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Design Model of Horizontal Axis Wind Turbine Blade at Technological University (Thanlyin)

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Abstract: In this study, a horizontal axis wind turbine (HAWT) blade with 1 kW power output has been designed for Technological University (Thanlyin) and the blade aerodynamics are also simulated to investigate its flow structures and aerodynamic characteristics. As the technology of wind power generation is improved; the blade of wind turbine is becoming the main sector for perfect and effective design. The designed wind turbine blade should have enough strength, stiffness, elasticity, hardness and stability. Therefore, modeling and strength check of wind turbine blade is very important for the designing of wind turbines. This paper purposes to express the design calculation and strength check of HAWT blade. In this paper, the selection of airfoil shape from NACA series was done by using Comsol Multiphysics software and the 3D model of blade was proactive by using Design Foil and SolidWorks software. Finite element analysis on the blade was done in SolidWorks. The numerical simulation for strength check was done by investigating the Von Mises Stress distribution over the blade.

Keywords: modeling; strength; airfoil; aerodynamic; blade element theory; finite element analysis

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1. INTRODUCTION

There are varieties of clean energy sources available on the world. The sustainable resources such as sun, water and wind are very important and significant renewable sources of nature. Many of scientists and technologists are trying to produce the clean and effective energy from natural sources. Among renewable energy sources for Myanmar, wind is the most widely used resource due to its commercial acceptance, low cost and ease of operation and maintenance, and least adverse effect on the environment.

Wind power is really cost effective and also a free, clean and inexhaustible energy source. It is a proven, reliable and practically extractable source of energy for desired power generation. It is also a fast growing form of alternative energy has a potential to make an impact and community. Over hundreds of years, power has been extracted from the wind with many historic designs. The improved understanding of aerodynamics and advances in materials, has led to the return of wind energy extraction in the latter half of the 20th century.

Wind energy is an abundant resource in comparison with other renewable resources. Wind power devices are now used to produce electricity, and commonly termed wind turbines. A wind turbine is a device that converts the wind`s kinetic energy to electrical energy. A variety of wind turbines are being designed, manufactured and fabricated. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine (HAWT). A vertical axis wind turbine (VAWT) has its shaft normal to the ground.

A conventional horizontal axis wind turbine (HAWT) can be divided into three main components;

(i)rotor component includes the blades and hub for converting wind energy to low speed rotational energy,

(ii)generator component includes electrical generator, control electronics, gear box and variable transmission component for converting low speed to high speed rotation,

(iii)structural support component includes the tower and yaw mechanism [1].

2. DESIGN CALCULATION OF BLADE

2.1 Site Location

Technological University (Thanlyin)
Yangon Division, Myanmar
Reference height, $z_{ref} = 50m$
Wind velocity at 50m, $v_{zr} = 4.6m/s$
Tower height, h = 10.668m (above the ground)
The elevation of tower above sea level, z = 31.6992m

This location has the annual temperature of 92° F. The density (ρ_{air}) and dynamic viscosity (μ) of air are $1.2214 kg/m^3$ and $1.788x10^{-5}$ N-s/ m^2 respectively. It is near the sea and also the suburbs area of Thanlyin. So, the value of terrain index (m) is 0.257 [2].

Annual average wind speed at z,

$$v_{average} = v_z = v_{zr} \, (z / z_{ref})^m = 4.092 m/s \quad (1)$$

It is needed to calculate the design wind speeds of Site Location. The relation of annual average wind speed and design wind speeds are shown in Table 1.

Table 1. Relations and results of wind speed

Types of Wind Speed	Relations with Average Wind Speed	Results (m/s)
$v_{average}$		4.092
v_{cut-in}	$0.7\ v_{average}$	2.864
v_{rated}	$2\ v_{average}$	8.184
$v_{cut-out}$	$3\ v_{average}$	12.276

2.2 Sizing Rotor

$$\eta_{overall} = C_p \, \eta_{mechanical} \, \eta_{generator} \quad (2)$$

Max. power coefficient, C_p= 0.8 Betz`s limit = 0.4741

For wind turbine, $\eta_{mechanical} = 96\%$

Generator efficiency in general, $\eta_{generator} = 70\%$

∴ System overall efficiency, $\eta_{overall} = 0.3186$

$$\text{Power} = 0.5\rho_{air}\, A\, v_{rated}^{\ 3}\, \eta_{overall} \qquad (3)$$

Rotor swept area, $A = 9.3763\text{m}^2$

∴ Blade length, $R = 1.7276\text{m}$

$$\text{Solidity,} \quad \sigma = Bc/(2\pi R) \qquad (4)$$

For three blade rotor (B=3), solidity should be taken between 4.5% and 5%.

