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# Development and Performance Test of a Micro Horizontal Axis Wind Turbine Blade

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**ABSTRACT**
This study describes the development and experimental studies performed to investigate the performance of a 1.5 m long Horizontal Axis Wind Turbine blade on a 4meter tower using $8^o$ as an angle of attack. The blade was design using the Blade Element Momentum Theory (BEM), blade parameters such as the chord length, angle of attack, Tip Speed Ratio, Rotor diameter, Lift and Drag force were determined. The designed blade profile was developed and tested on an open field at Maiduguri where the average wind speed is 3.89m/s, the result shows that the maximum extractable power is 142.66 W at a wind relative velocity of 4.8m/s when the blade is at $8^o$ angle of attack and $3 \times 10^6$ Reynolds Number. However, measured power increase consistently with increased in wind speed. Therefore the developed HAWT blade profile has shown the ability to perform thus, the blade is expected to be a means of extracting and generating energy from wind which is a renewable, clean and locally available source of energy in Maiduguri and its environs. The use of this energy source will reduce the large dependence on non-renewable, expensive and environmentally unfriendly means of energy generation.

**Keywords:** BEM, Performance Test, Turbine Blade, Chord Length, Relative Angle

## I. NOMENCLATURE

| | |
|---|---|
| $P$ - | The Extractable Power from the wind |
| $A$ - | Swept Area of the Rotor |
| $\rho$ - | Air Density |
| $v$- | Wind Relative Velocity |
| $D$- | Rotor Diameter |
| $r$ - | Rotor Radius |
| $C$ - | Chord Length |
| $\Omega$ - | Angular Velocity of the Rotor |
| $\Theta$ - | Angle of Attack |
| $\phi$ - | Wind Relative Angle |
| $\eta$ - | Efficiency of the Blade on the Wind Turbine |
| $L$- | Blade Span |
| $\dot{r}$ - | Radial Length of the Blade Element |
| $d\dot{r}$ - | Increase in Blade Span Length |
| $T$ - | Rotor Torque |
| $\sigma$ - | Solidity |
| $\lambda_r$ - | Tip Speed Ratio |
| $C_p$ - | The Power Coefficient |
| $C_L$ - | Coefficient of Lift |
| $C_D$ - | Coefficient of Drag |
| $F_L$ - | Lift Force |
| $F_D$ - | Drag Force |
| $R_e$ - | Reynolds Number |
| $F$ - | Resultant Force |
| $B$ - | Number of Blades |
| $P_T$ - | Power Developed by the Turbine |
| $N$ - | Speed of the Rotor |
| $w$ - | Uniformly Distributed Load |
| $B.M.$ - | Bending Moment |
| $x$ - | Specified Distance along the Blade Span |
| $S.F.$- | Shear Force |
| $v_{max}$ – | Average Maximum Wind Speed |
| $v_{ulti.}$ – | Ultimate Wind Speed |
| $\gamma_F$ - | Factor of Safety |
| $C_{prob.}$- | Probability of Collapse |
| $m$ - | Meter |
| $W$ – | Watts |
| $s$ – | Second |

## II. INTRODUCTION

Wind is among the most popular and fastest-growing forms of electricity generation in the world, which is pollution free and available almost at any time of the day, especially in the coastal and arid regions like Borno State, Northeastern Nigeria (Ajao and Adegan, 2009).

Wind potentials are harness with the use of wind turbines; turbines are mechanical devices that use the kinetic energy of the wind and convert it to mechanical energy, this is then used to produce electricity (Raja *et al*; 2006). There are two types of wind turbines, horizontal and vertical axis wind turbines. Horizontal Axis Wind Turbines (HAWT) have their axis of rotation of their blades horizontal to the ground and almost parallel to the wind stream, while the Vertical Axis Wind Turbines (VAWT) have the rotor shaft and blades vertically (Ngo and Natiwitz, 2010). Most of the wind turbines fall under the category of Horizontal Axis Wind Turbines because they have some distinct advantages such as low cut-in wind speed and easy furling. In general, they show relatively high power coefficient (Rajakumar and Raviandran, 2010).

