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DESIGN AND FABRICATION OF A WIND TURBINE BLADE

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Abstract
A wind turbine blade design had been studied and fabricated at the CSIR-Institute of Industrial Research, Accra. Earlier turbine blades were manufactured from seasoned wood. The designed blade reported in the study was fabricated from fiberglass and epoxy resin compositions using wood for the mould pattern. The design is of the three-blade type for wind turbines which can be made from simple objects such as barrels. Dimensions and weights were measured to determine the possibilities of its performance. Factors that affect the spinning of the blade include the weight, blade count and its aerodynamic features. The new blades are assumed to be more reliable and efficient than wholly wood design. The calculated wind speed and power density at hub height of 12 m were 4.5 ms^{-1} and 149 W, respectively. The difference in the blade masses were reduced in the range between 39.2 and 52.6 per cent.

Introduction
The first turbine blade was made from massive steel in 1941 for which one of the blades failed in 1945 after flying for intermittent operations. It remained the largest wind turbine constructed for the past 40 years (Putnam, 1948). It is also known that the failure rates of wind turbine blades are of the order of 20 per cent within 3 years (Richardson, 2010).

Wind as an inexhaustible resource is noted for providing significant quantities of energy to support livelihood in developing countries. The rapid development in wind energy technology has made it convenient to apply the conventional energy systems. The cost of extending electricity to remote areas is very expensive, and the option is to decentralise small scale energy power systems that could meet the demand in those areas (Laryea & Otu-Danquah, 2012). It has been established that the demand for electricity from the national grid would grow from 18,000 GWh by 2015 to 24,000 GWh by 2020 (1200 GHh/year) (Energy Commission, Ghana, 2006). As Ghana continues with electricity load-shedding, it has become important to encourage wind power systems as stand-alone generator instead of relying on fossil fuels. It is, therefore, necessary to invest in small scale energy power systems, especially for households. Some decades ago, turbine blades were made from heavy materials which were used for slow speeds designs.

This, therefore, indicates the importance of material choice and selection in wind turbine designs. Modern designs are made from plastics, light-seasoned woods, aluminum and composite materials. The use of aluminum and composite materials has contributed to low rotational inertia. Wind energy potential at selected locations in the Volta Region of Ghana had been investigated (Laryea & Otu-Danquah, 2012). A wind power generation potential in three regions of Ghana outlined status and some challenges in operations and usage of the system (Laryea & Kotey, 2010). The objective of the study is to design and fabricate a wind turbine blade that could be used to replace the damaged wind turbine at the CSIR – Institute of Industrial Research, Accra.

Experimental

Blade design principles and criteria

The designing methodology of a wind turbine blade can be divided into three parts: 1) Establishment of a mathematical model to predict the operating performance, 2) determination of blade parameters, and 3) experiments for wind turbine blade operation. The mathematical model to design wind turbine based on the blade element momentum theory (BEM) has been studied (Jonkman, 2003; Burton *et al*., 2001), where the axial force (FN) and torque (T) acting on the blades are expressed, respectively, as:

$$dF_N = B\frac{1}{2}\rho V_o^2 \frac{(1-a)^2}{(\sin^2\varphi)}(C_L\cos\varphi + C_D\sin\varphi)cdr \quad (1)$$

$$dT = B\frac{1}{2}\rho V_o^2 \frac{(1-a)}{\sin\varphi}\frac{\omega r(1+a)}{\cos\varphi}(C_L\sin\varphi - C_D\cos\varphi)rcdr \quad (2)$$

where dF_N and dT are the differential rotor thrust and torques, respectively, B is the-number of blades, c is the chord length, dr is the thickness of the blade, ρ is the density of air, V is the speed of wind, φ is the angle of relative wind to rotor plane, a is induction factor, CL and CD are the coefficient of lift and drag aerodynamic forces, respectively. Parameter of induction factors are also expressed as:

$$a = \frac{1}{\left[\frac{4F\sin^2\varphi}{\frac{Bc}{2\pi r}(C_L\cos\varphi + C_D\sin\varphi)}\right] + 1} \quad (3)$$

$$a' = \frac{1}{2}\left[\sqrt{1 + \frac{4}{\lambda^2}a(1-a)} - 1\right] \quad (4)$$

