Designed Aerofoil Blade Model Performance Experimentation on Wind Tunnel

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Abstract— The design optimization of wind turbine blade aerofoil is an important characteristic feature to justify the performance of the blade in wind turbines for renewable energy generation. This could be performed in various ways but most often the wind tunnel is the most suitable device for this process. Therefore, the research of a designed aerofoil blade model performance experimentation was carried out in an educational based wind tunnel in the Mechanical Engineering laboratory of Niger Delta University with model number HM170, a product of GUNT Hamburg. Results obtained from the experiment confirms that study is justifiable due to the close march of achieved results to the proposed design point performance mostly for the rotor power yielding 134.6W, 125W and 99.86W for the wind tunnel aerofoil blade profile, simulation and fabricated aerofoil respectively against 100 – 150W design value of power at a minimal wind speed of 3.8ms^{-1}.Meanwhile, test samples of aerofoil for the tunnel, simulation and fabricated aerofoil blade profiles produces drag and lift coefficients as 0.731 and 0.439; 0.711 and 0.2; 0.722 and 0.289 respectively. Thus, established results validates the position of horizontal axial wind turbine (HAWT) as a lift force based turbine with high efficiency in power generation as results attest low drag coefficient than lift coefficient at a given 15°angle of attack. Hence, this confirms the avaliability of energy from theuncultivated naturally endowed wind around the coastal and hilly regions of Nigeria. Therefore, sourcing into wind renewable energy will enhence energy sustainabilty in our great country, Nigeria.

Keywords— Aerofoil, Drag and Lift Coefficients, Glide Ratio, HAWT, Wind Energy, Wind Tunnel, Wind turbine.

I. Introduction

The optimal performance of HAWT lies on a good modelled blade design. Thus, an aerofoil profile of the blade characterizes and predicts the performance of the design model. This therefore emerges as the dominant design configuration of HAWTs. The aerofoil blade profile is presented with different aerodynamics parameters which justifies a clear condition of the wind turbine though saddle with some difficult mathematical analysis. This complexity has led to multiple theories and has created baseline for collection of blade model analysis with wind tunnels and wind turbine test beds for easy determination of aerodynamic performance for wind turbines.

In accordance to this fact a scholarly reviewed research attests that the aerodynamic performance of a wind turbine is based on two major concepts, a numerical approach and experimentation of aerofoil in wind tunnel [1]. Though, the wind turbine design cannot be seen as an independent development but it is a linked process between the components of a wind turbine. However, the complexity of these processes cannot be over emphasized. Conversely, the design of a wind turbine is based on the cyclic design processes which involves optimization, verification and modification, depending highly not only based on the designer's experience but also modifies the optimum aerodynamic configuration of wind turbine blades [1], [2]. Therefore, a highly effective and reliable multi-objective optimization algorithm is needed to cope with the multi-variable, multi-objective and multi-constraint optimization problem of the wind turbine [1]. Hence, a study of the aerodynamic force analysis is necessary in the design process of the wind turbine blades in order to evaluate the optimum performance.

According to scholarly study, aerodynamic force; a combination of lift and drag force is the integrated effect of the pressure and friction caused by the flow of air over the aerofoil surface [3], [4]. [5]. The possibility of this scenario happens at a narrow corridor of varying angles normal to the wind direction. Thus, the relative velocity of the air striking the blade (W) causes an angle of attack (∝) is a

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ISSN 2229-5518

function of the blade velocity (U) at the radius under consideration and it is approximately two third of the wind velocity (v_1) [3], [6]. This generates a pitch angle (β) from the relative flow of air depending on the various velocities in the velocity triangle enclosing the aerofoil profile. Similarly, the efficiency of the wind turbine depends primarily on the design shape of the rotor blade. However, the drag and lift coefficients are aerodynamic influential variables from analysis of their respective forces which depends on the angle of attack. In accordance to reviewed study, a design aerofoil blade having angle of attack higher than 15 – 20° suffers from extraction of wind air to the blade causing a phenomenon called stall [6].