A Horizontal Axis Wind Turbine consists of four main parts, i.e. the rotor, generator, gearbox and the control system. The rotor consists of the blade, the hub and the shaft, the blade is key element of wind turbines which converts the kinetic energy of the wind in to electricity through generators. In order to extract the maximum kinetic energy from the wind, the blade airfoil (geometry) should be effectively design. An airfoil means a two dimensional cross-section shape of a blade whose purpose is to either generate lift or minimize drag when exposed to a moving fluid (Chandrala *et al;* 2012). The rotor (blades fixed on a hub) is driven by the wind and rotates at predefined speed in terms of the wind speed, the power produced by the generator depend on the relative wind speed especially of the area where the turbine is sited.

The blade geometry of this study is to be develop for Maiduguri and environ, Maiduguri is located on latitude 11$^o$ 51'N and longitude 13$^o$09'E Borno State Northeastern Nigeria; the area is characterized by somewhat lower elevations, level terrain, and sandy soils with an estimated population of 1.5 million people (CENSUS, 1995).

Investigation carried out on the prospect of wind energy utilization reveal that an extractable power from wind in Borno State northeastern Nigeria gives a mean energy density of 42 kWh/m$^2$ of electricity with the mean wind speed at 10 meter height of about 3.89 m/s and probability of occurrence between 75% to 80% in a year, these gives Maiduguri in Borno State to be one of the highest prospects for wind generated electricity in Nigeria (Ngala et al, 2004). The aim of the study is to develop and carry out performance test of a micro Horizontal Axis Wind Turbine blade. Based on this goal, the study is set to achieve the following objectives:

i. design the micro Horizontal Axis Wind Turbine blade.
ii. physically develop the micro HorizontalAxis Wind Turbine blade
iii. experimentally verify the design criteria by testing the micro blade

## III. THEORITICAL BACKGROUND

There are two important reasons why wind turbine blades are able to spin in the wind: Newton's Third Law and the Bernoulli Effect:

i. Newton's Third Law states that for every action, there is an equal and opposite reaction. In the case of a wind turbine blade, the action of the wind pushing air against the blade causes the reaction of the blade being deflected, or pushed. If the blade has no pitch (or angle) the blade will simply be pushed backwards (downwind). But since wind turbine blades are set at an angle, the wind is deflected at an opposite angle, pushing the blades away from the deflected wind (Peter and Richard, 2012).

ii. The Bernoulli Effect tells us that faster moving air has lower pressure. Wind turbine blades are shaped so that the air molecules moving around the blade travel faster on the downwind side of the blade than those moving across the upwind side of the blade. This shape, known as an airfoil, is like an uneven teardrop. The downwind side of the blade has a large curve, while the upwind side is relatively flat. Since the air is moving faster on the curved, downwind side of the blade, there is less pressure on this side of the blade. This difference in pressure on the opposite sides of the blade causes the blade to be "lifted" towards the curve of the airfoil (Petal and Damania, 2013).

The design of a horizontal axis wind turbine blade start first by knowing the amount of wind energy the turbine blade can be able to extract from the wind. The wind energy that can be extracted by a wind turbine blade is given by half the air density, the cross-sectional area of the rotor and the cube of the free steam velocity as given in Equation 1 below. The rotor diameter (*D*) is calculated from the same equation at the rated wind power and wind speed (Peter and Richard, 2012).

$$P = \frac{1}{2}\rho A v^3 \qquad (1)$$

Where: $P$ is the wind energy extracted
$\rho$is the air density (1.225 kg/m$^3$)
$A$ is the swept area and is given by $\frac{\pi D^2}{4}$
$v$is the air velocity
From equation (1) the rotor diameter $D$ will be