Lift and drag are two significant variables that can indicate the quality of the aerodynamics of a blade design.

$$C_L = \frac{2F_l}{pV^2A} \quad (5)$$

$$C_D = \frac{2F_d}{pV^2A} \quad (6)$$

Also, two other modules that have been used for the design of a horizontal-axis wind turbine blade (HAWT), are the particle swarm optimization (PSO) algorithm and a structural analysis model (FEM). These were used to study the behavior of blades (Cai *et al.,* 2012). High ratio of CL/CD results in higher power coefficient of the rotor. Pro/Engineer Professional 3D CAD software has also been used to generate representative models of blade designs (Krause & Robinson, 2009).

Airfoil, pitch angle and blade shape

Aerodynamic forces (lift and drag force) are primarily the result of airfoil geometry, and the angle of attack (α), which is defined as the angle between the chord and the direction of the flow. The angles of the blade relative to the plane of rotation, and to the apparent wind are called the pitch angle and angle of attack, respectively. The angle of attack is very important and complicated, which changes as the real wind speed changes relative to the speed of the blade (headwind). On most airfoil blade shapes, an angle of attack of 10 -15° creates the most lift with the least drag and, thus, helps to generate lift by taking advantage of the Bernoulli effect. Even a minor change in the blade shape can dramatically affect the power output and noise produced by a wind turbine. The geometry of wind turbine blades is such that lift is always oriented in the upward direction. Wind turbine blades are, therefore, designed to the optimum in order to efficiently convert oncoming winds into mechanical energy to rotate the main driveshaft. Good blades must also account for the apparent wind that is experienced as the blade passes through the air.

Blade count

Determining the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability, and aesthetics. Noise emissions are also affected by the location of the blades upwind or downwind of the tower and the speed of the rotor. It is known that noise emissions from blades' trailing edges and tips vary by the fifth power of blade speed. A small increase in tip speed can make a large difference. Wind turbines developed over the last 50 years have almost used either two or three blades ((*http://en.wikipedia.org/wiki/Wind_turbine*).

Aerodynamic efficiency increases with increasing number of blades but with diminishing returns. Increasing the blade count from one to two yields a six per cent increase in aerodynamic efficiency, whereas increasing from two to three yields an additional three per cent. Further increasing the blade count yields minimal improvements in aerodynamic efficiency, and also sacrifices too much in blade stiffness as the blades become thinner (*http://www.ukessays.com/essays/engineering/wind-turbine-blades-and-efficiency-engineering-essay.php*). It has been established that the power output decreases with increasing blade count and blade pitch angle. Increase blade pitch angle is to extract more air and, hence, creates more resistance for the blade to turn. More turbulence are created at greater or wider pitch angles, which causes the blades to loose lift and slow down by churning up the fast moving air (*http://www.ecoCadDesignGroup.com*). In the case when wind is slower, a larger blade pitch may produce more power by capturing more air without much turbulence. To harvest more output power with increasing wind speeds, it is necessary to reduce the blade count and the blade length and width should be smaller.

Blade material

Material choice and selection play an important role in wind turbine blade designs. Some decades ago, turbine blades were manufactured from seasoned wood. However, these have been replaced by galvanised or steel blades and later by aluminum (lighter and stronger). Modern wind turbine designs are pushing power generation from 1 MW to 10 MW. For the past two decades, rotor blades that were manufactured from fiber glass have become very popular (Twidel & Weir, 2006). New materials and manufacturing methods provide the opportunity to improve wind turbine efficiency by allowing for larger and stronger blades. Some of the new materials used to manufacture wind turbine blades include composite from steel spars with aluminum shell supported by wooden ribs. It has been established that the only material with the very high strength, fatigue resistance, and stiffness is a composite material, and can be used in wind turbine blades (Mishnaevsky, 2011). Table 1 shows the properties of some fibers used for wind turbine blades

Other manufacturers use variations of the materials, which include carbon and wood with fiberglass in an epoxy matrix. Other options also include pre-impregnated fiberglass and vacuum-assisted resin transfer moulding. Epoxies improve wind turbine blade composite manufacture by allowing for shorter cure cycles, increased durability, and improved surface finish. Pre-impregnating operations is noted to further improve cost-effective operations by reducing processing cycles and, therefore, manufacturing time over wet lay-up systems.

