
- F:The Bending Moment of S-818 series blade at 12 m/s wind speed is 30 Nm as shown in below

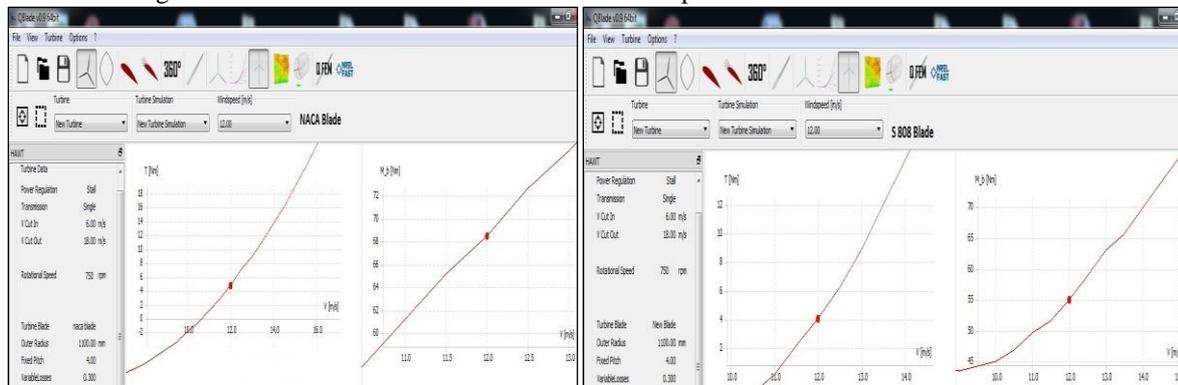


Fig 21: Torque and Bending Moment value of Fig 22: Torque and Bending Moment value of S-808 NACA series blade series blade