$$D = \sqrt{\frac{8P}{\pi \rho v^3}} \qquad (2)$$

## IV. METHODOLOGY

The method adopted for this study is to design a Horizontal Axis Wind Turbine Blade using Blade Element Momentum (BEM) Theory,Blade Element Momentum (BEM) method is the oldest and remains to be the most widely used method for predicting wind turbine performance. It was originally developed by Glauert H. a German aeronautical engineer in 1935, who combined blade element theory and momentum theory to analyze the airplane propeller performance (Petal and Daminia, 2013). Blade element theory assumes that blades can be subdivided into multiple elements, which can act independently as two-dimensional airfoils. The forces and moments can be calculated separately then summed to obtain the overall blade forces and moments. Blade parameters which include chord length (*C*), rotor diameter (*D*), blade radial length ($\dot{r}$), blade relative angle ($\phi$), blade span (*L*), angle of attack (*θ*), tip speed ratio ($\boldsymbol{\lambda_r}$), solidity ($\sigma$), lift force ($F_L$), drag force ($F_D$), the power coefficient ($C_P$), turbine blade efficiency ($\eta$), ( shear force (*SF*) and bending moment (*BM*) as shown in Figure 1 below. These are calculated from the following equations;

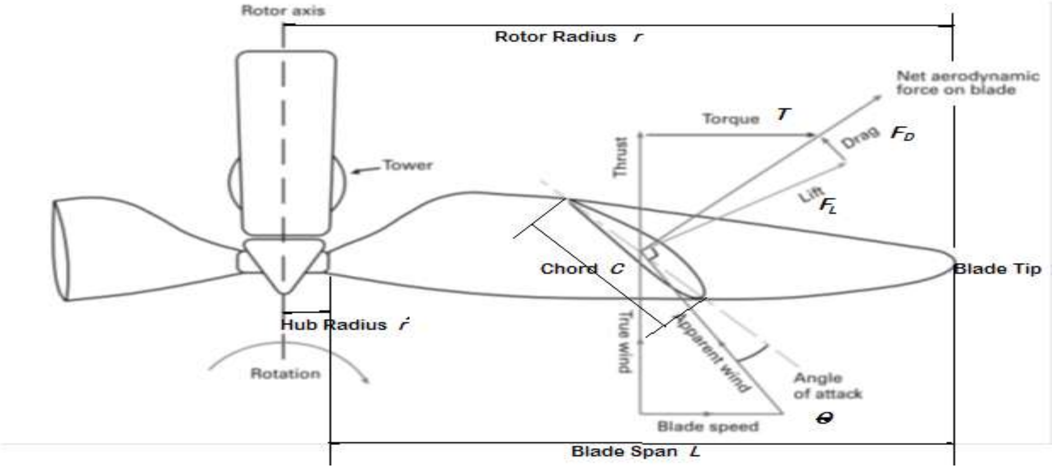

Figure 1. Blade Aerodynamic Parameters

The chord length (*C*) is the length from the leading edge to the trailing edge of a blade cross section that is parallel to the vertical axis of symmetry(Chandrala, *et al*; 2012) and is given by Equation 3 below and the wind relative angle ($\phi$) is given by Equation 4.

$$C = \frac{8\pi\dot{r}}{BC_L}(1 - cos\phi) \tag{3}$$

$$\phi = \frac{2}{3}tan^{-1}\left(\frac{1}{\lambda_r\left(\frac{\dot{r}}{r}\right)}\right) \tag{4}$$

The tip speed ratio ($\boldsymbol{\lambda_r}$) is the ratio of the blade tip speed over wind speed. It is a significant parameter for wind turbine design (Han, 2011) and its definition is shown in Equation 5 below. The blade

$$\boldsymbol{\lambda_r} = \frac{\omega r}{v} = \frac{2\pi N r}{60 v} \tag{5}$$

The angle of attack ($\theta$) is the angle between the incoming flow stream and the chord line of the airfoil. At low angles of attack, the dimensionless lift coefficient increases linearly with angle of attack and drag is reasonably small. Flow is attached to the airfoil throughout this regime. At an angle of attack of roughly 100, the flow on the upper surface of the airfoil begins to separate and a condition known as stall begins to develop. The dimensionless lift coefficient peaks and the dimensionless drag coefficient increases as stall increases (Ajao and Adegan, 2009). The angle of attack is given by Equation 6 below.

