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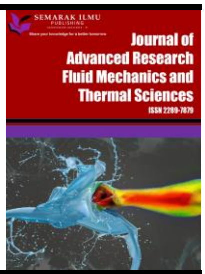

Numerical Analysis of Wind Turbine Performance Using Different Blade Materials under Wind Load Deflection

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ABSTRACT

A numerical investigation of the deflection on blades of three different materials against the range of wind speeds, and the effect on the blades' aerodynamic performance was carried out. ABS plastic, wood and glass fiber were used to make blade solid models with Eppler E387 airfoil. Using ANSYS software, wind load impact simulation was carried on the blades over range of operation wind speeds to determine blade tip deflections. Highest and lowest deflection over the range of wind speeds were found to be for ABS plastic blade and glass fibre blade respectively Deflected blades were adopted to a commercial 20 kW wind turbine as a case study. The turbines were subjected to air flow simulation to determine aerodynamic performances over the range of 5m/s to 20m/s wind speeds. At rated wind speed of 10m/s, power coefficient values of 0.52175, 0.53685 and 0.53710 at optimum tip speed ratio (TSR) of 5 were produced by ABS, wood and glass fibre blades respectively. At severe wind speed of 20m/s, corresponding power coefficient values were 0.29911, 0.47458 and 0.58666 respectively. The study indicates that at normal operating winds speeds, all the materials are suitable for blade adoption, while glass fibre material seems to withstand severe wind speed most in aerodynamic performance.

1. Introduction

Wind is one of the most important sources of renewable energy. Wind energy is an abundant resource in comparison with other renewable resources. Like other renewable sources of energy, wind originates from the Sun. About 1-2% of the sun's energy impacted on the Earth is converted to wind. This amount is enormous and roughly equivalent to about 100 times the energy converted into biomass by all plants on Earth [1].

The amount of electricity generated by wind increased by almost 273 TWh in 2021 (up 17%), 45% higher growth than that achieved in 2020 and the largest of all power generation technologies. Wind remains the leading non-hydro renewable technology, generating 1870 TWh in 2021, almost as much as all the others combined [2]. The International Renewable Energy Agency (IRENA) puts wind energy

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as one of the lowest-cost sources of electricity available. Onshore wind now has weighted average levelized cost of electricity (LCOE) by region of between USD 0.06/kWh to USD 0.09/kWh [3].

Wind turbine prices in developed countries have fallen by around 30% since their peak in 2008/2009, while Chinese wind turbine prices fell by 35% from their peak in 2007. The regional weighted average installed costs for onshore wind range from $1,280 to $2,290/kW. China and India have weighted average installed costs 35% to 44% lower than in other regions. The installed costs and the LCOE of offshore wind projects have stabilised, after rising through much of the last decade. Cost reductions are expected by project developers out to 2020, but offshore wind will remain more expensive than onshore [3].

Developing countries can access this energy with appropriate wind turbine technologies to address energy generation challenges. Nigeria for instance, has viable wind generation capacities as stated by various studies. Adekoya and Adewale [4] analyzed the wind speed data of 30 stations in Nigeria, determining the annual mean wind speeds and power flux densities, which vary from 1.5 to 4.1 m/s to 5.7 to 22.5 W/m^2, respectively. Fagbenle and Karayiannis [5] carried out a 10-year wind data analysis from 1979 to 1988, considering the surface and upper winds as well as the maximum gusts, whereas Ngala *et al.,* [6] performed a statistical analysis of the wind energy potential in Maiduguri. Enaburekhan [7] has determined better suitability of small to medium size turbines for application in Nigeria compared to large turbines.

Research in wind turbine development is mostly focused on the turbine blades. The rotor blades are the most important component of the wind turbine in terms of cost and performance of the wind power system. Blade material cost account up to 61% of total blade cost as reported by Fingersh *et al.,* [8]. Blade efficiency improvement is most critical as aerodynamic characteristics of the blades have the most important effect in producing energy efficiently. Approximately 60% of the total energy loss of typical wind turbine systems is the aerodynamic loss [9].