Studies have shown that matrix–polymers are the main choice for wind turbine composites, which controls fracture toughness, delamination strength and out of plane strength (Haberken, 2006). Light weight highly flexible turbines, usually two and three bladed, are structure stiff and robust. The structural dynamic difference between two and three blades is the rotor moment of inertia (Bansal *et al*., 2002).

TABLE 1

Properties of some fibers used for wind turbine blades

Material	*Properties*		
	Young Modulus of Elasticity (GPa)	*Density (kg m^{-3})*	*Failure strain (%)*
E-glass fibers	70 – 77	2.55 – 2.64	4.5 – 4.9
S-glass fibers	86 – 90	2.46 – 2.49	5.4 – 5.8
R-glass fibers	84 – 86	2.55	4.8
Carbon fibers	220 – 240	1.7 – 1.8	0.7
Aramid (aromatic polyamide)	133 – 135	1.44	2.5 – 4

In addition, the fewer the blade count the higher the rotational speed which reduces peak torques in the drive train, resulting in lower gearbox and generator costs. The tip speed ratio (TSR) (λ) for wind turbines is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind. If the velocity of the tip is exactly the same as the wind speed, the TSR is equal to one. A higher TSR generally indicates a higher efficiency, but is also related to higher noise levels and a need for heavier, stronger blades.

$$\text{TSR} = \frac{\text{Tip speed of blade}}{\text{Wind speed}} \tag{7}$$

It has been shown empirically that the optimum TSR for maximum power output occurs at;

$$\lambda_{max} = \frac{4\pi}{n} \tag{8}$$

where n is the number of blades. Blade stiffness was required to avoid interference with the tower limit and determined how thin the blades were manufactured.

Wind speed

To predict wind speed at any height above ground level, Wind Atlas Analysis and Application Programme,

$$v = v_o 2.5^{\left(0.37-0.0881\ln\left(\frac{v_o}{1-0.0881 ln\,(v_o)}\right)\right)} \quad (9)$$

has been used. Feregh, (1993) predict wind speed through horizontal velocity variation with height as:

$$v = v_o\left(\frac{H}{H_o}\right)^{\alpha} \quad (10)$$

where V_0 is the wind speed at height H_o above the ground level, v is the wind speed at height H above ground level and α is the roughness factor which depends on the site type. The value of α varies from 0.1 to 0.4 (Tchinda & Kaptouom, 2004).

Covering a larger area effectively increases the TSR of a turbine at a given wind speed, thus, increasing the energy extraction capability of a turbine system. As a rule of thumb, the noise from a wind turbine increases with the fifth power of the relative wind speed (as seen from the moving tip of the blades). In noise-sensitive environments, the tip speed can be limited to approximately 60 ms^{-1}.

Wind power density

The power output P, from a wind turbine is given by:

$$P = \frac{1}{2} C_p \rho A V^3 \quad (11)$$

where ρ is the density of air (1:225 kg m^{-3}), C_P is the power coefficient, A is the rotor swept area (m^2), and V is the wind speed (m s^{-1}). It has well been established that only a fraction of the power in the wind can be converted by the turbine into mechanical work. It has a theoretical maximum value of 0.593 which is called Betz limit Wind. According to the Betz Limit, the theoretical maximum power efficiency of any design of wind turbine is 0.59 (i.e. no more than 59% of the energy carried by the wind can be extracted by a wind turbine). Once it is factored into the engineering requirements of a wind turbine, strength and durability in particular, the real world limit is well below the Betz Limit with values of 0.35 – 0.45 common even in the best designed wind turbines. The power coefficient of a rotor varies with the TSR (the ratio of rotor tip speed to free wind speed), and is only a maximum for a unique TSR.

Physical and chemical property of the resin NCS 985 PA

A typical physical and chemical properties of the resin NCS 985 PA are shown in Tables 2 and 3, respectively, which is cured between 10 to 15 min at 25 – 30 °C . (*http://www.ncsresins.com.au/msds/Msds%20 985PA.pdf*). NCS 985PA is a pre-accelerated, orthophthalic, unsaturated polyester resin. The low exothermic temperature buildup of NCS 985PA allows several layers of resin and reinforcement to be applied consecutively, giving a faster production rate and a shorter overall mould turn-around time. NCS 985 PA needs only the addition of catalyst to start the curing reaction. The material is designed for hand lay-up, and may be used without modification in most types of spray-up equipment. It has an exceptionally high water resistance and excellent mechanical properties.