Meanwhile, the reference point of study presentation is based on using educational wind tunnel for the determination of aerodynamic parameters such as wind velocity, angle of attack, pitch angle, drag and lift coefficients, bending moment, rotor power, twist angle, angle of relative wind, glide ratio, etc. Wind tunnel testing can be executed under controlled test conditions and therefore is generally used to determine the wind turbine aerodynamic performance. However, a good knowledge of the interrelationship of these parameters for the justification of wind turbine is of paramount importance.

II. Blade Design Drawings

The presentation in figures 1 and 2 are blade design drawings of NACA 68025 aerofoil blade section and aero-parametric analysis on the blade profile respectively. The HAWT blade as a constrained of objective optimization problem with respect to geometric and operational characteristics, it is imperative to analyze the aerodynamic performance of the design blade prototype in a wind tunnel to test its reliability, observability and durability. Hence, this necessitate to have brief literature on the operational envelop and data analysis of the aerofoil profile.

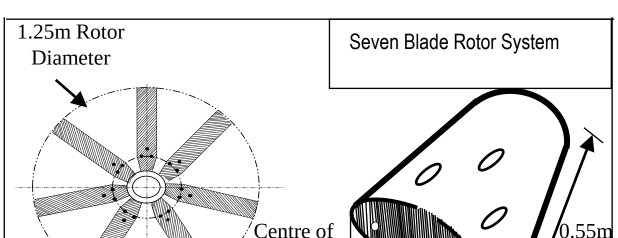

Figure 1: NACA 68025 Aerofoil Blade Section

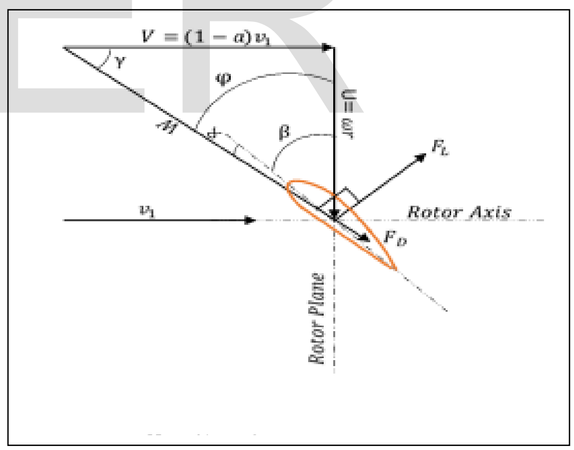

Figure 2: Aerofoil Blade Section Representation of Velocities, Angles and Forces

III. Performance Test Profile and Working Principle of Wind Tunnel

ISSN 2229-5518

An educational based wind tunnel with model number HM170, designed and manufactured by GUNT Hamburg in the fluid mechanics laboratory of the Department of Mechanical Engineering of Niger Delta University is used for the study. The presentation in figures 3 – 5 shows the cross section of the tunnel and some test aerofoil performance profiles for aerodynamics and fluid mechanics respectively.

Figure 3: Cross Section of Wind Tunnel
Source: [7]

Figure 4: Aerodynamics Test Sample Profiles
Source: [7]

Figure 5: Fluid Mechanics Test Sample Profiles
Source: [7]

The HM170 educational wind tunnel serve as a demonstration and experimentation test bed in the fields aerodynamics and fluid mechanics. It is a subsonic open wind tunnel with a square measurement section profile which allows different measurement accessories. It is capable of obtaining experimental data both from digital measurement amplifier with force display screen and also from a personal computer (PC). The provision for the PC is made available through a computer aided data acquisition and evaluation using electronic pressure transducers and position sensors. Thus, this is made possible by a special package software from the manufacturers which produces information for lift and drag forces, pressure distribution curves, wind velocities, etc in a prefer interface.

Conversely, in the measurement section of the tunnel the aerofoil profile is held by an electronic two-component force transducer fixed upon a circular measurement plate used for the adjustment of the angle of attack. An inclined tube manometer for the determination of wind velocity is incorporated to the tunnel to enable read-off the corresponding wind speed as the fan control switch is adjusted from the range of 0 – 10ms^{-1}.