For $\sigma = 4.9\%$, chord length, $c = 0.1773\text{m}$

2.3 Optimization of Airfoil

Blade optimization is the main sector for resulting higher efficiency of wind turbine. The optimized airfoil design can contrive the optimized blade design model and also give out the higher efficiency of wind turbine. So, airfoil optimization is very essential and important for the design of wind turbine blade and also the structure of wind turbine.

Comsol Multiphysics is commercial software that can solve many problems from Science and Mathematics fields. Selection of airfoil depends on the maximum value of lift/drag ratio and maximum lift force for better performance of wind turbine. Domain size is needed to be enough for calculating of flow field around airfoil. Initially, the Software defined the domain size as build in. The selection of enough domain size may cause no boundary effect.

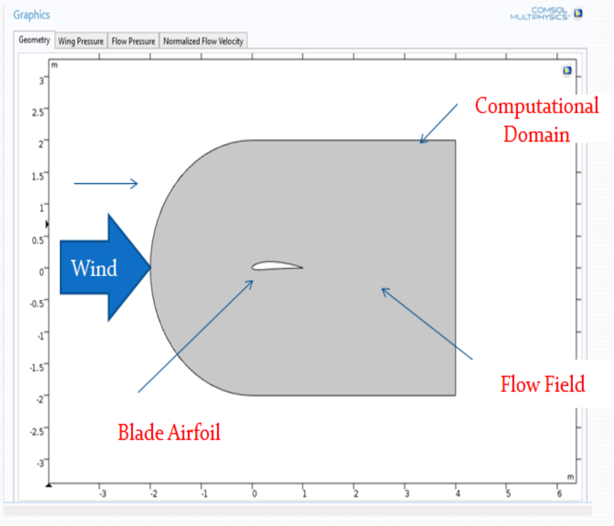

Figure 1. The CFD analysis in Comsol Multiphysics

The flow can be classified as Laminar and Turbulent according to Reynolds Number. If the flow was laminar, the mesh will be made coarsely. If the flow was turbulent, we can find the flow field stress and velocity by using Sparlet-Allmaras Turbulent Model.

$$\text{Reynolds Number, Re} = \rho_{air}\, v_{average}\, c/\mu \qquad (5)$$
$$= 49560 \text{ (Approximated)}$$

By using Comsol Multiphysics software, the airfoil can be chosen at Re = 49560. Firstly, it is necessary to choose most common airfoil shapes for three bladed wind turbines. Then, the airfoil which can give maximum ratio of lift coefficient (C_L) and drag coefficient (C_D) to make the design efficient must be selected.

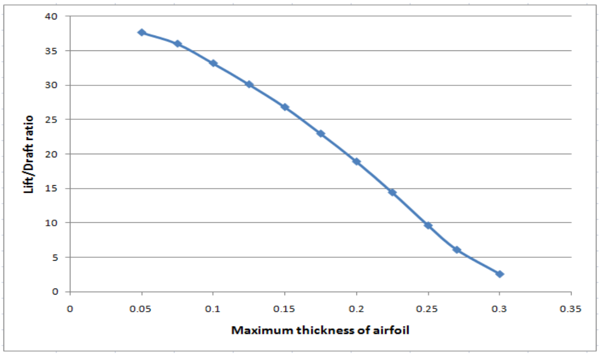

Figure 2. Lift/drag ratio Vs maximum thickness of airfoil

According to the Figure 2, the curve is conspicuously clear. It is seen that the lift/drag ratio and maximum thickness of airfoil are inversely proportional. The increasing of airfoil thickness can cause the decreasing of lift/drag ratio. So, in the design of wind turbine blade, the minimum value of airfoil thickness will gain the optimum condition.