With availability of various materials for wind turbine blade fabrication, it is important to ascertain their suitability in terms of performance and cost. Wind turbines under operation may be subjected to severe wind loading that lead to blade deflections. This may affect their performance and life span. Many collapse cases of wind turbines which operated in wind farms are caused by the event that blade tip hits the tower [10]. This study is aimed at determining effect of tip deflection of blades made of three different materials on the aerodynamic performance of the wind turbine.

2. Methodology

This study involves using three materials: ABS plastic, wood and glass fiber to create 5m solid blades with an Eppler E387 airfoil profile. Using ANSYS software, each blade was subjected to wind load simulation at a range of operating wind speeds to determine blade tip deflection. The deflected blade was then simulated to ascertain its aerodynamic performance at the wind speed ranges.

2.1 Blade Materials

Three materials; wood, plastic and glass fiber were used as blade material.

Almost any type of wood can be used for making blades for turbines. Wooden blades are normally strengthened by lamination to add strength. They were cheap, easy to manufacture, and light. The wood in this study is a tropical wood Afzelia Africana, commonly known in Nigeria as Apara. It has relatively high moduli of elasticity and rigidity as reported by Jamala *et al.,* [11] and shown in Table 1.

ABS plastic is a structurally strong plastic that is an ideal choice for various applications that need strength and resistance to external strength impacts. ABS plastic sheeting creates rigid parts that are much more durable than any other plastic. ABS plastic sheeting also has a textured haircell finish that hides and resists scratches, allowing it to withstand heavy duty use. Its physical properties as obtained from literature [12] are given in Table 1.

Glass fiber is the most common fiber among fiber-reinforced polymers. It used in the manufacture of polymer composites. The matrices used are polyester, epoxy, vinyl ester, phenolic, organic, and thermostable resins. Glass fiber-reinforced polymeric composites have high specific strength and stiffness and good environmental resistance. E glass fibre was used in the study. Prepreg layers are made of E-glass plain-weave fabric, 295 g/m^2 in areal weight, and Cycom 7701 epoxy resin. Its properties as obtained from literature [13, 14] are shown in Table 1.

Table 1
Properties of blade materials

Material	Modulus of elasticity (GPa)	Modulus of rigidity (GPa)	Poisson's ratio
Wood	6.317	0.136	0.43
ABS plastic	3.2	1.79	0.34
Glass fiber	72.4	30.167	0.20

2.2 Airfoil Profile

The airfoil selected for production of solid and physical models of the blades is Eppler E387. The airfoil was selected from a vast number of standard airfoils in UIUC database. The choice is preferred as the airfoil is suitable for low wind speed applications. Eppler E387 is a low Reynolds number airfoil. It has maximum thickness of 9.1% at 31.1% chord. The maximum camber is 3.2% at 44.8% chord.

2.3 Blade Solid Modeling

A 5m wind turbine blade model was produced using SolidWorks. Using parts, the Spline feature was used to sketch the leading and trailing edges. Geometry Planes feature was utilized to provide a guided cross-section to generate the turbine blade form. These planes were placed along the previously created sketch lines and position each plane in a perpendicular relation to the sketch line. E387 profiles were then sketched upon each plane in accordance to the relevant specifications of the profile at each chord length.

Prior to using surfacing features, the Split Entities Tool was utilized to break the E387 profile shapes into segments. This step is important to ensure a smooth uniform transition will occur in tandem with the surfacing tools. Sketching phase of this model was completed to form a reference for the surfacing tools to form the main geometry. The primary surfacing tool of Surface Loft was used to exploit the interpolating planes between the various cross-sections created earlier. Profiles selected for the Surface Loft tool were represented by the two main spline sketches and utilized as the foundation to create this lofted geometry. The guide curves were pre-selected to enforce the surface loft shape as it was guided through the spline profile. The Surface Loft tool was repeated for the opposite side to generate the full turbine blade section.

The Planar Surface Tool was used to enable surface geometries to be enclosed. To generate a solid form, Knit Surface tool was used in order to fully seal the surface edges and provide mass within the enclosed surface shape.