IV. Aerofoil Blade Model of Wind Tunnel

A sample of the wind tunnel aerofoil profile similar to the design study model as shown in figure 4 was selected and used as a reference blade model for the study has the following design specifications as presented in table 1. The experiment involves the determination of the drag and lift coefficients, glide ratio, bending moment and rotor power on the profile as wind air passes over it. The tunnel is able of generating the drag and lift forces on the profile, with regulated wind velocities, pressures and different angle of attack whereas generated governing equations as presented in equations 1 – 9 are used for the determination of other parameters.

Table 1: Design Specifications of HM170 Wind Tunnel Aerofoil

S/N	Parameters	Symbols	Unit	Values
1	Radius	R	m	0.04
2	Wind Velocity	V	ms^{-1}	25
3	Rotational Speed	N	rpm	60

ISSN 2229-5518

4	Density of Air	ρ	Kgm^{-3}	1.225
5	Temperature	T	ºC	18
6	Pressure	P	mbar	1026
7	Relative Humidity	RH	%	60
8	Area	A	m^2	0.005027

$$F_D = \frac{1}{2}\rho\, C_D\, A\, V^2 \qquad 1$$

$$F_L = \frac{1}{2}\rho\, C_L\, A\, V^2 \qquad 2$$

$$\beta = \varphi - \propto \qquad 3$$

$$\varphi = \frac{2}{3}tan^{-1}\frac{R}{\lambda r} \qquad 4$$

$$\lambda = \frac{\omega R}{v_1} \qquad 5$$

$$\gamma = 90° - \varphi \qquad 6$$

$$BM = F_D\, x\, a \qquad 7$$

$$GR = \frac{C_L}{C_D} \qquad 8$$

$$Rotor\ Power = \frac{1}{2}C_P\, \rho A\, V^3 \qquad 9$$

V. Result Presentation

Consequently, figures 6 – 9 are graphical results analysis obtained from the wind tunnel sampled aerofoil profile in figure 4. The objective of this investigation is for the proficient use of the graphical data as a reference point to analyze the simulation and fabricated aerofoil blade profiles. This will enhance and yield an ideal HAWT blade for optimum power generation.

