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Research Article

Design and Analysis of 5 kW wind Turbine Blade for Rural and Remote Areas Institutions in Ethiopia: Case of Degua Warren Kebele

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ABSTRACT

Small wind turbine has great role in rural and remote areas in which the electric accesses from the grid is difficult. In this paper, horizontal axis wind turbine blade which has capacity of 5 kW was designed and verified with the help of the blade element momentum theory. Using this theory, the twist angle and chord length for each section the mid radius and the local tip speed ratio blade were calculated. Lift force is the main force for operating the wind turbine to produce useful power. Thus, Maximum lift-to-drag ratio is criterion for choosing the air foil family. Here SG air foil family were selected because they specifically designed for small wind turbine.

Keywords: Small wind turbine; Blade element momentum theory; Remote areas; SG family

INTRODUCTION

About 85% of the total population of Ethiopia are living in rural areas. But only few of the rural population have access to the electricity from grid. This is because of scattered way of settlement; difficult geographical landscape and low population density of the communities providing grid electricity for the rural population of Ethiopia require huge budgets for its implementation. Even if there is little introduction of solar photovoltaic to the rural societies in recent times but still the societies of rural areas use traditional way of lighting system in both the governmental and non- governmental institutions like schools, clinics churches and mosques. So in order to wider the electric facility in rural institutions small wind turbines has great roles. Currently Small wind turbines are used for a variety of applications including on or off-grid residences, telecom towers, offshore platforms, rural schools and clinics, remote monitoring and other purposes that require energy where there is no electric grid, or where the grid is unstable. Small wind turbines can also work in combination with other energy technologies such as photovoltaic, small hydro or Diesel engines.

SMALL WIND TURBINES (SWTS)

There no strict definition of a small wind turbine exists in literature. Thus, some countries define small wind turbines by their own (local definition) and put their own standard. But as defined International Electro technical Commission (IEC) 61400-2 standard Small wind turbines (SWTs) are characterized by a roto area of less than 0 m^2 and rated power below 50 kW.

Parts small wind turbines

A small wind turbine generally consists of the following minimal components: (I) A rotor with a variable number of blades (II) an electric generator and (III) tower and (IV) control system [1].

Design theories of wind turbines

Wind turbines governed by different principles and theory but today the most popular theory related to wind turbine is Blade Element Momentum Theory (BEM). This theory equates two methods of examining how a wind turbine operates. The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine. The second is to examine the forces generated by the aero foil lift and drag coefficients at various sections along the blade. These two methods then give a series of equations that can be solved iteratively.

The Blade Element Momentum (BEM) method is the main design tool for the aerodynamic analysis of wind turbines. The BEM method is basically composed of two theories: Blade Element theory and Momentum theory. As inputs this method requires geometrical features of the wind turbine such as lift and drag coefficient (CL and CD) data of the aero foil sections as a function of angle of attack (α), span wise pitch angle (ϕ) distribution, span wise distribution of chord (c), the number of blades (n), tilt and

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blade coning and operating conditions such as wind speed (U∞) and direction, turbulence, wind shear, density (ρ) and rotational speed (Ω). From these inputs the BEM method calculates power (p), torque (T) and the distribution of both the induction factors (a and a') as outputs.

The BEM method begins by discretizing the rotor plane into a number of radial segments. By applying linear and angular momentum theory, the BEM method calculates the thrust force perpendicular to the rotor plane) and the torque around the rotor axis for each segment. Due to its capability to do calculations very fast, the BEM method is the most widely used aerodynamic model for the analysis of wind turbines. However, it strongly relies on good experimental aero foil data and several empirical correction factors.

Aerodynamics of wind turbines

Aerodynamics deals with the motion of air or other gaseous fluids and the forces acting on bodies moving through them [2]. Aerodynamics plays an important role in determining the efficiency of a wind turbine blade as this is where the kinetic energy in the wind, transforms into mechanical energy. An efficient wind turbine blade is one that produces high lift with relatively low drag for a desired range of Reynolds's number. According to Castellano [1] Design rated power and rated wind speed, Design tip speed ratio, Solidity, Air foil, Number of blades, Rotor power control (stall or variable pitch), Rotor orientation (upwind or downwind of the tower) and so on the primary aerodynamic factors affecting the blade design. The overall size of the rotor swept area, and hence the length of the blades, is directly related to design rated power and rated wind speed [1].

Loads on wind turbine rotor blades

There are different kind forces which can be considered in the design of wind turbine blade but lift and drag force have major effect on design of wind turbine blade. The lift and drag both depends on their coefficients which in turn depends on the cross section of the blade and angle of attack at which the wind strikes the blade. For lift type designs, the increase in angle of attack increases the lift force until the point is reached where blade stalls (Figures 1 and 2) [2].

We can resolve lift and drag forces into forces normal and tangential to the rotor plane:

$$F_N = F_L \cos\phi + F_D \sin\phi \text{ And}$$

$$F_T = F_L \sin\phi - F_D \cos\phi$$

We can normalize these forces to obtain force coefficient

$$C_N = \frac{F_N}{\frac{1}{2}\rho V_{rel}{}^2 c} \quad C_N = C_L \cos\phi + C_D \sin\phi$$

Hence:

$$C_N = C_L \cos\phi + C_D \sin\phi$$

$$C_T = C_L \sin\phi - C_D \cos\phi$$

As define in the Wind energy explained theory [3] turbine loads are the forces or moments that may act upon the turbine. The loads are the primary elements concerning in wind turbine blades design (Table 1) [3].

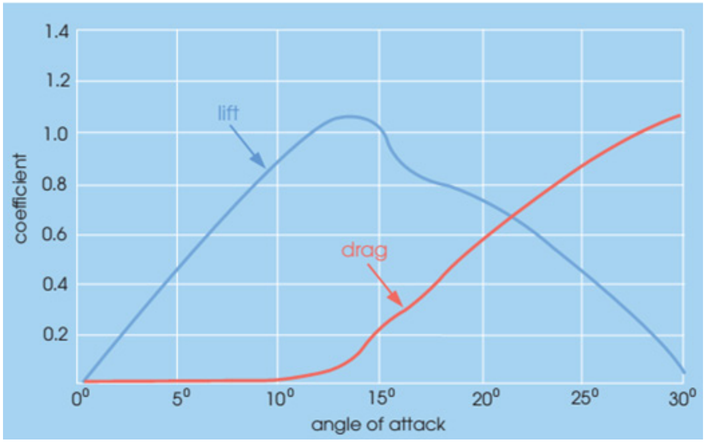

Figure 1: Lift and drag coefficients.