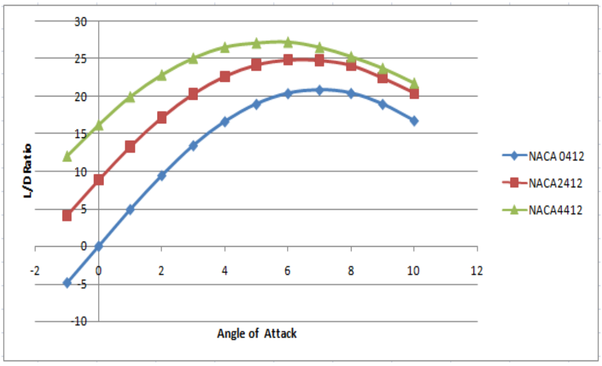

Figure 3. Lift/ drag ratio respect to angle of attack

According to the Figure 3, NACA- 4412 was chosen in order to get the maximum ratio of (C_L) and (C_D).

C_L/C_D is maximum at angle of attack $\alpha = 6°$.

$C_L=1.034$, $C_D=0.03792$ and $C_L/C_D = 27.2679$

2.4 Design Parameters of Each Section

To make modeling, the designed parameters are to be calculated and so the detailed shape of geometry of the blade profile will be available for strength check. The blade chord length for each section will vary with the radius of the blade. The twist angle (or blade setting angle) has to be determined. The areas of sections must be calculated to investigate the surface aerodynamic load on the blade surface.

The angle of attack depends on the linear speed of each local radius. The twisted blade is more efficient than constant blade due to the optimum angle of attack for each radius. The blade is divided into (10) equal sections.

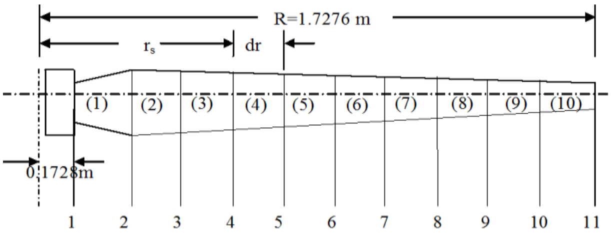

Figure 4. Elements of blade section

The length 0.1728m at the root of blade is to attach the blade and hub. The numbers 1 to 10 within parentheses are referring to the 10 elements and the numbers 1 to 11 are blade sections number from root to tip of the blade. Radius of rotor axis to each section are denoted by r_s , the subscript (s) refers to the section number.

$$dr = (1.7276-0.1728)/10 = 0.1555 \text{ m}$$

$$r_1 = 0.1728 \text{ and } \quad r_s = r_{s-1}+dr \qquad (6)$$

$$\text{Speed ratio at each section, } \lambda_r = \lambda \times r_s/R \qquad (7)$$

Tip speed ratio, $\lambda = 6$ for three blade rotor

By substituting r_1 to r_{11} values in Equation (7), speed ratio at each radius can be calculated and their respective shape parameters can be defined [3]. So, speed ratio of each radius is 0.60, 1.14, 1.68, 2.22, 2.73, 3.30, 3.84, 4.38, 4.92, 5.46, 6.00 and shape parameters are 3.20, 3.15, 1.60, 1.17, 0.70, 0.55, 0.40, 0.32, 0.25, 0.19, 0.17respectively.

2.5 Dimensions of Airfoil

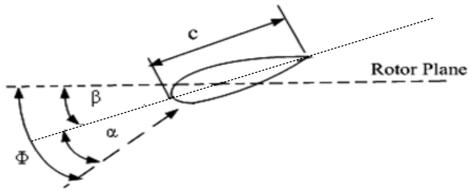

Figure 5. Blade angles and chord length of airfoil

Chord length, $c = (r_s \times SP)/(C_L \times B)$ (8)

Twist angle, $\phi = \tan^{-1}(2/3\lambda_r)$ (9)

Blade setting angle, $\beta = \phi - \alpha$ (10)

Airfoil maximum thickness, $t = 0.12xc$ (11)

For each section, chord length, twist angle, blade setting angle and airfoil maximum thickness can be calculated and these results are shown in Table 2. [4].