Twist feature was used to twist the solid blade through pitch angles of 2.3 and 37.3^{o}.

2.4 Simulation of Wind Loads on ANSYS

Static forces related to wind speeds a turbine is subjected to during operation has must be determined to obtain its tip deflection. The wind speeds were divided in appropriate levels in order to simulate actual operating weather conditions. These levels range from 5m/s to 20m/s, a range that likely encompasses cut in, rated and cut off speeds of most turbines in region of study. 20 m/s is considered extreme natural condition. The blades of wind turbine may be locked beyond such speeds to avoid damage to structure and electrical generator, but wind loads will continuously develop at the blade surfaces. The model generated in SolidWorks was imported into ANSYS Design Modeller where boundary conditions were set and meshing applied. Meshed files were exported to ANSYS Fluent to solve all the simulation cases.

To simulate the blade, its model was imported into Design Modeller in ANSYS and air domain created with cuboid fluid enclosure with inlet face at distance of 5m upstream of the blade and outlet face 15m downstream to form two bodies, the blade and the air domain. Other faces surrounding the blade form symmetrical faces 5m away from the blade.

The boundary conditions for the fluid domain were inlet and outlet air velocity of 5m/s to 20m/s corresponding to free airstream velocity. For each case, inlet velocity equalled the outlet velocity. Fluid velocity differential through the symmetric boundaries of the computational domain was set at zero.

Four different simulation cases were run on Fluent for the blade at 5m/s, 10m/s, 15m/s and 20m/s. The blade angle was set at 5°, being the optimum obtained in previous study [15], to obtain pressure distribution. The structural response of blade against wind loads can be obtained through fluid- Structure interaction in the form of vector pressure distribution on the surface of blade [16, 17]. This is one of the available methods to obtain load concentration at various points against the input load but a different approach was used from the available options in the operating window of software. The resultant forces in the x, y and z axes of blade were obtained against the generated pressure distribution and converted into resultant forces as shown in Table 2.

2.5 Finite Element Modeling Using ANSYS

The development of blade geometry, element selection, mesh generation, applying load and boundary conditions were performed using the three blade materials on ANSYS. For each blade, the structure was considered as materially filling the volume core. Linear structural isotropic model was selected for the core of the blade. Several elements capable of modeling composite materials are available in ANSYS. Such element includes SHELL 91, SHELL 99, SHELL181, SHELL 281, SOLID 146, SOLID 185, SOLID 186 and SOLID 191. The core material required a structural solid element, so SOLID 186 with eight nodes element was selected out of the available element models. It supports large deflections and is well suited to model irregular meshes more accurately. Each blade was fixed at the root depicting condition of turbine hub; so similar boundary condition was created and applied in ANSYS.

The boundary conditions in this case are the fixed stand (root of blade in hub) and the load (resultant force). For the fixed stand, support was selected as fixed support and displacement and rotation fixed at zero (U_x=0, U_y=0, U_z=0 and Θ_x=0, Θ_y=0, Θ_z=0). The blade was constrained at root points in all degrees of freedom. The load is the calculated pressure force (resultant force in Table 2) and was applied on the surface at middle distance between root and blade tip. Under load, middle position of the blade was selected as the vertex and components of the resultant force were inputted.

2.6 Modeling of Scale Model Wind Turbine

Three scale models of the wind turbine with wood, ABS and fibre glass blades were produced using SolidWorks and marked BLDW, BLDP and BLDG respectively. To model a blade, the Spline feature (in parts) was used to sketch the leading and trailing edges. Root and tip had splines produced apart in ratio of 3 to 1. Geometry Planes feature was utilised to provide a guided cross-section to generate the wing blade form according to the deflection figure obtained in Table 3. These planes were placed along the previously created sketch lines and position each plane in a perpendicular relation to the sketch line. E387 profiles were then sketched upon each plane in accordance to the relevant specifications of the profile at each chord length. Split Entities Tool and surface features before sketching phase of the model form a reference for the surface tools to form the main geometry.