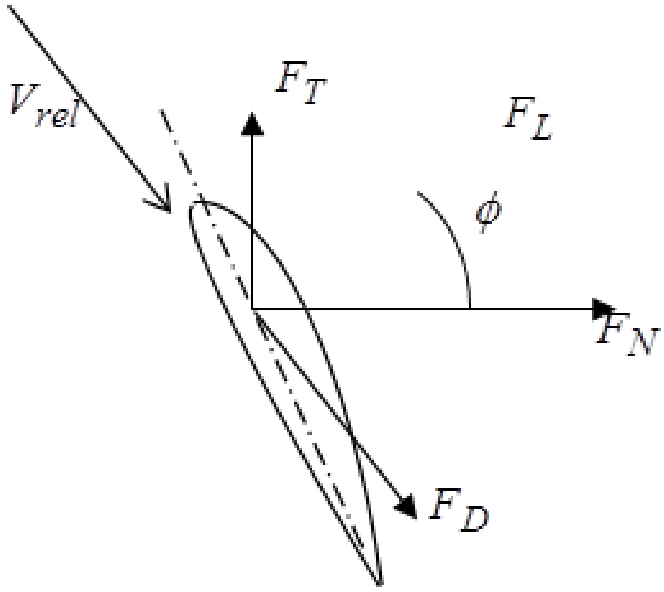

Figure 2: Free body diagram of the main forces acting on air foil.

The rotor blade is loaded in a combination of flap wise and edgewise loads. Basically the blades are exposed to three different load sources. One is the wind load that through the lift and drag on the aerodynamic profile loads the blade primarily in bending flap wise. The second load source is the gravity varying edgewise from tension/compression in leading edge and compression/ tension in trailing edge. This is the main reason for the edgewise fatigue bending of the blade. Finally, the blades are exposed to centrifugal forces during the rotation. However, these longitudinal loads are relatively low and often not taken into account in the design. Furthermore, the design loads are divided into static loads and cyclic loads. International design recommendations (e.g. IEC 61400-1 [1]) specify both types of loads. Moreover, the blades will be subjected to a wide range of environmental conditions [4].

METHODOLOGY

The methodology of this project is mainly based on literature review of published research papers and books concerning the design of wind turbine loadings applied, and their different effects of loads on the turbine and BEM theory is used for evaluating the forces on the wind turbine. It is obvious that wind turbine has

Table 1: Wind turbine loads.

No	Load	Definition	Sources
1	Steady (Static and rotating)	Static loads are loads that react on anon-moving structure whereas rotating loads react with the moving structure. For example, a wind blowing on a stationary wind turbine would induce static loads whereas a wind blowing on a rotating wind turbine rotor while it is generating power would induce steady rotating loads on the blades.	■Mean wind. ■Rotation of the rotor
2	Cyclic	Cyclic loads refer to the loads which arise due to the rotation of the rotor	■Wind shear. ■Gravity. ■Rotation of the rotor.
3	Stochastic	Stochastic loads are time varying, as are cyclic, transient, and impulsive loads	■Turbulence. ■Rotation of the rotor.
4	Transient	Transient loads only occur in occasionally and are associated with starting and stopping	■Wind gusts. Change in wind direction ■Starting /stopping. ■Pitch motion. ■Teetering
5	Resonance induced	Resonance-induced loads are cyclic loads that result from the dynamic response of some part of the wind turbine being excited at one of its natural frequencies. Resonance induced loads should be avoided. However, it may occur under unusual operating circumstances or due to poor design	■Structure. ■Excitation. · ■Turbulence. · ■Rotation of the rotor

different but designing of wind turbine blade is the core points this project. So to design rotor blade I read a lots of literature and I follow the most common procedures in which most of the literatures are share in common one of them discussed in topic already.

Generalized rotor design procedure

Designing a wind energy conversion system is a complex process. The environmental conditions to which the turbine is exposed can be severe and unpredictable. Principles of aerodynamics, structural dynamics, material science and economics are to be applied to develop machines which are reliable, efficient and cost effective. In this paper a simple procedure for an approximate design of a wind rotor is discussed, based on the fundamental aerodynamic theories. So the following input parameters are to be identified (calculated) for 5 kW rotor a design.

Let us follow the following procedures provided [3,5].

1. Begin by deciding what power, P, is needed at a particular wind velocity. Include the effect of capacity factor (Cp) efficiency of various other components (e.g., gearbox, generator, pump, etc.). The radius, R, of the rotor may be estimated from equation (1) below

$$P = 1/2(Cp \times ng \times nd \times V^3 \times \rho \times \pi R^2) \quad \text{............. (1)}$$

Where Cp=Power coefficient or capacity factor; ŋd=Drive train coefficient

V=velocity (The velocity of the wind in flow); ŋg =Generator efficiency

So by re arranging equation we can calculate the radius of rotor as follow equation (2)

$$R = \left[\frac{2P}{Cp \times ng \times nd \times Vd^3 \times \rho)}\right] \wedge 1/2 \quad \text{.......................... . (2)}$$

According to the type of application, choose a tip speed ratio (TSR). For a water-pumping windmill, for which greater torque is needed, use 1< λ <3. For electrical power generation use

4< λ <10. The higher speed machines use less material in the blades and have smaller gearboxes, but require more sophisticated airfoils [3].

Design tip speed ratio depends on the application for which the turbine is being developed. For example, when we design the rotor for a wind pump which require high starting torque, low tip speed ratio is chosen. On the other hand, if our intention is to generate electricity, we require a fast running rotor and hence high tip speed ratio (Figure 3 and Table 2) [5,6].

2. Choose the number of blades (B), either Figure 1 or Table 1.

If fewer than three blades are selected, there are a number of structural dynamic problems that must be considered in the hub design [3]. A key consideration in selecting the number of blades is that the stress in the blade root increases with the number of blades for a turbine of a given solidity. Thus, all other things being equal, increasing the design tip speed ratio entails decreasing the number of blades [7]. So here in these paper 3 blades is chosen due to the above reasons and its aerodynamic balancing, our application being generating electrical power.