$$\theta = tan^{-1}\frac{2}{3\lambda_r} \tag{6}$$

Solidity ratio ($\sigma$) is the ratio of the area occupied by the blade to the available free space and is given by Equation 7 below.

$$\sigma = \frac{B\ x\ C}{2\pi r} \tag{7}$$

The ultimate wind speed ($v_{ulti\,.}$) is the maximum wind speed the blade is expected to withstand base on the blade design and is given by Equation 8 below. As well the probability of collapse ($C_{prob\,.}$) that is the probability that the blade can with stand such a wind speed without failing considering 1.5 as factor of safety is given by Equation 9 below.

$$v_{ulti\,.} = v_{max}\,\gamma_F C_{prob\,.} \tag{8}$$

$$C_{prob\,.} = \left[\frac{1 - k\ xIn\big(-In(1 - 0.01)\big)}{1 - k\ xIn\big(-In(0.98)\big)}\right]^n \tag{9}$$

The lift force ($F_L$) given by Equation 10 above is the force acting on the blade perpendicular to the undisturbed wind flow and the drag force ($F_D$) given by Equation 11 below is the force acting on the blade in the direction of the undisturbed wind flow.

$$F_L = \frac{1}{2}\ \rho\ v^2 C\ L\ C_L \tag{10}$$

$$F_D = \frac{1}{2}\ \rho\ v^2 C\ L\ C_D \tag{11}$$

The shear force (*SF*) on the blade is given by Equation 12, while the bending moment (*BM*) at a distance *x* along the span of the blade is by Equation 13.

$$S.F. = -wx \tag{12}$$

$$B.M. = -\frac{1}{2}w(L - r)^2 \tag{13}$$

The power coefficient is a measure of the mechanical power delivered by the rotor to the turbine's low-speed shaft. It is defined as the ratio of the mechanical power to the power available in the wind (Ajao and Adegan, 2009) and is given by Equation 14 below..

$$C_P = \frac{2P_T}{\rho\pi v^3 r^2} \tag{14}$$

The turbine efficiency which largely depends on the blade performance is given Equation 15 below.

$$\eta = \frac{C_P x 27}{16} \tag{15}$$

### 4.1 Blade Material and Method of Construction

The blade was constructed using high density wood for the skeletal, aluminum sheet for the body and mild steel for the coupler; High density dry wood which forms the core of the blade is to be cut to 1.5 meter (blade span) and 0.26 meter (chord length) with a thickness of 0.05 meter. The wood is then to be shaped to the required airfoil section based on the design parameters and the brown shaded spaces based on the dimension in Figure 2 below were cut-off along the span of the blade, this is to reduce the weight of the blade. The wooden skeletal is to be treated with wood insecticide and coated with wood sealant to reduce moisture absorption.

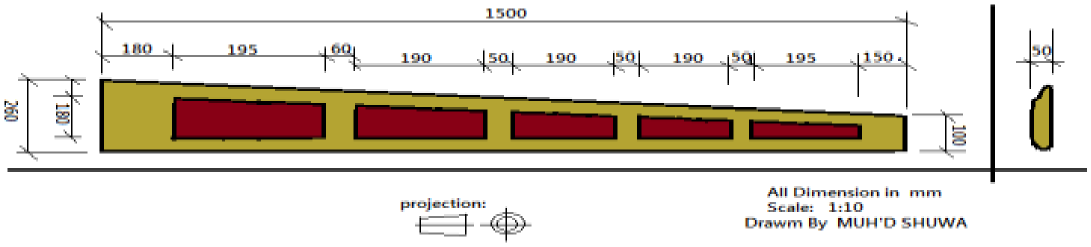

Figure 2 The Blade's Dimensions

The skeletal will be further allowed to dry and thereafter it is to be covered with 0.75 mmAluminium sheet, glue (Top-Bond Glue) will be applied in-between the wooded skeletal and the Aluminium sheet to bond the two together. One inch nails will be used to further secure the sheet on the wood. This will be done for each of the blade and they will be weight to insure they are of the same weight. Experimental trial of the constructed blade is to be carried out to observe the performance of the develop blade profile; the developed blades will be bolted to a hub which is connected to an alternator via a gearbox with a spur gear ratio of 1:8. The whole unit will be bolted on a four meter steel tower at the study site (University of Maiduguri). The performance of the blades will be observed, this includes their ability to extract the energy in the wind and convert it to electric energy via the alternator. Parameters to be measured are wind speed, voltage generated and resistance developed to determine the power output of the turbine.