Surface loft, planar surface and knit surface tools were utilised to generate full blade section, ensuring sealing of surface edges and provide mass within the enclosed surface. Hub was created of length 200mm and diameter 200mm. using extrude tools, three holes to accommodate roots of the blade were made. Using Assembly, the hub and blade parts created were joined to form an assembled turbine.

2.7 Simulation of Scale Model Wind Turbine

Three scale models of the wind turbine generated were simulated in 5m/s to 20m/s wind speeds to analyse the moment and performance coefficients at tip speed ratio (TSR) of 3 to 7. To simulate each wind turbine, its model was imported into Design Modeller in ANSYS and air domain created with circular fluid enclosure extruded a distance of 1d upstream of the turbine and 3d downstream to form two bodies, the turbine and the air domain.

The circular faces formed the inlet and outlet for the airflow while the curved surface formed the symmetric boundary. The boundary conditions for the fluid domain were inlet and outlet air velocity of 5m/s to 20m/s corresponding to free airstream velocity. For each case, inlet velocity equalled the outlet velocity. Fluid velocity differential through the symmetric boundary of the computational domain was set at zero.

An unstructured meshing technique was used and final mesh imported into Fluent for the simulation. k-ω turbulent model as a closure to obtain solution to the flow. The pressure-based was used to perform the simulations. Solution was calculated until convergent moment coefficient and conservation parameters was reached. The setup definition was adjusted by changing flow from steady to transient state, and meshing mode from fixed to moving. Rotational speed was put as $\omega = \frac{v}{5}$ where v is tip velocity of blade at TSR of 3, 4, 5 and 6 respectively. The rotational values were set as negative to account for the relative motion of the moving mesh against stationary blades. With time step of 0.001seconds and maximum of 20 iteration per time step, solution was run again until convergence of moment coefficient and other convergence parameters were reached.

The values of power coefficient c_p were calculated from the expression by Ozdamar and Kavas [18]:

$$c_p = c_m \lambda \tag{1}$$

where, c_m is the moment coefficient, and λ is the tip speed ratio of the turbine blade.

2.8 Data Validation

The extreme theoretical performance coefficient value of wind turbine known as Betz limit is 0.593 [20]. The values of coefficients of performances of the blades in this study are not beyond this limit but did not reach the limit by small amount for practical reason, and hence result validated.

3. Results and Discussion

The resultant forces generated by pressure distribution over the range of wind speeds are shown in Table 2 and the deflections obtained with the different blades over corresponding resultant pressure forces are shown in Table 3. It can be seen from the values of deflection that ABS blade deformed most while fiber blade was least affected. Through the range of wind speeds, average deflection ratio to blade radius were 0.5%, 1% and 13.5% for glass fiber, wood and plastic blades respectively. Values of moduli as given in Table 1 are indicative of their deflection responses to the forces applied.

The deflection values obtained in the simulation are likely to match with analytical or experimental values, as prior studies by Muzamil *et al.,* [19] and others have shown.

Table 2
Resultant forces generated by pressure distribution

Wind speed (m/s)	Forces in x-axis (N)	Forces in y-axis (N)	Forces in z-axis	Resultant force (N)
5	5.53674	38.29751	-0.00105	38.69567
10	8.92055	84.82041	-0.00291	85.2882
15	10.61646	185.8943	-0.01324	186.1972
20	30.8243	313.6607	-0.04088	315.1716

Table 3
Blade deflection values in simulation

Force (N)	Blade material deflection (mm)		
	Wood	ABS plastic	Glass fiber
38.6957	1.137	12.519	0.861
85.2882	4.414	29.082	2.841
186.1972	23.555	162.061	10.513
315.1716	48.649	676.543	26.282

Table 4 to 7 show the power coefficient of the turbines at various TSR values for the range of wind speeds. Through the wind speed range, the figures indicate optimal values of power coefficient at TSR of 5. At low wind speed of 5m/s and rated wind speed of 10m/s (case of Polaris turbine model in the study), the power coefficients for all the blades seemed to match closely. This indicates that up to rated speed of 10m/s, the performance of the blade materials doesn't vary significantly.