4. Select an air foil. If λ <3, curved plates can be used. If λ >3, use a more aerodynamic shape [7,8]. There are many different air foil designs in use in the wind energy industry. SG aero foils are specially designed for small wind turbine application [3].

5. Obtain and examine lift and drag coefficient curves for the aero foil in question. Note that different aero foils may be used at different spans of the blade; a thick aero foil may be selected for the hub to give greater strength.

6. Choose the design aerodynamic conditions for each aero foil. Typically select 80% of the maximum lift value, this choice effectively fixes the blade twist. On long blades a very large degree of twist is required to obtain 80% of the maximum lift near the hub. This is not necessarily desirable as the hub produces only a small amount of the power output, a compromise is to accept that the aero foils will have very large angles of attack at the hub.

7. Choose a chord distribution of the aero foil. There is no easily physically accessible way of doing this but a simplification of an ideal blade is given by

$$C = \frac{8\pi r \cos\beta}{3B\lambda r} \quad \text{.. (3)}$$

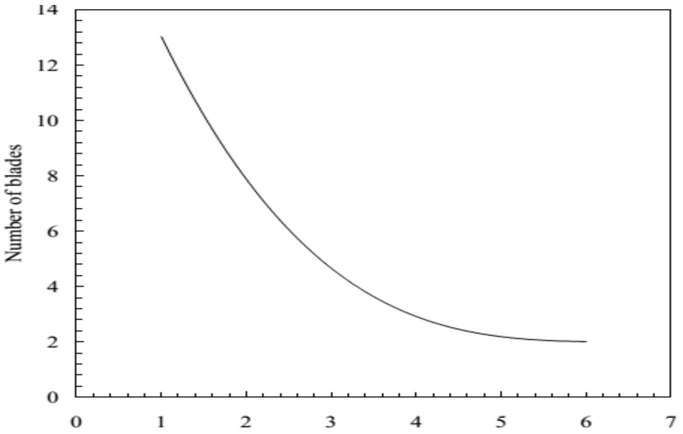

Figure 3: Number of blades and design tip speed ratio.

Table 2: Number of blades and design tip speed ratio.

TSR (λ)	No of blades
1	8-24
2	6-12
3	3-6
4	3-4
>4	1-3

This gives a moderately complex shape and a linear distribution of chord may be considerably easier to make.

8. Divide the blade into N elements. Typically 10 to 20 elements would be used.

9. As a first guess for the flow solution use the following equations. These are based on an ideal blade shape derived with wake rotation, zero drag and zero tip losses. Note that these equations provide an initial guess only. The equations are given as follows:

$$\beta = 90 - \frac{2}{3}\tan^{-1}\left(\frac{1}{\lambda r}\right) \qquad (4)$$

$$\alpha = 1 + \frac{4\cos^2\beta}{\alpha CL\sin\beta} \qquad (5)$$

$$\alpha^1 = \frac{1-3\alpha}{4\alpha - 1} \qquad (6)$$

10. Calculate rotor performance and then modify the design as necessary. This is an iterative process.

The essential outputs of a wind turbine design are the number of blades, the aero foil shape, the chord distribution and the twist distribution. Although the design procedure above provides some simple recommendations it is quite likely the designer will have to spend a considerable amount of time refining the twist and chord distribution to reach an acceptable solution.

RESULTS AND DISCUSSION

Rotor design

The mechanical power captured by the rotor from the wind is influenced by the geometrical shape of the rotor blades. Determining the aerodynamically optimum blade shape, or the best possible approximation to it, is one of the tasks of the designer. Given parameters

Power output (p)=5 kW ρ=1.225 kg/m^3 Cp=0.4 Ŋg=0.9

Rotor power coefficient (Cp) is selected from the figure below for three blade turbine which is 0.4 less than the maximum limit (Betz limit ≈ 0.59) (Figure 4).

1. Rotor diameter required for 5 kW

The determination of blade radius is fundamental as it significantly affects the power which is proportional to the swept area of the wind turbine. So we calculated the rotor radius as follow

$$P = 1/2(Cp \times ng \times nd \times V^3 \times \rho \times \pi R^2)$$

As described in Small wind turbine by Castellano [1] the power law represents a simple model for the vertical wind speed profile. Its basic form is:

$$\frac{V_2}{V_1} = \left[\frac{H_2}{H_1}\right]^{\alpha} \qquad (7)$$

V_1=Wind speed measured at the reference height H_1 (i.e., known wind speed),

V_2=Wind speed estimated at height H_2, (i.e., unknown wind speed) and

α=Ground surface friction coefficient or it also called Hellman coefficient, wind shear coefficient (Table 3) [3,6].

The average velocity proposed site 10 m is around 4.65 m/s. So to harness more wind speed let us assuming that the turbine rotor is located 20 m in height and the rough (forest, small houses) is α is 0.20-0.27 so let the average value 0.23.

$$V_{20m} = V_{10m} \times \left[\frac{Z}{Zr}\right] \wedge 0.235 \rightarrow V_{16m} = 4.65 \times \left[\frac{16}{10}\right] \wedge 0.235 = 5.547 \cong 6\,m/s$$

Then $R = \left[\dfrac{2P}{Cp \times ng \times nd \times V^3 \times \rho \times \pi}\right] \wedge 1/2$

So $R = \left[\dfrac{2 \times 5000\,W}{0.4 \times 6^3 \times 0.9 \times 1.225 \times 3.14}\right] \wedge 1/2 = 5.78\,m$

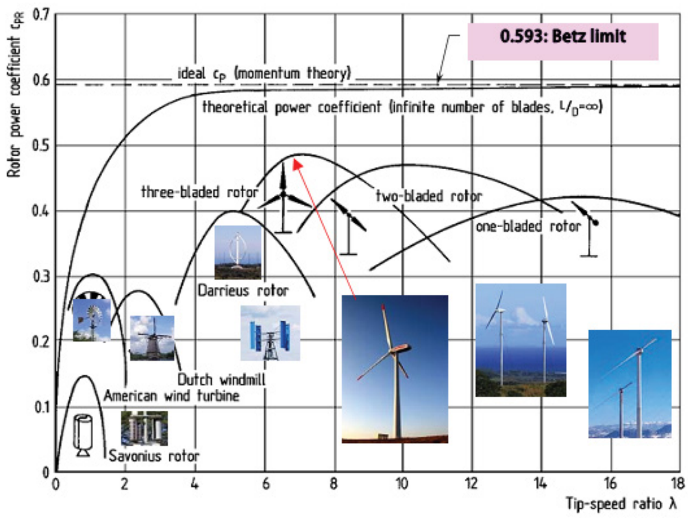

Figure 4: Power coefficient of different wind turbine design configuration.