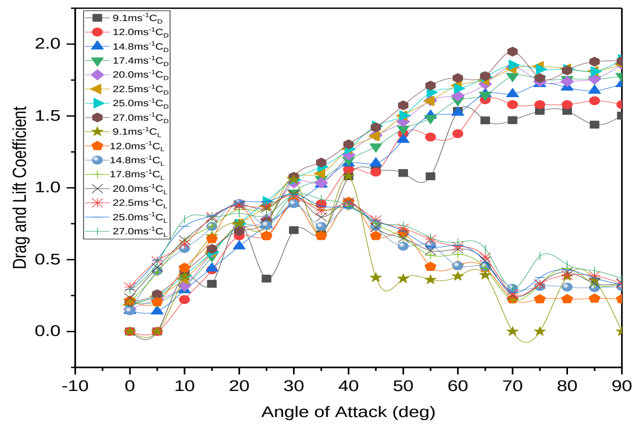

Figure 6a: Drag and Lift Coefficients for Wind Tunnel Sampled Aerofoil Profile

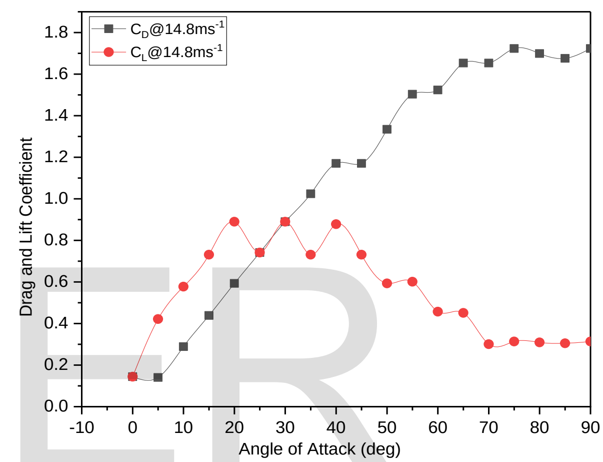

Figure 6b: Drag and Lift Coefficients for Wind Tunnel Sampled Aerofoil Profile

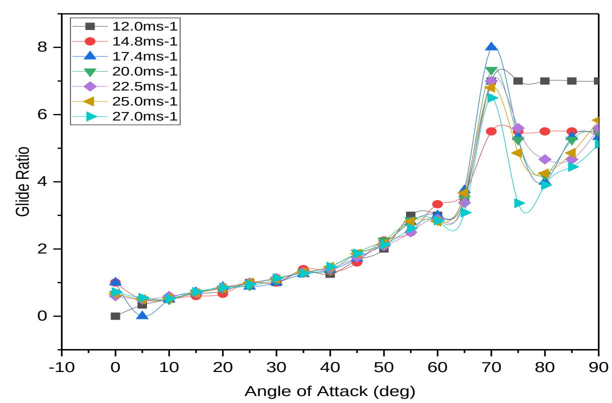

Figure 7a: Glide Ratio for Wind Tunnel Sampled Aerofoil Profile

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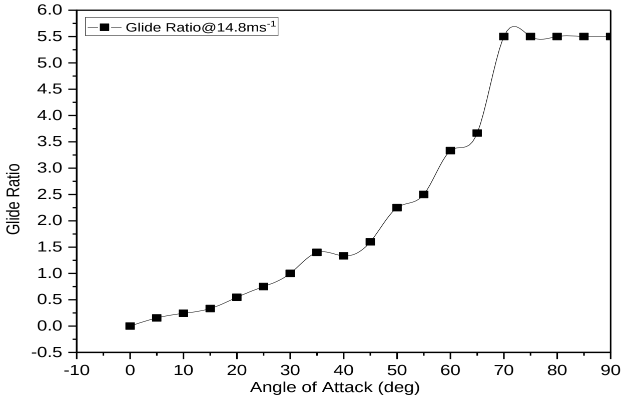

Figure 7b: Glide Ratio for Wind Tunnel Sampled Aerofoil Profile

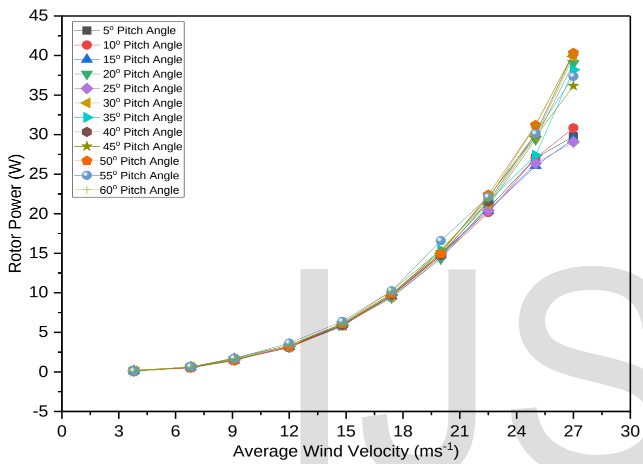

Figure 8: Power against Wind Velocity for Wind Tunnel Sampled Aerofoil Profile

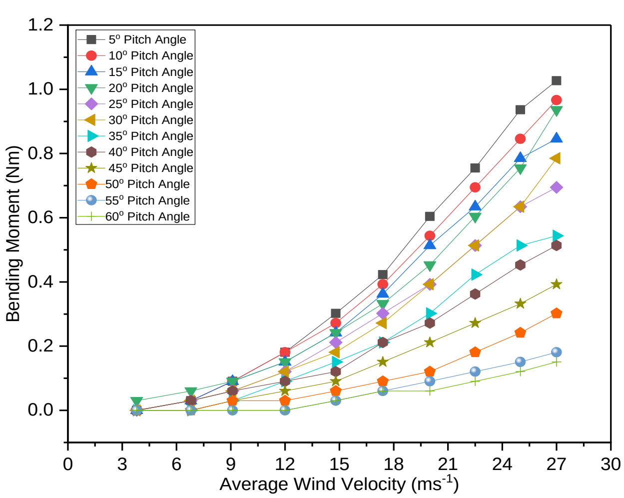

Figure 9: Bending Moment against Wind Velocity for Wind Tunnel Sampled Aerofoil Profile