TABLE 2

Typical physical and chemical properties of NCS 985 PA

Physical state	*Slightly viscous liquid*	
Colour	Cloudy pink	
Odour	Pungent	
Boiling point/range	145 – 148 °C	Styrene
Freezing point	-30.6 °C	Styrene
Flash point	31 °C	Styrene (closed up)
Flammability	1.1 – 6.1% v/v	Styrene
Auto ignition temperature	490 °C	Styrene
Explosive properties	LEL 1.1% UEL 6.1%	Styrene
Oxidising properties	None	
Vapour pressure	0.60 kPa @ 20 °C	Styrene
	0.81 kPa @25 °C	Styrene
Density	1.11 – 1.13 g cm^{-3}	
Solubility – water	Practically insoluble 0.03%	Styrene
Vapour density (Air = 1)	4.33	Styrene

Table 4, shows the features and benefits of using fiberglass for the turbine blade. The resin is allowed to attain a temperature of 25 °C before being formulated for use, and this takes 21 min to cure. The correct amount of catalyst is then added and thoroughly stirred with the resin shortly before use. The gel time of the resin formulation is controlled by the ambient temperature and the amount of BUTANOX M50 used. Gel times at various temperatures are shown in Table 5. Table 6 also shows the liquid properties of materials used to fabricate the turbine blades.

Fabrication of the blade

To create the fibreglass blades, an original sample (1250 mm × 160 mm similar to the existing blade, (dried seasoned wood-odum) was first produced as a mould which was used to make five copies. A wind turbine blade sample was made from wood following the blade design process. The mould was created with accuracy, and imperfections which allowed subsequent blades to be fabricated. The outer surface of the wooden blade sample was given a layer of resin to create a hard surface which was left to dry. This was sanded down, and another layer of resin applied which was also sanded down when dried. After drying, four to five coats of Durawax were built up on the wooden blade sample to buff the surface. At this stage, the actual mould was made in two halves, with the joining points along the two edges of the blade (leading edge and trailing edge). This was to allow the easy removal of the pieces from the moulds.

In order to make the mould, the waxed wooden blade was covered on the correct side with hard ‘outer layer’ resin and layers of chopped strand reinforce glass fiber mat of density 2.55 kg m^{-3}, Young Modulus of Elasticity of 84-86 GPa with failure strain of 4.8 per cent (Table 1). Additional resins were applied to built up a thick layer over the wooden blade. The thicker the layer (10

TABLE 3

Typical physical properties of NCS 985 PA cured within 10 min @ 25 °C

Typical properties of cured NCS 985 PA (unfilled casting) SABS 713-1974	
Temperature of deflection- under load (1.80MPa) °C	
water absorption:	
a) Increase in mass after 38 days immersion, mg	82
b) Loss in mass after drying, mg	45
Barcol (GYZJ934-1) hardness	40
Typical properties of cured NCS 985 PA (unfilled casting) BS 2782-1976	
Elongation at break#, %	2.2
Tensile strength, MPa	65
Tensile Modulus, MPa	3500
Volumetric shrinkage, %	79
#Filtered resin, void-free casting	
Typical properties of cured NCS 985 PA chopped strand mat laminated SABS 419-1972 (1992)*	
Tensile strength, MPa	150
Flexural strength, MPa	150
Flexural modulus, MPa	6000
Shear strength, MPa	60
Compression strength, MPa	170
Barcol (GYZJ 934-1) hardness	40
Glass content, % m/m	30
Typical properties of cured NCS 985 PA standard glass cloth laminated SABS 713-1974	
Glass content, % m/m	62
Flexural strength:	
a) At 23°C – original, MPa	580
b) At temperature of deflection –after aging, MPa	275

layers), the stronger it becomes. Due to the length of the blade, the layer will not be rigid enough to be used as a mould (it may bend), therefore, additional strengthening material (high density foam) was used as a former. This was run along the length of the mould to stop it from flexing. Fibreglass and resin were then applied around the foam to form a strong box section of fibreglass. Moulded fiberglass blades are usually better for batch production (Piggott, 2004). Rigidity in the mould was due to the fiberglass.