Table 4
Turbine performance at 5m/s

Turbine	Coefficient of Performance C_p				
	TSR 3	TSR 4	TSR 5	TSR 6	TSR 7
BLDW	0.24313	0.39453	0.46865	0.40434	0.29001
BLDP	0.24909	0.39052	0.46905	0.39282	0.29085
BLDG	0.24192	0.39794	0.46640	0.39432	0.29925

Table 5
Turbine performance at 10m/s

Turbine	Coefficient of Performance Cp				
	TSR 3	TSR 4	TSR 5	TSR 6	TSR 7
BLDW	0.25810	0.48812	0.53685	0.46554	0.30464
BLDP	0.25941	0.49752	0.52175	0.45606	0.30835
BLDG	0.25659	0.46536	0.53710	0.48426	0.30296

Table 6
Turbine performance at 15m/s

Turbine	Coefficient of Performance Cp				
	TSR 3	TSR 4	TSR 5	TSR 6	TSR 7
BLDW	0.26843	0.50764	0.55832	0.48416	0.31683
BLDP	0.19456	0.37314	0.39881	0.36455	0.23126
BLDG	0.29058	0.52830	0.59241	0.51570	0.34394

Table 7
Turbine performance at 20m/s

Turbine	Coefficient of Performance Cp				
	TSR 3	TSR 4	TSR 5	TSR 6	TSR 7
BLDW	0.22816	0.43150	0.47458	0.41154	0.26930
BLDP	0.14592	0.27986	0.29911	0.27341	0.17345
BLDG	0.28488	0.51795	0.58666	0.50559	0.33719

The plot of power coefficients of the turbines at each TSR are shown in Figure 1 to 5. The plots indicate low power coefficient at low TSR of 3 and high TSR of 7. The power coefficient is highest for all the blades at TSR5. This indicates that TSR5 is optimal for the turbine irrespective of the materials they are made of or the deflection they undergo. At TSR3 and TSR7, the power coefficients of the three blades range between 0.15 and 0.35. At the optimal TSR of 5, the coefficients seem uniform between 5m/s to 10m/s wind speed range. Beyond 10m/s, coefficient glass fiber blade coefficient shows improvement, while that of wood stabilizes. However, the coefficient of ABS plastic shows decline in performance.