Table 3: Level terrain roughness.

Aerofoil	Thickness (t/c) (%)	Camber (%)	Design C_L	Design Reynolds Number (Re)
SG6040	16	2.5	1.1	2,00,000
SG6041	10	2	0.6	5,00,000
SG6042	10	3.8	0.9	3,33,333
SG6043	10	5.5	1.2	2,50,000
SG6050	16	3.3	1.1	2,50,000
SG6051	12	3.2	1.2	4,50,000

Let us take average wind speed flow for ease of calculation as 6 m/s

Choose a tip speed ratio for the machine.

Because this wind turbine (the turbine in this paper) used for electric power purpose the tip speed ration is b/n 4 and 10. So let's take 7 with three blades as our tip speed ratio for this project.

Number of blades and solidity

The performance of wind turbines is influenced by many factors and the number of blades integrated in to the system is one of them. The blade number not only affects the solidity ratio of the blade but also the tip speed ratio (TSR). Solidity ratio, which is the ratio of the plan form area of the blade and the swept area of the blade, influences the tip speed ratio

Select an aero foil

From the table above, the SG6041, SG6042 and SG6043 have the same thickness chord ratio but however their design lift coefficient and camber varies. Although these aero foils provide us with a very low thickness to chord ratio (t/c) that is very much desired for aerodynamic performance, it would present significant problems at the root of the blade where the loads acting on the blade are most critical and thus requires a higher thickness chord ratio aero foils (Table 4) [9,10].

Most blades are designed with three different aero foils: a very thick one close to the hub, an aero foil with average thickness in the middle part of the blade, and a very thin one close to the tip [11-15]. SG6040 and SG6050 are thicker than 16% and SG6051 but SG6051 has greater C_l. So for this project SG6051 is selected. Its 12% thickness to chord ratio (t/c) is sufficiently enough at the root to support the centrifugal loads (Figure 5).

Figure 6 below shows the lift coefficient characteristics of the SG6051 aero foil as a function angle of attack (AoA) for various Reynolds numbers. An optimum angle of attack of 6° which corresponds to the highest lift to drag ratio of the aero foil is chosen for the design of the blade.

Blade element analysis: Divide the blade into N elements (usually 10–20). Use the optimum rotor theory to estimate the shape of the *ith* blade with a midpoint radius of r_i.

So lets us divide the blade into 10 blades. If radius is 5.78, Width of each element is 0.578. The blade shape is estimated with a midpoint radius ri (Figure 7).

$\lambda_{r,i} = \lambda(r_i / R)$ Where λ_r is the local tip speed ratio

R=is rotor radius

Blade element 1

ri=0.578/2=0.289

λ ri=7 × (0.289)/5.78=0.35

$$\Psi_i = \left(\tfrac{2}{3}\right)\tan^{-1}\left(1/\lambda_{r,i}\right)$$

φi = (2/3)tan^{-1} (1/0.35)=2/3 × 70.70=47.13°

Where φi is the angle of relative wind of the aero foil

We also calculate th cord length of the aero foil as follow

$$C = \frac{8\pi ri}{\beta(C_{id})}(1-\cos\Psi_i)$$

Where C=chord length, β-number of blades, ri-midpoint radius of blade, φi-angle of relative wind and Cid-coefficient of lift design.

C= (8 × 3.14 × 0.289)/3 × 1.2 (1-cos 47.13)=0.6447 m

Relative wind speed V_{rel} has direction $\varphi = \alpha + \theta$ as show in

Table 4: SG aero foil family.

Aerofoil	Thickness (t/c) (%)	Camber (%)	Design C_L	Design Reynolds Number (Re)
SG6040	16	2.5	1.1	2,00,000
SG6041	10	2	0.6	5,00,000
SG6042	10	3.8	0.9	3,33,333
SG6043	10	5.5	1.2	2,50,000
SG6050	16	3.3	1.1	2,50,000
SG6051	12	3.2	1.2	4,50,000

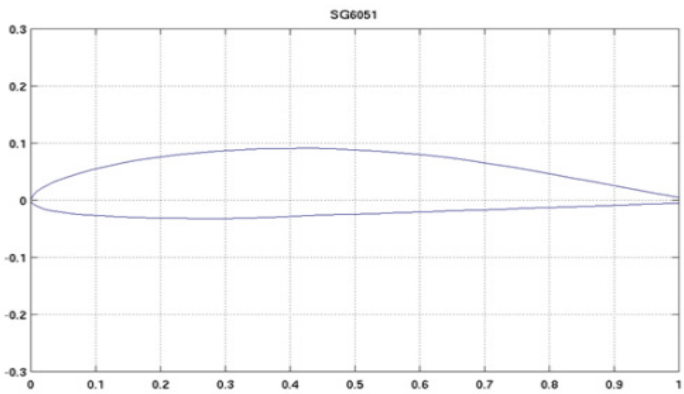

Figure 5: SG 6051 aero foil.

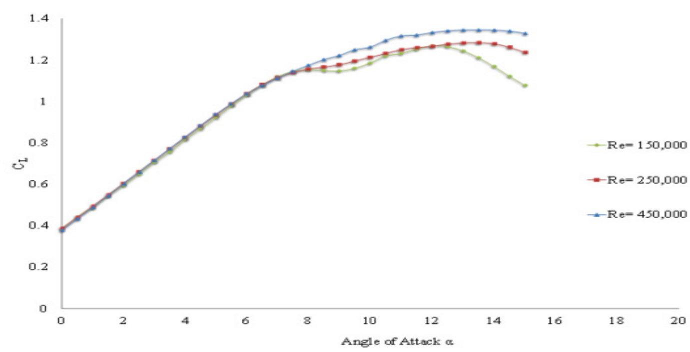

Figure 6: Lift coefficient characteristics of SG6051 aero foil at various angles of attack (aoa) and Reynolds number.

the Figure 8 below:

θ=angle of twist (i.e., the angle between the chord and the rotor plane)

And α=angle of attack i.e., the design value here (6°)