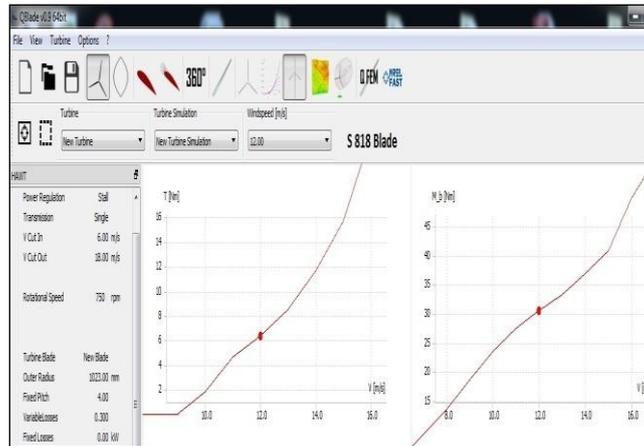


Figure 23: Torque and Bending Moment value of S-818 series blade

G: POWER AND COEFFICIENT OF POWER WITH LOSS FACTOR OF 0.3

H:The power generated by NACA series blade is 285 Watts with a Cp of 0.10

I:The power generated by S-808 series blade is 220 Watts with a Cp of 0.09

J:The power generated by S-818 series blade is 420 Watts with a Cp of 0.18

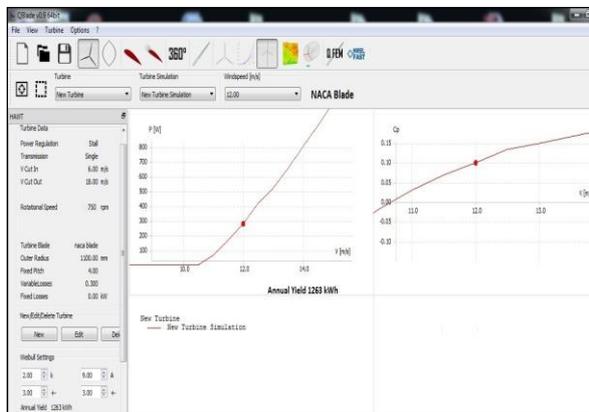


Fig24: Power and Coefficient of Power values of NACA series blade

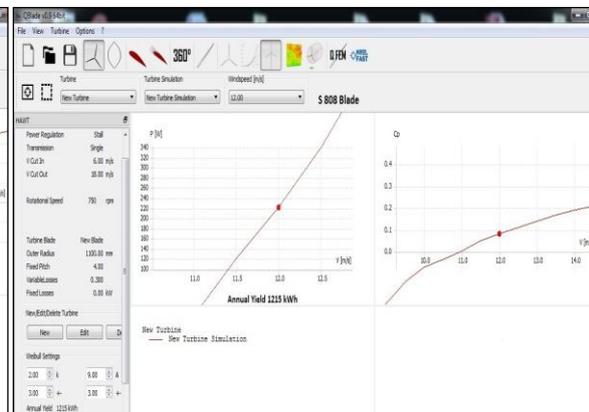


Fig 25: Power and Coefficient of Power values of S-808 of series blade

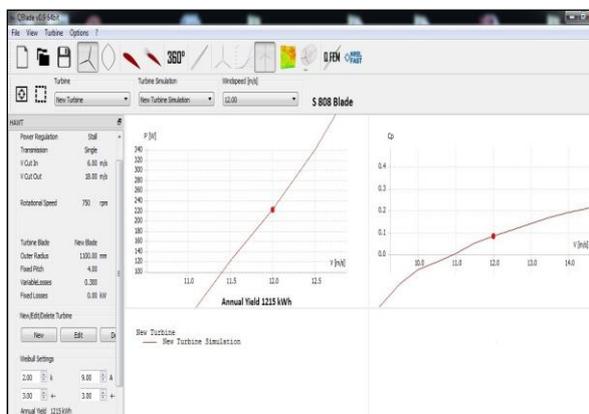


Fig25: Power and Coefficient of Power values of S-808 series blade

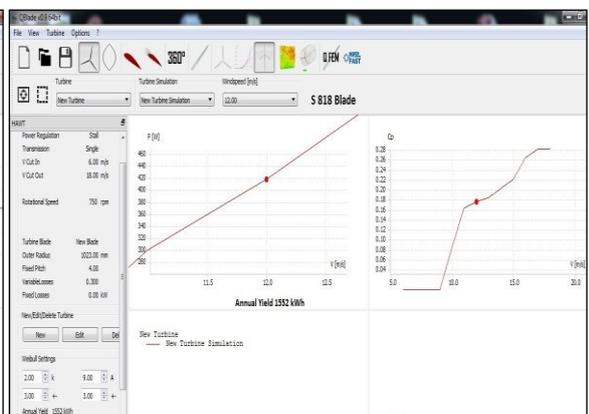


Fig 26: Power and Coefficient of Power values of S-S-808 series blade 818 series blade

X. COMPARISON OF RESULTS

Table 5: Comparison of results obtained from Qblade software

PARAMETERS		NACA SERIES BLADE	S-808 SERIES BLADE	S-818 SERIES BLADE
Lift/Drag	Tip	47	38	60
	Middle	37.5	24	39
Power developed		52.6 Watts	52.6 Watts	52.6 Watts
Torque		5 Nm	5 Nm	5 Nm
Bending Moment		68 Nm	68 Nm	68 Nm
Power generated at loss factor of 0.3		285 Watts	285 Watts	285 Watts
Cp Coefficient of Performance		0.10	0.10	0.10
Annual Yield		1263 kWh	1263 kWh	1263 kWh

From the above results it is clear that the s-818 series blade is the best in all parameters. Therefore S-818 blade design is selected for further analysis.

XI. MANUFACTURING PROCESS OF THE WIND TURBINE BLADE:

A: Composite materials

A composite material is formed by combining two or more materials to achieve some superior properties. By combining two or more materials together, we can tailor make composite materials, which are lighter and stiffer, stronger than any other materials man has ever used. A variety of materials, which we see around us, are composites e.g. wood, bones etc.

B: Requirements of blade materials:

1. High stiffness to ensure aerodynamic performance as well as structural rigidity.
2. Low density to minimize mass.
3. Wear resistance.
4. Corrosion resistance.

C: Extruded Polystyrene (XPS) foam

The Extruded Polystyrenes foams are widely used as insulating and core materials for furniture, cooling and freezing systems, in house building, shipbuilding etc. The use of rigid foams is resulted from their low heat conduction coefficient, low density, low water absorption, relatively good mechanical strength.

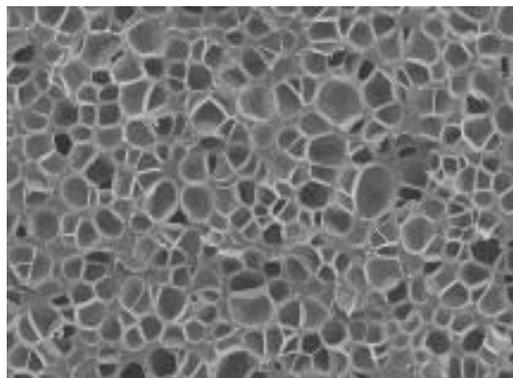


Fig 27: Microscopic View of Extruded Polystyrene foam

6.3 Fiber glass

Glass fiber also called fiberglass. It is material made from extremely fine fiber of glass which is lightweight, extremely strong, and robust material. Though strength properties are slightly lower than that of carbon fiber and it is less stiff, the material is typically far less brittle, and the raw materials are less expensive.

Fiberglass is an immensely versatile material due to its light weight, inherent strength, weather-resistant finish and variety of surface textures. While various materials have been applied successfully in wind turbine blades, fiberglass based composites predominate. The manufacture process of horizontal axis wind turbine blades is by the skin lamination technique. In which the upper skin, lower skin has a glass fiber and in between both skins a plastic core sheet of Extruded Polystyrene foam is placed.