The fiber-mat was trimmed to shape in layers (10 layers) where resins were applied on each layer. It was prepared at 25 – 30 °C with curing time of 10 – 15 min. The moulds were made to allow both the top and the bottom to obtain the shape of the existing blade. The two halve blades were joined to produce hollow blades. The joined blades were physically inspected to detect any defect before drying, shaped and polished. The shape has been specified at a series of six stations along the length of the blade. Fig. 1. shows that at each station, the blade has chord width (1200 mm), blade angle (30°) and thickness (37 mm). The station and width distribution of the blade is shown in Table 8. The process was repeated for the other side of the blade, and the sides of the two mould halves were cut so they fit together neatly. There after, the inner surfaces of the mould were sanded well to make it smooth.

As shown in the basic design, the blade comprised of two blade halves, the windward half and the backward half. Each half blade is built up from 10 layers of fibreglass-mat. The fabricated blades were mounted on the wind turbine and free-hand turning to determine the balance.

TABLE 4

Features and benefits for using fiber glass material

Features	*Benefits*
Excellent colour	Readily pigmentable
Low viscosity	Excellent fiberglass wet-out
Thixotropic	Minimal drainage
Pre-accelerated	Requires only the addition of catalyst for gelation and curing
Non air-inhibited	Cures to a tack-free finish
Low exotherm	Suitable for construction of multi-layer laminates
Lloyds approved	Meets international quality standards
Low water absorption	Suitable for marine applications

TABLE 5

Typical curing characteristics of Butanox M50

Parts of BUTANOX M50 to 100 parts NCS 985 PA	*1*	*2*
Geltime @ 15 °C minutes	60	45
Geltime @ 20 °C minutes	35	20
Geltime @ 25 °C minutes	21	11
Geltime @ 30 °C minutes	11	8

TABLE 6

Typical liquid properties of Butanox M50.

Property	*Nominal*	*NCS test method*
Relative density	1.12	14
Viscosity @ 25 °C, MPa.s	450	5.3
Thixotropic index, ratio	1.4	5.3
Acid value, mg KOH/g	20	13
Volatile content, %	40	78
Geltime @ 25 °C using 1 phr* butanox M50, minutes	21	9
Liquid appearance	Cloudy, pale straw	2
Stability in the dark @ 25 °C, months	6 minimum	4.1
phr*=parts per hundred resin, by mass		

Results and discussion

Three wind turbine blades fabricated at the CSIR-IIR with R-fiberglass material to replace the wooden type are shown in Fig. 2. The masses of the first (Product I) and second batches (Product II) are shown in Table 8. From Table 9, it was observed that the differences in the masses were reduced in the range between 39.2 per cent and 52.6 per cent. Table 8 shows the properties of the finished turbine blade.

The fabricated blade was mounted on the wind turbine at the CSIR-IIR. The unbalanced blade was observed to be much heavier and was, therefore, reduced by grinding. TSR was calculated to be 4.2.

The installed three-cup anemometer with data logger measured wind speed at 10 m high. The average wind speed ranged between 3.8 – 4.3 m s^{-1} in October 2010. The height of the turbine hub was 12 m above the ground. The calculated speed at that height was 4.5 m s^{-1} where the value of α was assumed to be 0.2. The wind power density was 149 W.

Conclusion

From the study, it was concluded that the new fabricated blades will be more reliable than the wooden type, and will be attractive to large and small turbine manufacturers.