So the twist angle can be calculated as

$\varphi = \alpha + \theta$ →47.13=6+θ so let say θ as θ_1 thus θ_1 =47.13-6=41.13°

Blade element 2

ri=0.289+0.578=0.867

Just we follow the same procedure as previous

λ ri=7 × (0.867)/5.78=1.05

φi= (2/3)tan^{-1} (1/1.05)=2/3 × 43.60°=29.06

C= (8 × 3.14 × 0.867)/3 × 1.2 (1-cos 29.06)=0.6416 m

$\varphi = \alpha + \theta$ →29.06-6=θ_2 thus θ_2=23.06

Blade element 3

ri=0.289+0.867+0.289=1.445 and we can calculate λ ri=7 × (1.445/5.78)=1.75

φi = (2/3)tan^{-1} (1/1.75)=2/3 × 29.74°=19.82

C= (8 × 3.14 × 1.445)/3 × 1.2 (1-cos 19.82)=0.5902 m

→19.82-6=θ_3 thus θ_3=13.82°

Blade element 4

ri=0.289 +0.1.445+0.289=2.02 so λ ri=7 × (2.02/5.78)=2.44

φi = (2/3)tan^{-1} (1/2.44)=2/3 × 22.28°=14.85

C= (8 × 3.14 × 2.02)/3 × 1.2 (1-cos 14.85)=0.4707 m

$\varphi = \alpha + \theta$ Let say θ as θ_3→14.85-6=θ_3 thus θ_4=8.85°

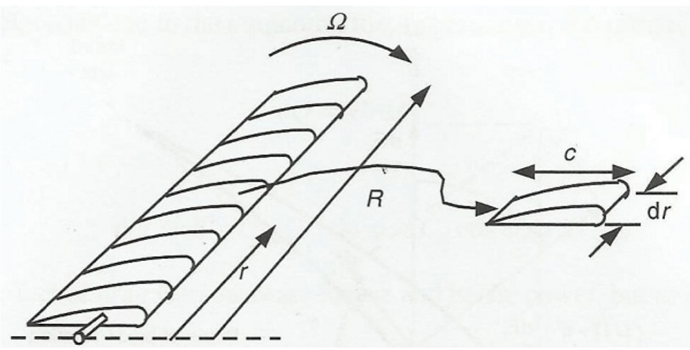

Figure 7: Schematic of blade elements; c, airfoil chord length; dr, radial length of element; r, radius; R, rotor radius; , angular velocity of rotor.

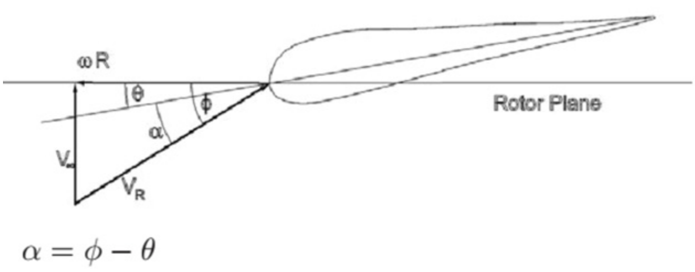

Figure 8: Relative wind speed V_{rel} has direction $\varphi = \alpha + \theta$.

Blade element 5

ri=0.289 +2.02+0.289=2.59

λ ri=7 × (2.59/5.78)=3.13

φi= (2/3)tan^{-1} (1/3.13)=2/3 × 17.71°=11.81

C= (8 × 3.14 × 2.59)/3 × 1.2 (1-cos 11.81)=0.3825 m

$\varphi = \alpha + \theta$ Let say θ as θ4→11.81-6=θ3 thus θ5=5.81°

Blade element 6

ri=0.289 +2.59+0.289=3.16

λ ri=7 × (3.16/5.78)=3.82

φi = (2/3) tan^{-1} (1/3.82)=2/3 × 14.66°=9.77°

C= (8 × 3.14 × 3.16)/3 × 1.2 (1-cos 9.77)=0.3197 m

$\varphi = \alpha + \theta$ →9.77-6=θ6 thus θ6=3.77°

Blade element 7

ri=0.289 +3.16+0.289=3.73 so λ ri=7 × (3.73/5.78)=4.5

φi= (2/3)tan^{-1} (1/4.5)=2/3 × 12.528°=8.35°

C= (8 × 3.14 × 3.82)/3 × 1.2 (1-cos 9.77)=0.3865 m

8.35-6=θ5 thus θ7=2.35°

Blade element 8

ri=0.289 +3.73+0.289=4.30 thus λ ri=7 × (4.30/5.78)=5.20

φi = (2/3)tan^{-1} (1/5.20)=2/3 × 10.88°=7.25°

C= (8 × 3.14 × 4.30)/3 × 1.2 (1-cos 7.25)=0.2398 m

→7.25-6=θ7 thus θ8=1.25°

Blade element 9

ri=0.289 +4.30+0.289=4.87 and λ ri=7 × (4.30/5.78)=5.90

φi = (2/3)tan^{-1} (1/5.90)=2/3 × 9.61°=6.41°

C= (8 × 3.14 × 4.87)/3 × 1.2 (1-cos 6.41)=0.2124 m

$\varphi = \alpha + \theta$ →6.41-6=θ9 thus θ8=0.41°

Blade element 10

ri=0.289 +4.87+0.289=5.448 λ ri=7 × (5.448/5.78)=6.58

φi = (2/3)tan^{-1} (1/6.58)=2/3 × 8.64°=5.76°

C= (8 × 3.14 × 5.44)/3 × 1.2 (1-cos 5.76)=0.1916 m

$\varphi = \alpha + \theta$ →5.76-6=θ9 thus θ10=-0.24° (Table 5).

Key TWA=twist angle ARW=Angle Of Relative Wind

PA=Pitch Angle R=Rotor Radius R=Midpoint Radius

From the above table we can conclude that the as we go from the root to the tip of the baled Angle of twist, angle of relative wind and chord length parameters decrease on the other hand the mid radius and the ratio of r/R As we go from the root to the tip of the baled following parameters increase (Figures 9-12).

N.B: The above arrows inside the blade elements represent equal distance that is 0.578 m

Structural and aero dynamic load analysis of the blade

The lift force which drives the turbine round is distributed along

Table 5: Blade elements sections summary values of chord length, twist angle, and angle of relative wind.