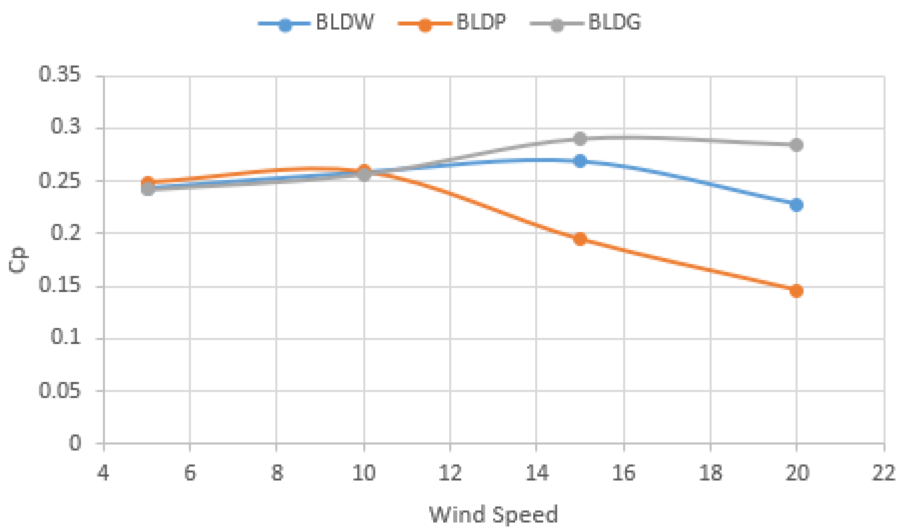

Fig. 1. TSR 3 power coefficient variation over wind speed range

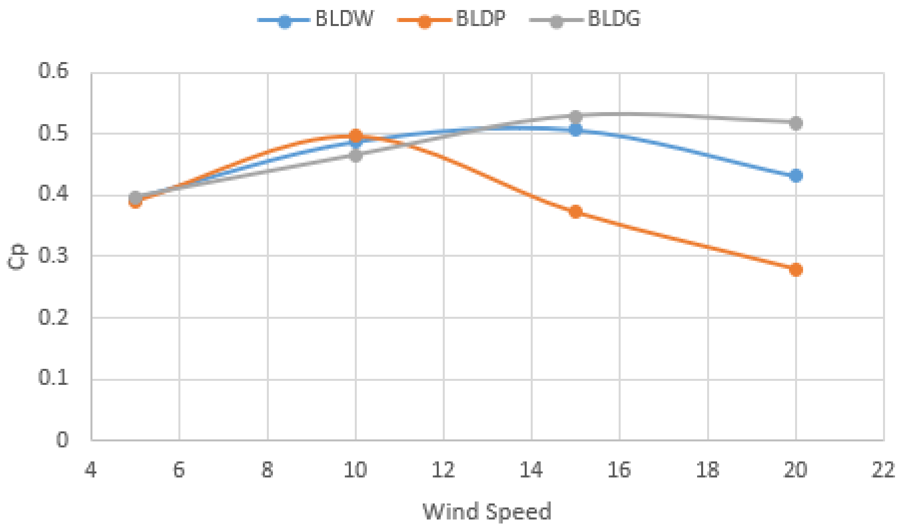

Fig. 2. TSR 4 power coefficient variation over wind speed range

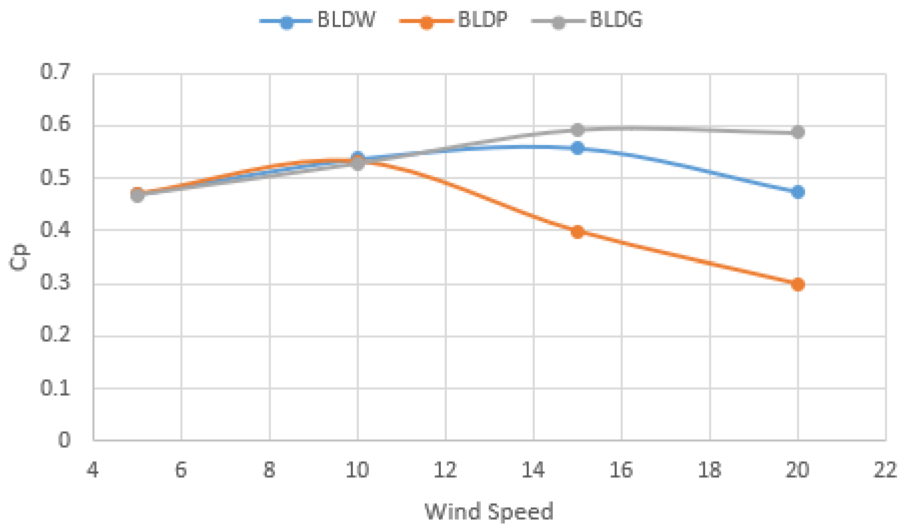

Fig. 3. TSR 5 power coefficient variation over wind speed range

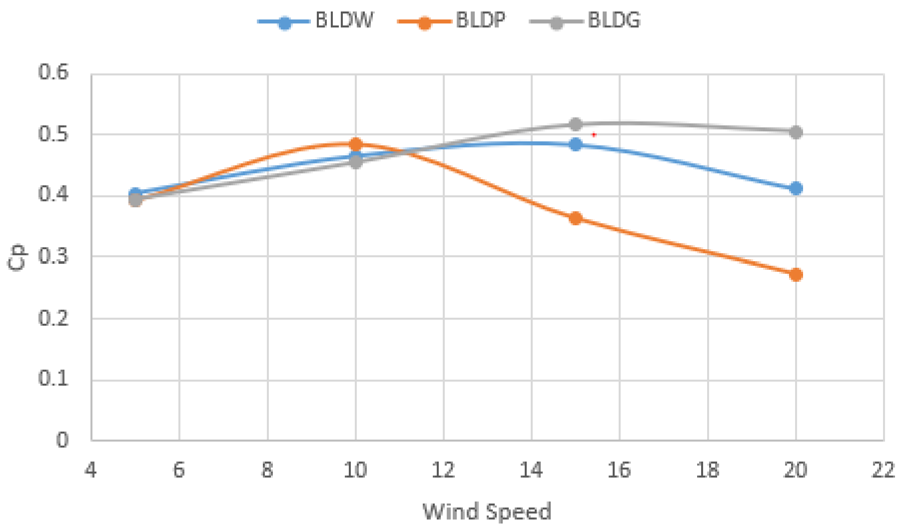

Fig. 4. TSR 6 power coefficient variation over wind speed range

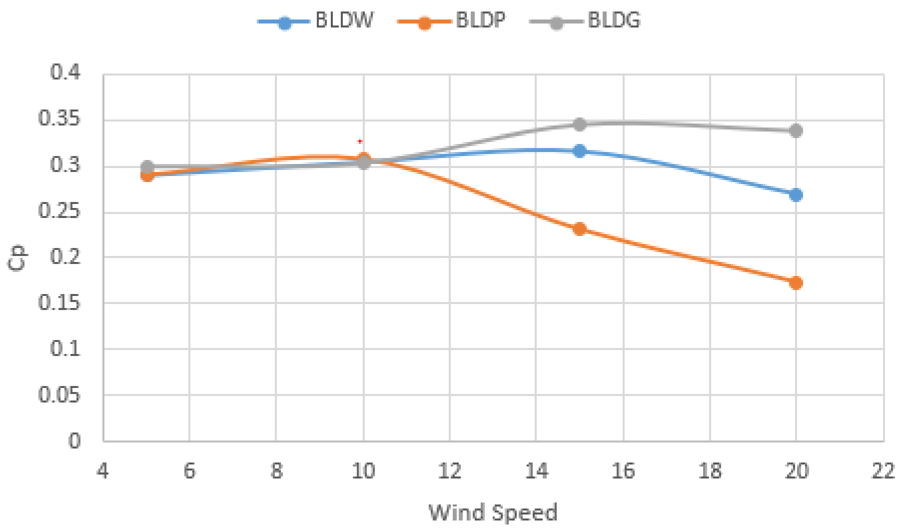

Fig. 5. TSR 7 power coefficient variation over wind speed range

At extreme speed of 20m/s, the power coefficient of glass fiber blade peaked while those of wood and plastic showed reduction. With no significant deflection at extreme wind speed, the glass fiber blade maintained high power coefficient. But plastic blade subjected to extreme wind showed reduction of its power coefficient to about 0.3 from its peak of about 0.54 at 10m/s. This indicates that if extreme wind condition is taken into consideration, the preference for the blades in application would be in the order glass fiber, wood, and then ABS plastic. But under normal wind speed of between 3m/s to 10m/s in Nigeria, each of the materials may be adopted for application.

The results of simulation data were assumed to be reliable and correct based on initial grid study carried out. Then gradient adaption carried out in each simulation process ensured relaxed mesh locations in the computational domains were highly resolved to give more accurate results, in addition to validation outlined and comparison to related studies. The grid study aimed at subjecting typical blade parameters to various cell resolution simulation to ascertain result consistency and computing economy.

In this case, the lift and drag coefficients were simulated with mesh resolution between 200,000 and 1,000,000. Consistency was achieved between 500,000 to 900,000 for both lift and drag coefficient of the blades as shown in Figure 6 and 7.