Table 2. Lift and drag ratio respect to angle of attack

Cross sect. no, s	Opt. angle of attack	Twist angle (deg)	Blade setting angle (deg)	Chord length (m)	Airfoil max. thickness (m)
1	6	48	42	0.1783	0.0214
2	6	30	24	0.3334	0.0400
3	6	22	16	0.2495	0.0299
4	6	17	11	0.2411	0.0289
5	6	14	8	0.1794	0.0215
6	6	11	5	0.1685	0.0202
7	6	10	4	0.1426	0.0171
8	6	9	3	0.1301	0.0156
9	6	8	2	0.1142	0.0137
10	6	7	1	0.0963	0.0116
11	6	6	0	0.0947	0.0114

2.6 Linearization of Chord Length

Linearization of chord length is needed because smooth geometric construction and aesthetic option will be required for the blade. The chords and the blade angles are calculated vary in a non-linear manner along the blade. These kinds of blades are usually difficult to manufacture and lead to an uneconomic use of materials. To reduce these difficulties, it is required to linearize the chords and the blade angles.

It is required to linearize the values of 'c' between r = 0.5R and r = R without too much deviation to the computed theoretical values. The chord length, c can be linearized with the following way:

$$c = a_1 r + a_2 \qquad (12)$$

With the values of chord length at r = 0.8638m and r = 1.7276m, the constants a_1 and a_2 can be calculated by solving the two equations from two different values of radius.

$$a_1 = -0.0908,\ a_2 = +0.2516$$

$$\therefore\ c = -0.0908\, r + 0.2516$$

Table 3. Approximated values of chord length

Cross sect. no, s	Radius (m)	Exact chord length(m)	Linearized chord length (m)	Deviation (m)
1	0.1728	0.1783	0.1783	0
2	0.3283	0.3334	0.2218	0.1116
3	0.4833	0.2495	0.2077	0.0418
4	0.6393	0.2411	0.1936	0.0476
5	0.7948	0.1794	0.1794	0
6	0.9503	0.1685	0.1653	0.0032
7	1.1058	0.1426	0.1512	-0.0086
8	1.2613	0.1301	0.1371	-0.0070
9	1.4168	0.1142	0.1230	-0.0088
10	1.5723	0.0963	0.1088	-0.0125
11	1.7276	0.0947	0.0947	0

2.7 Velocity Components of the Blade

Linear velocity at each element, $\omega_i = r_{ei}\,\Omega$ (13)

Angular velocity, $\Omega = 2\pi N/60$ (14)
$= 28.4233$ rad/s

Rotor Speed, $N = 60\lambda\, v_{rated}/(2\pi R)$ (15)
$= 271.422$ rpm

Radius at center of element (1),
$r_{e1} = 0.1728+dr/2$ and $r_{ei} = r_{ei-1}+dr/2$ (16)

Relative wind velocity at each element,

$$v_i = (v_{rated}^2 + \omega_i^2)^{0.5} \quad (17)$$

Table 4. Velocity components of the blade

Section element number, i	Equivalent radius (m)	Rated wind speed (m/s)	Linear velocity (m/s)	Relative wind speed (m/s)
1	0.2506	8.184	7.1229	10.8496
2	0.4061	8.184	11.5427	14.1496
3	0.5616	8.184	15.9625	17.9382
4	0.7171	8.184	20.3824	21.9641
5	0.8726	8.184	24.8022	26.1176
6	1.0281	8.184	29.2220	30.3464
7	1.1836	8.184	33.6418	34.6229
8	1.3391	8.184	38.0616	38.9315
9	1.4946	8.184	42.4815	43.2626
10	1.6501	8.184	46.9013	47.6100