Blade	r	R	r/R	Chord Length, m	TWA (deg)	ARW (deg)
1	0.289	5.78	0.05	0.6447	41.13	47.13
2	0.867	5.78	0.15	0.6416	23.06	29.06
3	1.445	5.78	0.25	0.5902	13.82	19.82
4	2.02	5.78	0.3495	0.4707	8.85	14.85
5	2.59	5.78	0.4481	0.3825	5.81	11.81
6	3.16	5.78	0.5467	0.3197	3.77	9.77
7	3.73	5.78	0.6453	0.2398	2.35	8.35
8	4.87	5.78	0.8426	0.2124	1.25	7.25
9	5.44	5.78	0.9412	0.1916	0.41	6.41
10	5.802	5.78	1.0415	0.1728	-0.24	5.76

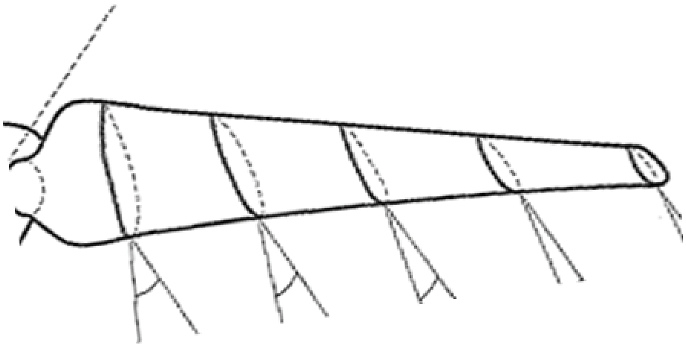

Figure 9: angle of twist of different blade sections.

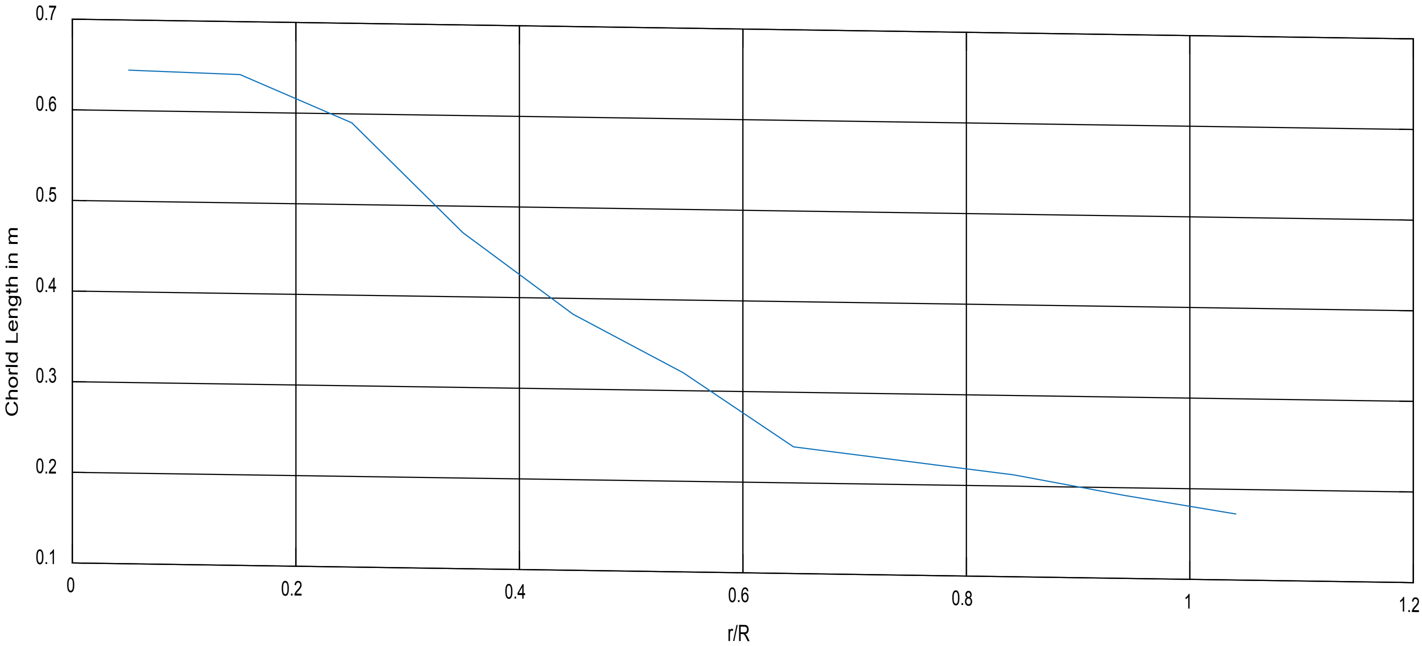

Figure 10: Chord length VS. R/R.

the blade approximately in proportion to the local radius i.e., there is more force close to the root than the tip. Lift force makes the blade bend. If a section of the blade is subjected to lift at some point along its length all the force outboard at that point will have cumulative effect on the tendency to bend. This effect is called the bending moment.

The root flap wise bending moment on a single blade, Mβ, for a turbine with B blades is:

Mβ=T × 2/B × 3.R .... (7)

Where R=radius T=torque B=number of blades

The mean torque (T) is the power divided by the rotational speed.

T (NM)=Power (w)/Angular velocity (r/s)................................ (9).

Angular velocity (ω)=Tip Speed Ratio (TSR × Wind speed/rotor radius)... (10).

Edgewise (Lead-Lag) Moment

The bending moment in the edgewise direction at the root of single

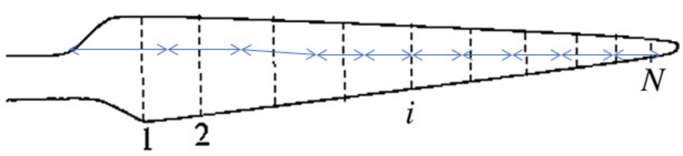

Figure 11: A sketch of blade elements sections arrangement.

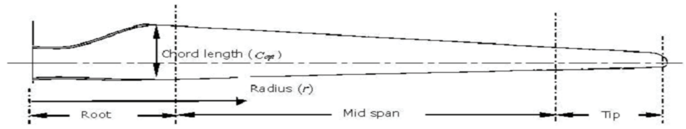

Figure 12: A typical blade plan and region classification.

blade (Mz), is simply the torque divided by the number of blades (Figure 13):

Mz=T

/B... ... (11)

The flap wise bending moments of various blade elements: The flap wise bending moment is a result of the aerodynamic loads, which can be calculated using BEM theory (Figure 14) (Tables 6 and 7).