## V. RSULTS AND DISCUSSION

The blade design analysis gives the blade specification calculated are shown in Table 1 below.

Table 1. The Developed Blade Specifications as calculated.

| S/No. | PARAMETER | SPECIFICATION |
|---|---|---|
| | Chord Length ($C$) | 0.26 m |
| 1 | Blade Span ($L$) | 1.5 m |
| 2 | Rotor Diameter ($D$) | 3 m |
| 3 | Swept Area ($A$) | 7.55 $m^2$ |
| 4 | Tip Speed Ratio ($\lambda_r$) | 5 |
| 5 | Angle of Attack ($\theta$) | $8^o$ |
| 6 | Wind Relative Angle ($\phi$) | $48^o$ |
| 7 | * Coefficient of Lift ($C_L$) | 1.007 |
| 8 | Lift Force ($F_L$) | 19.97N |
| 9 | * Coefficient of Drag ($C_D$) | 0.0125 |
| 10 | Drag Force ($F_D$) | 0.23N |
| 11 | Reynolds Number | $3 x 10^6$ |
| 12 | Solidity Ratio ($\sigma$) | 0.08 |
| 13 | Power Coefficient ($C_P$) | 0.189 |
| 14 | Turbine Theoretical Efficiency ($\eta$) | 32% |
| 15 | Ultimate Wind Speed ($v_{ulti.}$) | 8.81m/s |
| 16 | Probability of Collapse ($C_{Prob.}$) | 1.04 |
| 17 | Shear Force ($SF$) | 16.30N |
| 18 | Bending Moment ($BM$) at $x$=0.5m | 21.43$Nm^2$ |
| 19 | Extractable Power from the Wind ($P$) | 272.21 Watts |

*Obtained from the Design Foil Workshop

### 5.1 Experimentation

The designed blade is tested at the University of Maiduguri campus in Maiduguri on a 4meter tower. The rotor is connected to an alternator via a gearbox with a ratio of 1:8 to determine the power generation ability of the blade; the developed blade and its assemblyon a 4 m tower are shown in Figure 3 and 4 respectively below.

Figure 3 The Developed Blade

Figure 4 The HAWT Blade on a 4 meter Tower at the site.

Air density for the experiment site is 1.225 kg/m$^3$ (NIMA, 2015). A cup anemometer by FLUKE Corporation USA Model 373is used to measure the wind speed, atmospheric temperature and a Multi-meter by FLUKE Corporation USA FLUKE Model 117 was used to measure the rectified voltage and resistance. Parameters (Wind Speed, DC Voltage, Resistance and Atmospheric Temperature) were recorded at 15minutes interval between 8am and 5pm each day. The direct current (DC) power output was then calculated using theformula$P = \frac{V^2}{R}$. The measured power outputs with the corresponding wind speeds are shown in Table 2 and the curve in Figure 5 below.

Table 2 Wind Speed and Power Output from the Experiments

| Wind Relative Velocity ($v$) in m/s | Power Output put ($P$) in Watts [$P=V^2/R$] from the Experimentation |
|---|---|
| 1.2 | 2.17 |
| 1.3 | 2.77 |
| 1.4 | 3.43 |
| 1.7 | 5.32 |
| 1.8 | 7.41 |
| 2.0 | 10.32 |
| 2.3 | 13.72 |
| 2.5 | 19.22 |
| 2.7 | 25.27 |
| 3.0 | 34.32 |
| 3.1 | 38.42 |
| 3.3 | 45.77 |

| | |
|---|---|
| 3.4 | 50.49 |
| 3.5 | 54.88 |
| 3.6 | 59.45 |
| 3.9 | 76.23 |
| 4.0 | 81.60 |
| 4.2 | 95.09 |
| 4.4 | 107.25 |
| 4.5 | 116.85 |
| 4.8 | 140.85 |