2.8 Lift and Drag Forces of Each Section

$$dF_{Li} = 0.5\,\rho_{air}\,dA_b\,v_i^2\,C_L \quad (18)$$

$$dF_{Di} = 0.5\,\rho_{air}\,dA_b\,v_i^2\,C_D \quad (19)$$

Elemental area,

$$dA_{bi} = 0.5(c_s\cos\beta_s + c_{s+1}\cos\beta_{s+1})\,dr \quad (20)$$

Table 5. Lift and drag forces on each blade section

Section element number, i	Section area (m^2)	Relative velocity (m/s)	Section Lift force(N)	Section Drag force(N)
1	0.0261	10.8496	1.9368	0.0712
2	0.0313	14.1496	3.9574	0.1451
3	0.0303	17.9382	6.1571	0.2258
4	0.0286	21.9641	8.7130	0.3195
5	0.0266	26.1176	11.4583	0.4202
6	0.0245	30.3464	14.2480	0.5225
7	0.0224	34.6229	16.9570	0.6219
8	0.0202	38.9315	19.3342	0.7091
9	0.0180	43.2626	21.2751	0.7803
10	0.0158	47.6100	22.6166	0.8295

Total lift forces exerted on each blade can be obtained by summation of all lift forces dF_{L1} to dF_{L10}. Total lift force of each blade, F_L is 126.6535N and that for three blade wind generator is 379.9605N.

Total drag forces exerted on each blade can be obtained by summation of all lift forces dF_{D1} to dF_{D10}. Total drag force of each blade, F_D is 4.6451N and that for three blade wind generator is 13.9353N.

Total lift force per total drag force is 27.2679. This value must be equal to maximum C_L/C_D.

2.9 Thrust and Moment Forces on Blade

Thrust force of each element,

$$dF_{Ti} = dF_{Li}\cos\phi_i + dF_{Di}\sin\phi_i \quad (21)$$

Moment force of each element,

$$dF_{Mi} = dF_{Li}\sin\phi_i - dF_{Di}\cos\phi_i \quad (22)$$

Table 6. Thrust and moment forces on each blade section

Section element number, i	Thrust Force (N)	Moment Force (N)
1	1.3489	1.3917
2	3.4998	1.8530
3	5.7933	2.0971
4	8.4257	2.2419
5	11.2196	2.3643
6	14.0859	2.2058
7	16.8074	2.3321
8	19.2071	2.3242
9	21.1767	2.1882
10	23.2713	1.9330

Total thrust force exerted on each blade can be obtained by summation of dF_{T1} to dF_{T10}. Total thrust force of each blade, F_T is 124.8357N and that for three blade wind generator is 374.5071N.

Total moment force exerted on each blade can be obtained by summation of dF_{M1} to dF_{M10}. Total moment force of each blade, F_M is 20.9313N and that for three blade wind generator is 62.7939N.

2.10 Available Power from Designed Blade

Moment of each element, $dM_i = dF_{Mi}\,r_{ei}$ (23)

Power of each element, $dP_i = \Omega\,dM_i$ (24)

Table 7. Moment and power on each blade section

Section element number, i	Moment(N-m)	Power(W)
1	0.3488	9.9141
2	0.7525	21.3885
3	1.1777	33.4741
4	1.6077	45.6961
5	2.0631	58.6401
6	2.2678	64.4584
7	2.7603	78.4568
8	3.1123	88.4618

9	3.2705	92.9584
10	3.1896	90.6589

Total moment of each blade can be obtained by summation of dM_1 to dM_{10}. Total moment of each blade, M is 20.5503N-m and that for three blade wind generator is 61.6509N-m.

Total power generated by each blade can be obtained by summation of dP_1 to dP_{10}.Total power of each blade, P is 584.1072 W and total power extracted by three blade wind generator at design wind speed 8.184 m/s is 1.7523kW.

The generator output power is calculated by multiplying mechanical efficiency (96%), and generator efficiency (70%).

P_e= 1.7523x 0.96 x 0.7 = 1.1776kW

For this design, the effect of wake, induction and tip loss factor are not considered. These effect may cause a slightly decrease of power. However, the designed wind turbine is enough to generate required 1 kW power.

3. STRENGTH CHECK

After calculating the required parameters of the blade, the blade 3D solid model can be created in SolidWorks and so that strength checks on blade can be made by simulating.