Where mr=mid radius BE=blade element #=number of blades

Av= Angular velocity R=radius of the rotor TSR=tip speed ratio

EWBM=Edge wise bending moment FWB=flap wise bending moment

AVS=Average wind speed Ps=perpendicular distance

From the above free body diagram the Forces can be calculated by the following formulas

$$F_N = F_L \cos\phi + F_D \sin\phi$$ And

$$F_T = F_L \sin\phi - F_D \cos\phi$$

FL=1/2 × [Cl × ρ × R_2 × V_2 × c × l] c=Chord length and l=Length of the blade element

FT=1/2[C_T × ρ × π × R_2 × V_2] .... (12)

Material selection

Based on the Table 8 let's compare the above two types Glass fiber's (Table 8).

- E-glass (a calcium alumina silicate glass) has low-cost material, with and has good tensile strength. On the other hand S-glass (a calcium-free alumina silicate glass) has higher tensile strength than E-glass but it is expensive (more than twice as much)
- E-glass is selected for this paper

Stress analysis

- So let us calculate the design stress

Design stress=Yield Strength/Safety Factor................................(13)

Here the selected air foil is 12% thick means that the thickness of aero foil is 0.12 times the chord length of the aero foil and design

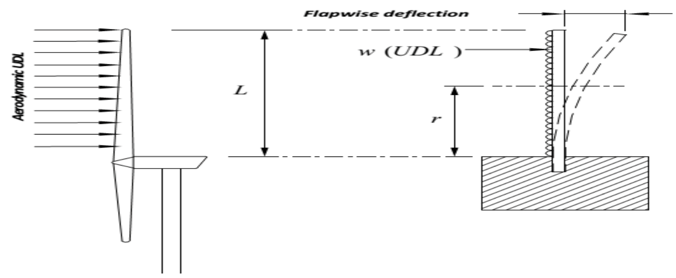

Figure 13: The blade modelled as a cantilever beam with uniformly distributed aerodynamic load.

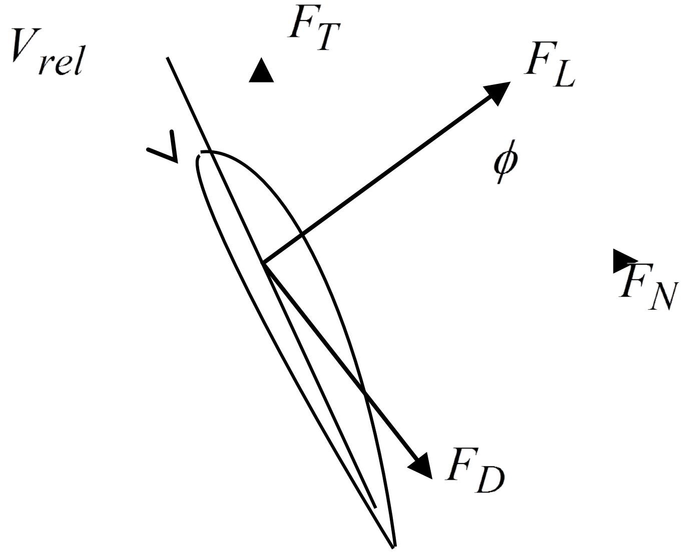

Figure 14: Showing the way of forces can be calculate.

factor of safety is 3 since a very high factor of safety would make the blades very heavy and reduce their efficiency

Therefore design stress=2000/3=666.66 MPa

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{E}{R} \text{..........} (14)$$

Where I=Moment of inertia E=Modulus of elasticity R=Radius of curvature

M=Moment bending Y=Distance from neutral the axis σ=Stress

Bending stress=My /I.. (15)

Where M=is the bending moment I= is the bending inertia of the beam (Figure 15)

Where BE=Blade Element CL=Chord Length BM=Bending Moment

Y=Distance from neutral axis BS=Bending strength I=Moment of inertia

From the above the blade root section carries the highest loads. Its low relative wind velocity is due to the relatively small rotor radius. The low wind velocity leads to reduced aerodynamic lift leading to large chord lengths so the structural loading increases as we move from tip to root of the blade but on the other hand on tip of the blade the aerodynamic loads are high (Tables 9 and 10).

Table 6: Blade element and corresponding bending moment.

BE	mr		ps	FWBM	Av(rad/s)	power(	AVS	TSR	R	torque(NM	EWBM	#
1	0.578	10	5.78	883.8201	7.266436	5000	6	7	5.78	688.0952	229.3651	3
2	0.578	9	5.2	795.4381	7.266436	5000	6	7	5.78	688.0952	229.3651	3
3	0.578	8	4.62	707.0561	7.266436	5000	6	7	5.78	688.0952	229.3651	3
4	0.578	7	4.05	618.6741	7.266436	5000	6	7	5.78	688.0952	229.3651	3
5	0.578	6	3.47	530.2921	7.266436	5000	6	7	5.78	688.0952	229.3651	3
6	0.578	5	2.89	441.9101	7.266436	5000	6	7	5.78	688.0952	229.3651	3
7	0.578	4	2.31	353.528	7.266436	5000	6	7	5.78	688.0952	229.3651	3
8	0.578	3	1.73	265.146	7.266436	5000	6	7	5.78	688.0952	229.3651	3
9	0.578	2	1.16	176.764	7.266436	5000	6	7	5.78	688.0952	229.3651	3
10	0.578	1	0.58	88.38201	7.266436	5000	6	7	5.78	688.0952	229.3651	3

Table 7: Calculated values of different parameters.

BE	CL(m)	ARW	r	area	FL
1	0.6447	47.13	0.289	0.372637	1.620641
2	0.6416	29.06	0.867	0.370845	14.58577
3	0.5902	19.82	1.445	0.341136	40.51604
4	0.4707	14.85	2.02	0.272065	79.17608
5	0.3825	11.81	2.59	0.221085	130.164
6	0.3197	9.77	3.16	0.184787	193.7606
7	0.2398	8.35	3.73	0.138604	269.9659
8	0.2124	7.25	4.87	0.122767	460.2027
9	0.1916	6.41	5.44	0.110745	574.2342
10	0.1728	5.76	5.8	0.099878	652.7506

Table 8: Comparison of different material used develop wind turbine blade.