D: Manufacturing procedure

1. There are 11 airfoils used at different stations in the blade of S-818 series blade. These airfoils consist of S-818, S-825, and S-826 profiles of different chord lengths profiles are cut out from the plywood sheet by taking the profiles in the paper as reference.
2. Hole is drilled on each and every template at a distance of 30% of its chord length from the leading edge. This hole can also be represented as centre of mass of the airfoil. Carbon fiber rod inserted into these holes of all airfoils and all airfoils are adjusted at their respective positions as per the design.
3. The airfoils angles are changed and fixed to incorporate the twisting of blade. Hence skeleton structure of the blade is achieved.



Fig 28: Carbon fiber rod inserted inside the airfoil profiles
 Fig 29: Airfoil profiles are fixed at different angles to incorporate twisting

4. The XPS Foam is cut into sections and pieces and kept in between two airfoils. In this manner all the vacant spaces between consecutive airfoils are occupied by the pieces of XPS. These XPS Foam pieces are fixed rigidly with the carbon fiber rod and airfoils by using Glue Gun and Araldite epoxy adhesive.
5. The rough and smooth file along with the emery papers are used to bring the XPS foam pieces in shape in order to match the airfoils. This shaping process is continued till a perfect blade shape is achieved. The XPS foam and the airfoils match quite well and an even surface with smooth finish is obtained.



Fig 30 : XPS Foam inserted between the airfoil profiles
 Fig 31: XPS Foam is shaped by emery paper to match the airfoil profiles

6. After continuous shaping, finally a smooth shape of the blade is obtained. The contour of XPS Foam is completely in shape with the airfoil profiles. Any small unevenness can be covered at the time of lamination with glass fiber.

6. The skin lamination technique is followed in which the upper skin, lower skin has a glass fiber and in between both skins a plastic core sheet of Extruded Polystyrene foam is placed similar like a sandwich process. The whole blade surface consisting of XPS and airfoils is covered with glass fiber. Then Epoxy Resin is applied all over the blade surface covered with glass fiber. Then the blade is left to cure for 24 hours



Figure 32: Blade laminated by glass fiber
 Figure 33: Blade after surface finishing

7. After curing the final blade is obtained with perfect finish. The blade is then painted in order to give aesthetic value and prevent it from harsh environmental conditions.



Figure 34: Top view of the blade after painting Figure 35: Front view of the blade after painting

XII. CONCLUSIONS

An attempt has been made to understand the designing procedure of a wind turbine blade. The wind turbine blade design is very typical consisting of several design parameters and all these design parameters should be balanced so as to achieve an efficient blade design.

REFERENCES

- [1] Mishnaevsky, L., Branner, K., Petersen, H., Beauson, J., McGugan, M. and Sørensen, B., 2017. Materials for wind turbine blades: an overview. *Materials*, 10(11), p.1285.
- [2] Holmes, J.W., Sørensen, B.F. and Brøndsted, P., 2007. Reliability of wind turbine blades: An overview of materials testing. *Proceedings of the Wind Power Shanghai*.
- [3] Manwell, J.F., McGowan, J.G. and Rogers, A.L., 2010. *Wind energy explained: theory, design and application*. John Wiley & Sons.
- [4] Lawrence, K.L., 2010. *ANSYS workbench tutorial: structural & thermal analysis using the ANSYS workbench release 12.1 environment*. SDC Publications.
- [5] Schubel, P.J. and Crossley, R.J., 2012. Wind turbine blade design. *Energies*, 5(9), pp.3425-3449.
- [6] Schubel, P.J. and Crossley, R.J., 2012. Wind turbine blade design. *Energies*, 5(9), pp.3425-3449.
- [7] Rani, M.U., Ayyanna, M., Hussain, P., Reddy, A.R. and Babu, S.S., STATIC AND FATIGUE ANALYSIS OF WIND TURBINE BLADE.
- [8] Marten, D. and Wendler, J., 2013. Qblade guidelines. *Ver. 0.6, Technical University of (TU Berlin), Berlin, Germany*.
- [9] Hansen, M.O., 2008. Aerodynamics of wind turbines, Earthscan. *James & James*, 8(9), p.14.
- [10] Hansen, M.O., 2008. Aerodynamics of wind turbines, Earthscan. *James & James*, 8(9), p.14.
- [11] Tangler, J., 2000. *The evolution of rotor and blade design* (No. NREL/CP-500-28410). National Renewable Energy Lab., Golden, CO (US).
- [12] Cowgill, R.T., Fouts, J., Haley, B. and Whitham, C., 2006. Wind Turbine Rotor Design. *Final Design Report*, ME480, Senior Design Project, Boise State University College of Engineering.
- [13] Cowgill, R.T., Fouts, J., Haley, B. and Whitham, C., 2006. Wind Turbine Rotor Design: Final Design Report. *College of Engineering, Boise State University*, pp.1-36.
- [14] Cowgill, R.T., Fouts, J., Haley, B. and Whitham, C., 2006. Wind Turbine Rotor Design. *Final Design Report*, ME480, Senior Design Project, Boise State University College of Engineering.