TABLE 7

Distribution of station and width for the blade

Station	*Width (mm)*
1	150
2	120
3	100
4	80
5	70
6 (tip)	60

TABLE 9

Typical calculation of manufactured sample

Expected wind turbine blades from fiberglass (density = 5.67 kg m^{-3})		
Blade No.	*Mass of product maximum (kg)*	*Vol. of material used (m^{-3})*
1	1.0	0.176
2	1.0	0.176
3	1.0	0.176

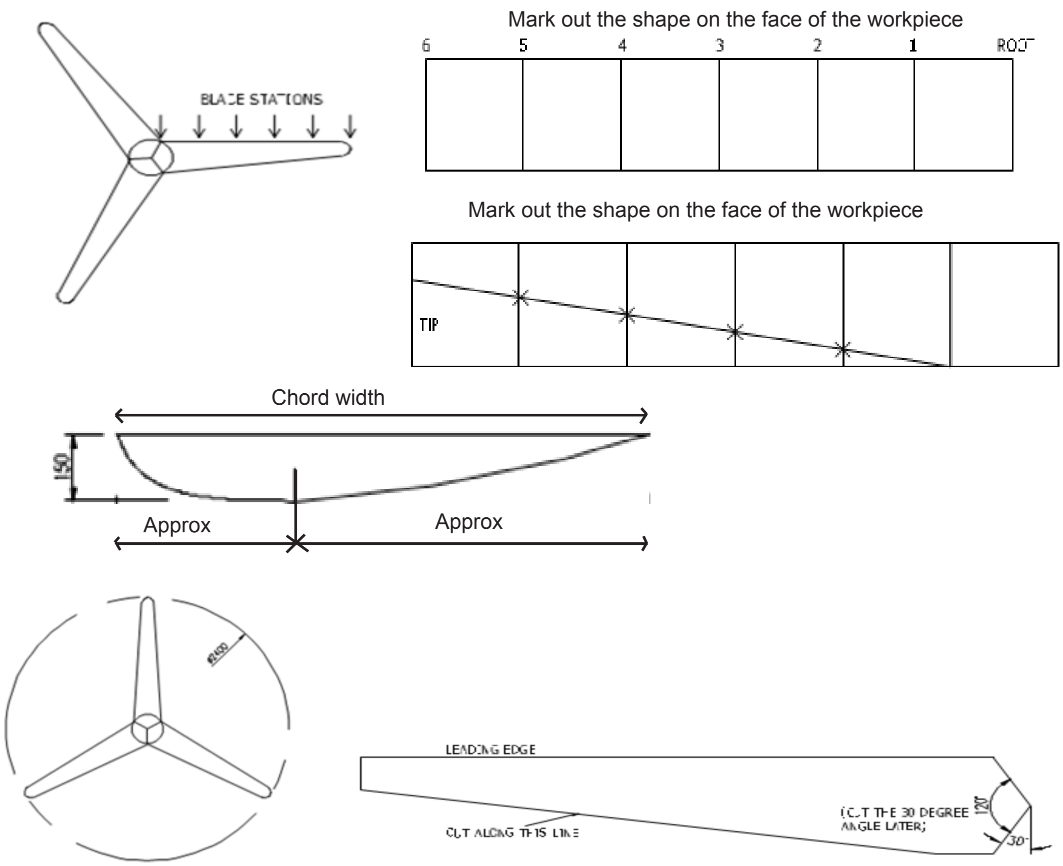

Fig. 1. Wooden blade shapes for mould pattern with features

TABLE 8

Typical calculation of fabrication and manufacturing sample

Wind turbine blades made from fiberglass (density = 5.67 kg m^{-3}; thermal conductivity = 0.05W/m.K				
Blade No.	*Mass of product (1) kg*	*Mass of product (2) kg*	*% Reduction*	*Vol. of material used (m^{-3})*
1	2.81	1.71	39.2	0.300
2	2.75	1.43	48.0	0.252
3	2.74	1.30	52.6	0.229

Wooden core root

Fibreglass turbine blades fabricated

Finished, polished and assembled wind blades

Fig. 2. The turbine blades designed and fabricated at the CSIR- IIR

The blade improves energy capture at lower wind speeds ranging between 3.8 – 4.3 m s^{-1}. Instead of the traditional linear shape, the blade features a curvature toward the tip edge, which allows the blade to respond to turbulent gusts in a manner that lowers fatigue on the blade. It is made of fiberglass and epoxy resin. The wind speed and power density at 12 m high were 4.5 m s^{-1} and 149 W, respectively. The difference in the blade masses were between 39.2 per cent and 52.6 per cent.

The material used in the design allows the blade to twist more than wooden blade designs, thus, relieving some of the effects of gusty turbulent wind on blade life.

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