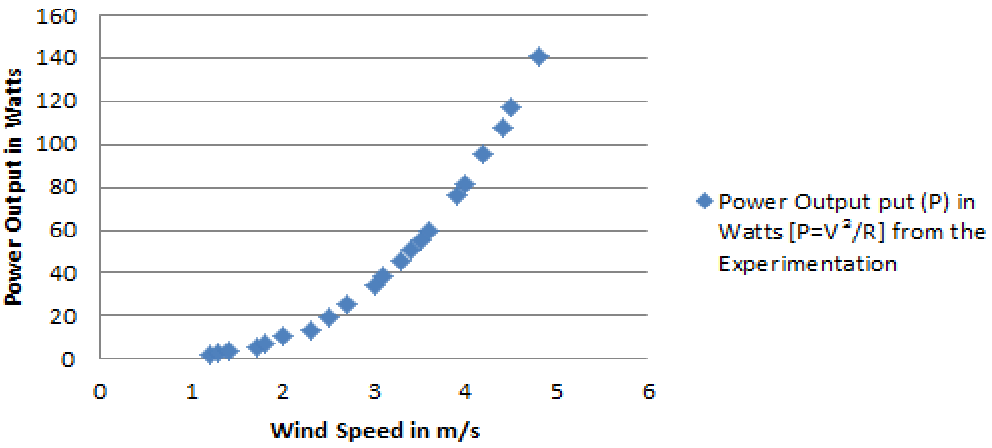

Figure 5 Experimental Wind Speed and Power Output Curve

From the experimentation result it was observed that the higher the wind speed the higher the power output will be, if the wind speed is 1.2m/s, power output will be 2.17W but as the wind speed increases to 4.8m/s the power output will be 140.85W as shown in Table 3 above. From the theoretical design the extractable power from the wind at a wind speed of 3.89 m/s is 272.21 W while at this wind speed experimentally a power output of about 76.23 W was recorded (Table 2), it shows that the blade was able to extract 28% of the theoretical power. This is because a physical limit exists to the quantity of energy that can be extracted, which is independent of design. The energy extraction is maintained in a flow process through the reduction of kinetic energy and subsequent velocity of the wind. The magnitude of energy harnessed is a function of the reduction in air speed over the turbine. 100% extraction would imply zero final velocity and therefore zero flow. The zero flow scenario cannot be achieved hence all the winds kinetic energy may not be utilized. This principle is widely accepted and indicates that wind turbine efficiency cannot exceed 59.3% (Farooq and Harmain, 2013). This parameter is commonly known as the power coefficient $C_p$, where max $C_p$= 0.593 referred to as the Betz limit. The Betz theory assumes constant linear velocity (Peter and Richard, 2012).

Therefore, any rotational forces such as wake rotation, turbulence caused by drag or vortex shedding (tip losses) will further reduce the maximum efficiency. Efficiency losses are generally reduced by:

i. Avoiding low tip speed ratios which increase wake rotation
ii. Selecting aerofoils which have a high lift to drag ratio
iii. Specialized tip geometries

## VI. CONCLUSION

The Horizontal Axis Wind Turbine blade profile has been designed, developed and tested. Experiment carried out on the developed blade shows that at $8^o$ angle of attack, air density of 1.225kg/$m^3$and a relative wind speed of 4.8m/s(the maximum wind speed recorded) the blade generates a power output of 140.85 W. However the experiment was carried out for only ten hours of each day but if extended especially through the night higher wind speed could have been recorded which will reflect to higher power output. Be that as it may the developed HAWT blade profile has shown the ability to perform and will really be a means of extracting and generating energy from wind; a renewable, clean and locally available source of energy in Maiduguri and environs.

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