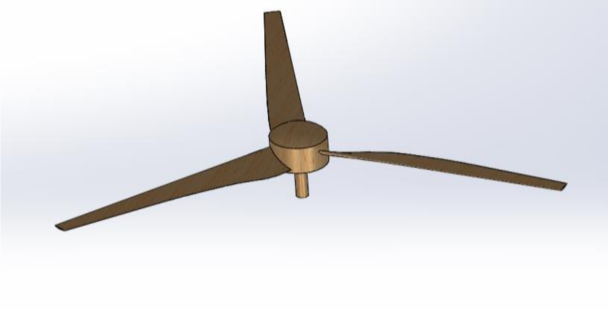

Figure 6. The 3D rotor of wind turbine

Table 8. Complete design parameters of the blade

C-S No.	Radius (m)	λ_r	α (°)	ϕ (°)	β (°)	c (m)	t (m)
1	0.1728	0.60	6	48	42	0.1783	0.0214
2	0.3283	1.14	6	30	24	0.3334	0.0400
3	0.4833	1.68	6	22	16	0.2495	0.0299
4	0.6393	2.22	6	17	11	0.2411	0.0289
5	0.7948	2.76	6	14	8	0.1794	0.0215
6	0.9503	3.30	6	11	5	0.1685	0.0202
7	1.1058	3.84	6	10	4	0.1426	0.0171
8	1.2613	4.38	6	9	3	0.1301	0.0156
9	1.4168	4.92	6	8	2	0.1142	0.0137
10	1.5723	5.46	6	7	1	0.0963	0.0116
11	1.7276	6.00	6	6	0	0.0947	0.0114

It is needed to make some hand calculation in order to examine the stress and deformation on the blade. Moreover, some factors are also necessary for that.

First of all, the solidity (the area ratio of blade and rotor) of the wind turbine must be known. Now, it has to use again the equation of solidity but insert the average value of chord length for (c).

Solidity, $\sigma = B\, c_{avg} /(2\pi R)$ (25)
From design, c_{avg} = 0.1753 m, R = 1.7276m, B = 3
Therefore, σ = 0.04844

Total Blade Area = Solidity ×Rotor Swept Area (26)

Solidity = 0.04844
Rotor swept area = 9.3763m^2
∴ Total blade area = 0.4542m^2

Area of each blade, A_b = Total blade area /3 (27)
= 0.1514m^2

Now calculate pressures and forces of lift and drag,

$F_L = 0.5\, \rho_{air}\, A_b\, v^2\, C_L$ (28)
$F_D = 0.5\, \rho_{air}\, A_b\, v^2\, C_D$ (29)

F_L = 6.4033N, F_D = 0.2348N
P_L = 42.2939 N/m^2, P_D = 1.5509 N/m^2

It is necessary to consider the centrifugal forces due to the blade mass and centrifugal stresses acting on the blades.

$F_c = W.SR.\, v^2/ (9.81 d_{CG})$ (30)

Where,
F_c = centrifugal force, W = blade weight
v = rated wind speed, SR= Speed ratio at blade C.G
d_{CG}= distance between the rotor center and blade C.G

Structural analysis finds displacement, strains and stresses. If solid elements are used, then three displacement components (three translations) per node must be calculated. With shell and beam elements, six displacements components (three translations and three rotations) must be calculated.

There are two commonly used failure criteria: Von Mises Stress failure Criterion and Maximum Normal stress Criterion. Von Mises stress, also known as Huber stress, is a measure that accounts for all six stress components of a general 3D state of stress. The Von Mises equivalent stress can be computed as:

$$\sigma_{VM}=[0.5\{(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2\}+3(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)]^{0.5} \quad (31)$$

Numerical simulation procedures include modeling geometry, meshing, adding material properties, applying loads and investigating stress.

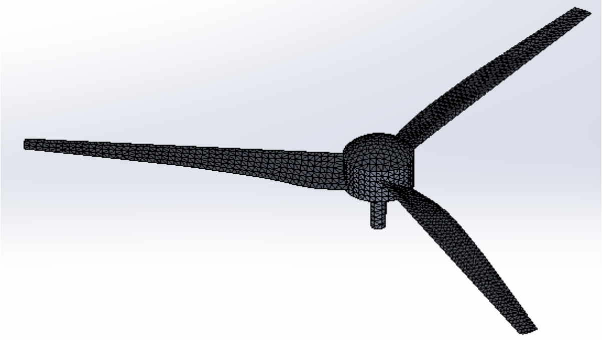

Figure 7. The rotor after meshing

Table 9. The material properties of Balsa Wood

Type	Magnitude	Unit

Elastic Modulus	2999.999232	Mpa
Poisson`s Ratio	0.29	-
Shear Modulus	299.9999105	Mpa
Mass Density	159.99	kg/m^3
Yield Strength	19.999972	Mpa
Thermal Conductivity	0.05	W/(m.K)

After adding material properties of Balsa Wood, simulation has to be made repeatedly from cut-in wind speed 2.8644m/s to cut-out speed 12.276m/s and increment is 2m/s.