Accordingly, the HAWT blade simulation analysis was also carried out using Ansys Fluent Computational Fluid Dynamics (CFD) simulation code. The CFD analysis on the modelled blade accompanied by blade meshing starts with flow analysis. This is to test for blade aerodynamics and flow characteristics of the wind turbine. It determines the possible amount of wind energy the turbine blades are capable of converting to useful energy. The solver is employed to analyze the boundary conditions of the blade in the computational domain representing wind tunnel in real concept to test the flow features and performance of the wind turbine blades as shown in figure 10.

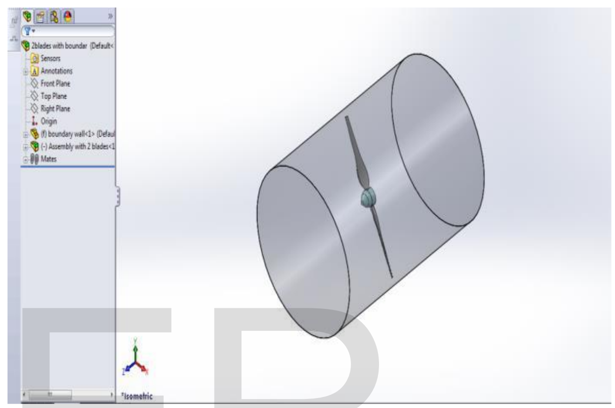

Figure 10 Computational Domain of blades Assembly

At the end of the simulation process of the modelled blade with CFD Ansys Fluent, the following results are achieved and presented in figures 11–14. They are graphical plots of lift and drag coefficients against angle of attack, glide ratio versus angle of attack, power and bending moment against wind speed respectively.

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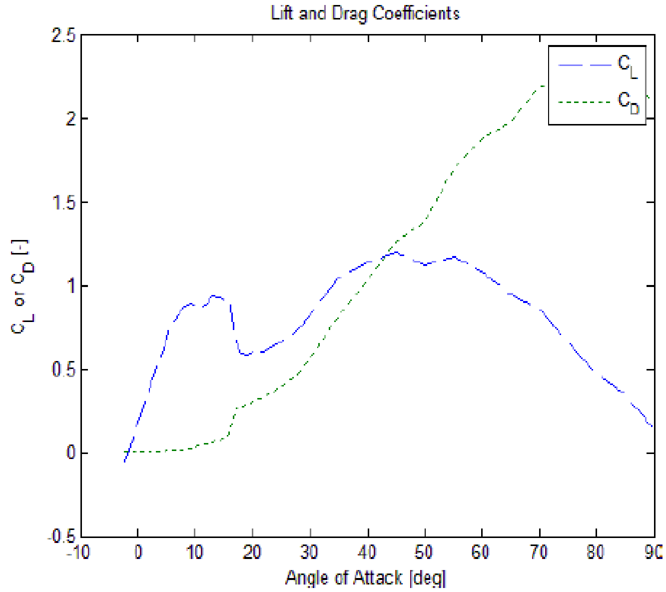