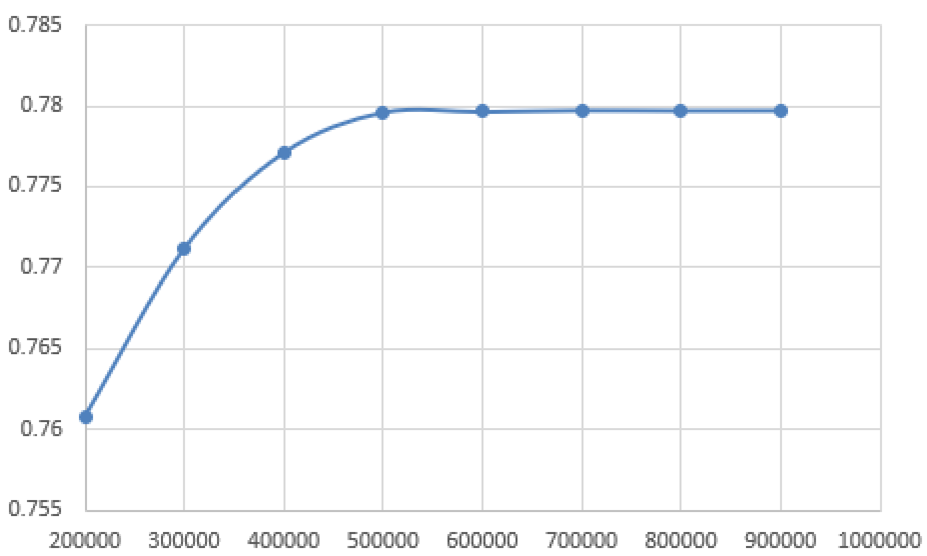

Fig. 6. Grid study on blade lift

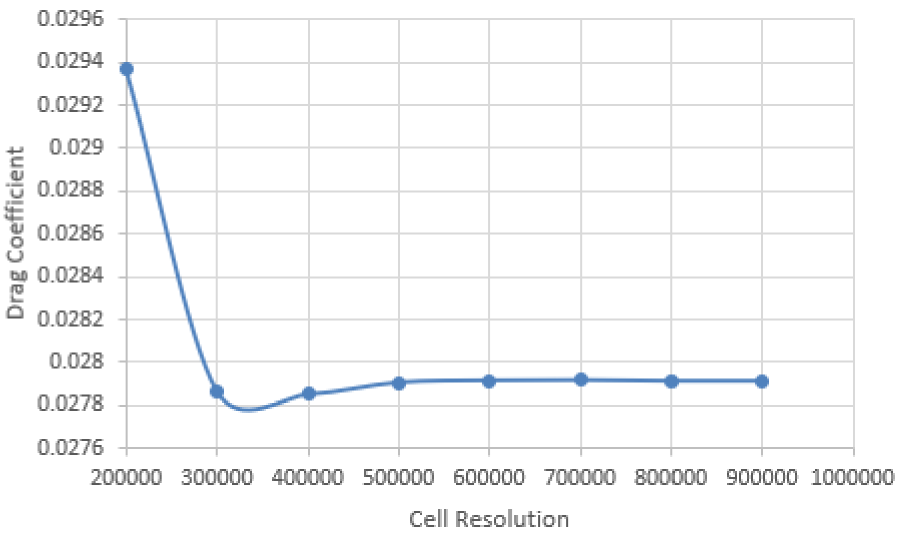

Fig. 7. Grid study on blade drag

The blade deformation could cause reduction of aerodynamic efficiency possibly by some factors. One is the reduction of blade swept area facing the wind caused by deflection, as swept area of turbine blade affects the power produced. Another factor is the possible distortion of the E387 profile of the blade during deflection. Such distortion of blade aerodynamic profile which invariably would affect lift and drag characteristics of the blade, hence its efficiency.

4. Conclusions

The study on wind turbine performance using different blade materials under wind load deflection was carried out. It discovered through simulation that blades made with wood, plastic and glass fiber subjected to wind loads had different tip deflections. Under the deflections, the blades aerodynamic performances at low to nominally rated wind speeds did not vary significantly. At extreme wind speeds however, there was decline in performance for wood and plastic blades, while glass fiber blade maintained high performance.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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