Finally, it can be seen that the maximum stress occurs at the blade root. In Figure 8, the maximum stress is shown in red color and the blade is like a cantilever beam because the maximum stress is at the fixed end of the blade.

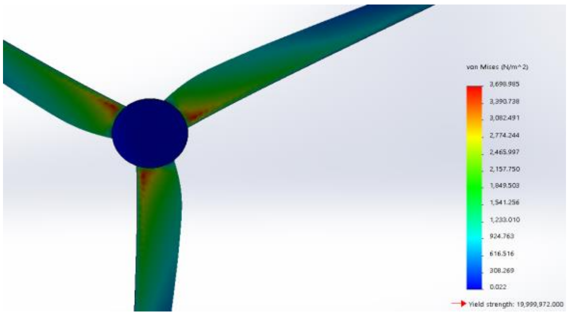

Figure 8. Stress distributions on the blades

After calculating lift and drag forces acting on the blade, it must be found that the lift and drag forces will not cause stress as much as centrifugal force does.

However, the Von Mises stress which is varied with wind speed must be determined because aerodynamic and centrifugal forces are acting on the blade. After making stress simulation, it is necessary to check whether the selected material can bear the maximum stress.

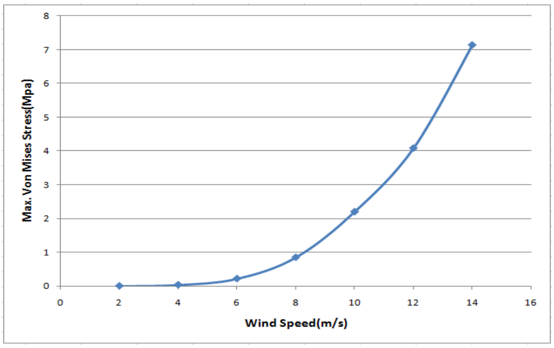

Figure 9. Max. Von Mises Stress at various wind speeds

The selected material, Balsa wood has yield strength of 19.999972 Mpa and then the working stress can be calculated by considering factor of safety of 3 for dead load condition. Then working stress is 6.6667 Mpa and the combined stress acting on each blade is within the range of acceptable working stress.

4. CONCLUSION

In the first part of this research work, it includes the investigations of expected wind speed in the selected site location. After that, aerodynamic theory has to be studied to calculate wind turbine rotor size and available power from wind source. In this paper, the relations of the blade design derived from Blade Element Momentum theory (BEM) are shortly described. Then, blade chord length, blade twist angle and optimum angle of attack have to be determined. In determining the best angle of attack, the maximum lift coefficient from three similar airfoil shapes has to be investigated by using Comsol Multiphysics Software. Modeling Geometry of blade includes getting coordinate points of selected airfoil NACA- 4412 and generating smooth curve for blade chord length variations by making numerical interpolation in SolidWorks. Then the forces acting on the blade in various directions have to be determined. Numerical simulation of strength check has to be made to investigate the stresses on each blade. In this paper, the work of reducing noising effect of rotating rotor blade, designing of tower, yaw and pitch control systems are not considered yet. However, this paper work will contribute to the development of designing blade structure. The designs of wind turbine blade with wood material are extensively used in many small wind turbines. So, the optimum design and strength check of wind turbine blade are very important for practical fields. Technological University (Thanlyin) has initiated the program of utilizing wind power in its existing energy portfolio. Accordingly, wind power resource assessment campaign, wind farm design, optimization, and power grid system integration studies have been initiated. The present effort of understanding the nature of wind power technological developments, existing performance enhancement methodologies, and developing local expertise and facilities is an initiative to contribute towards the national wind energy development program [5].

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