Material	Density g/cm³	Tensile strength (mpa)	Young's modulus (gpa)	Shear strength (mpa)	Price. £ per kg.
E -GLASS	2.55	2000	80	40	01-Feb
S -GLASS	2.49	4750	89	45	12-20
wood	0.745	87	64	65.33	3
bamboo	0.6-0.8	36-45	1500-2000	35-44	

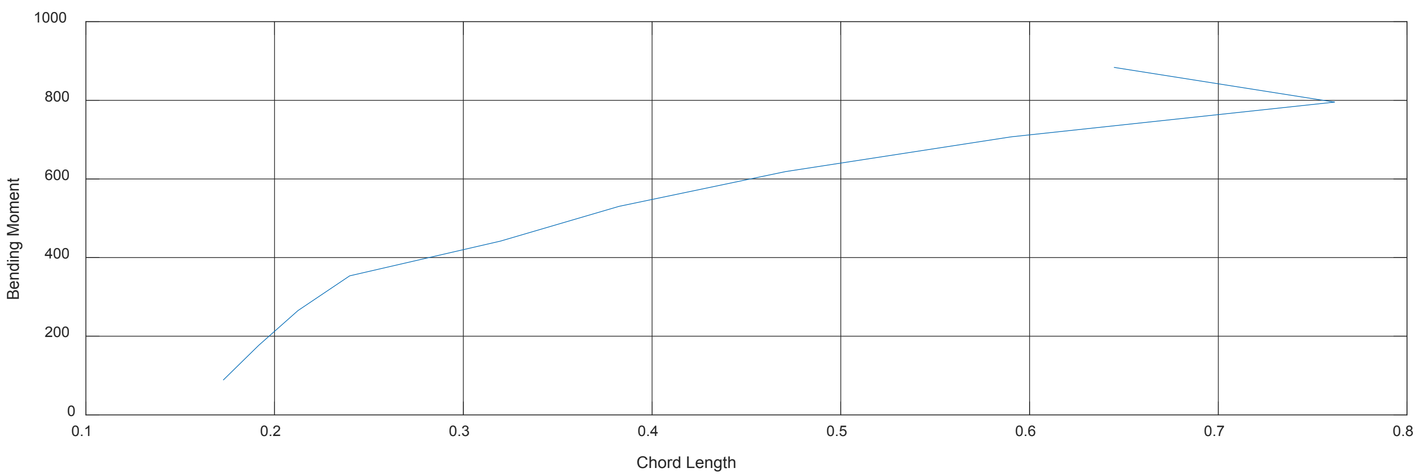

Figure 15: Bending moment versus chord.

Shear strength analysis

The thrust in a wind turbine can be calculated as:

$T=1/2[C_T \times \rho \times \pi \times R_2 \times V_2]$...(16)

The thrust coefficient (C_T) for an ideal wind turbine is equal to 4α [1-α]. C_T has a maximum of 1.0 when a=0.5 and the downstream velocity is zero. At maximum power output (a=1/3), C_T has a value of 8/9 [7]. So let's take the value of C_T that is 8/9≈0.9.

Thus, $T=8/9 \times 3.14 \times 1.225 \times 0.5 \times 6^2 \times 5.78^2=2056.08$ N

Shear force=thrust/number of blades =2056.08/3=685.36 N

Table 9: Bending stress and moment of inertia.

BE	CL(m)	thickness(m)		BM	Y	BS	I
1	0.6447	0.077364	0.12	883.8201	0.038682	6.67E+10	5.13E-10
2	0.7616	0.091392	0.12	795.4381	0.045696	6.67E+10	5.45E-10
3	0.5902	0.070824	0.12	707.0561	0.035412	6.67E+10	3.76E-10
4	0.4707	0.056484	0.12	618.6741	0.028242	6.67E+10	2.62E-10
5	0.3825	0.0459	0.12	530.2921	0.02295	6.67E+10	1.83E-10
6	0.3197	0.038364	0.12	441.9101	0.019182	6.67E+10	1.27E-10
7	0.2398	0.028776	0.12	353.528	0.014388	6.67E+10	7.63E-11
8	0.2124	0.025488	0.12	265.146	0.012744	6.67E+10	5.07E-11
9	0.1916	0.022992	0.12	176.764	0.011496	6.67E+10	3.05E-11
10	0.1728	0.020736	0.12	88.38201	0.010368	6.67E+10	1.37E-11

Table 10: Summary of calculated and assumed value.

S/N	Parameterizes	Result	Formula and remark	Reference
1	Rotor radius	5.78 m	Square root of rated power	3
2	velocity	6m/s	Calculated using power law	12
3	Air density	1.225	Standard	13
4	TSR	7	Selected	3,6
5	Air foil type	SG6051	selected	9
6	Cl	1.2	Experimentally value of the selected aero foil	9
7	Angle of attack	6	From graph	9
8	CP	0.4	Assumption	6,5,7
9	CT	08-Sep	Assumption	3
10	Cut in speed	3	=1/2×Average wind speed (AV)	6,14
11	Rated speed	9	=1.5 ×AV	6,14
12	Cut out speed	18	=3×AV	6,14
13	Tower height	20.7m	≥R+15m	15
14	Area	$5.78 \times \sum_1^{10} C_l / 10 = 2.3\ m^2$	Mean chord length× radius of the rotor	

Test whether the blade would be rotate or not?

For an aerodynamic body to move vertically upwards the lift force must be greater than the weight of the body. The lift force is given by

$FL = 1/2 \times Cl \times \dot{\rho} \times R_2 \times V_2 \times A = 1/2\ (1.2 \times 32.49 \times 1.225 \times 36 \times 2.3 = 1977$ N

$W_g = m \times g = 2.55$ kg $\times 9.81 = 250$ N. ∴ Fl>W so the turbine can rotate or move.

CONCLUSION

Small wind turbine has great role in rural and remote areas in which did electric accesses from the grid is difficult. Small wind turbines are characterized by a rotor area of <200 m^2 and rated power below 50 kW. The design of the blade requires a great number of design procedures, process, variables and parameters to reach the final design of the rotor blade. So the most key elements which are used to design blade the rotor diameter, wind velocity, air density, the number of blade, the chord of sections, and twist angle across the blade and the lift that depend on the angle of attack. Generally the following results were obtained.

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