Figure 11: Lift and Drag Coefficient for Designed blade

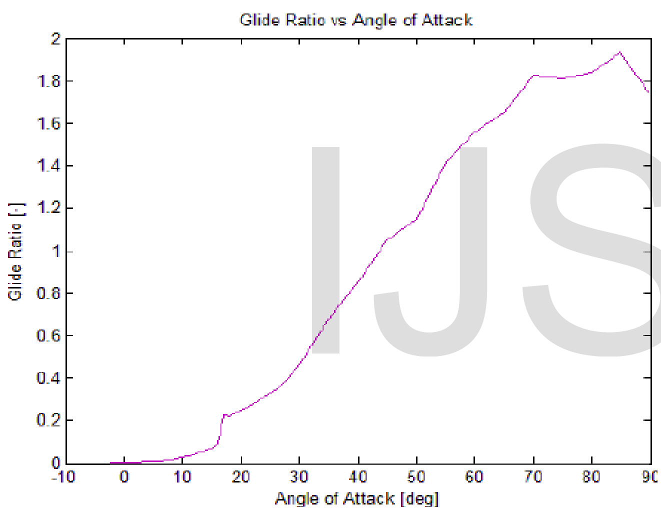

Figure 12: Glide Ratios for Modeled Blade

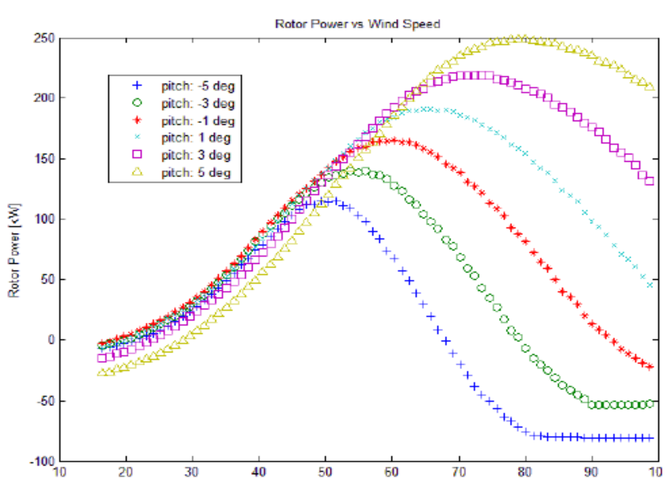

Figure 13: Power against Wind speed of rotor

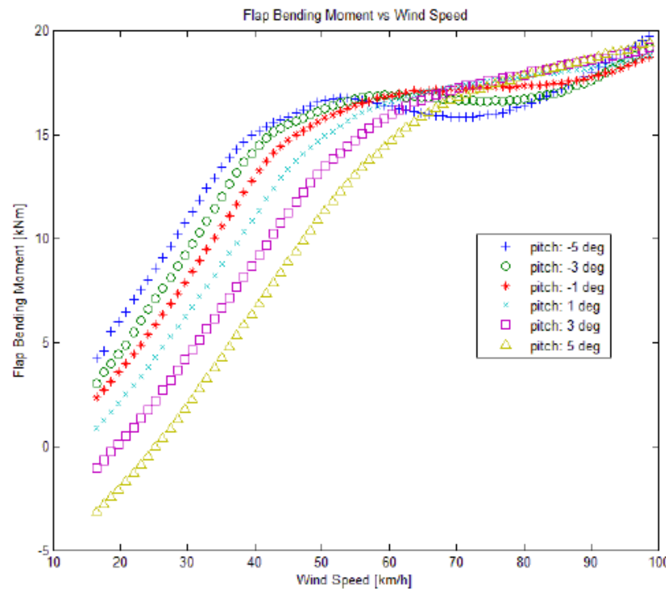

Figure 14: Bending Moment against Wind Speed

Conversely, an aerofoil fabricated blade model with respect to its design specifications as shown in figure15 is tested in the measurement section of wind tunnel to determine its performance when constructed finally in the study of the HAWT. Results obtained from test experimentation are presented in figures 16 – 19.

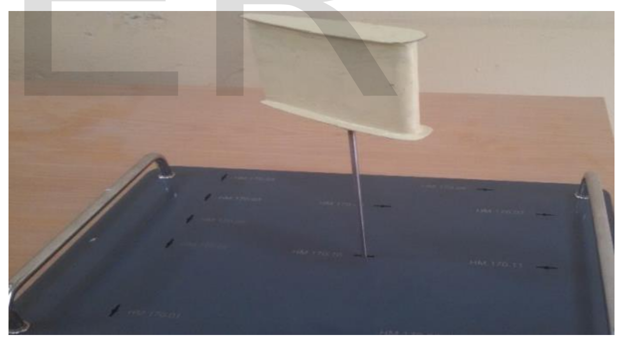

Figure 15: Fabricated Aerofoil Blade Model

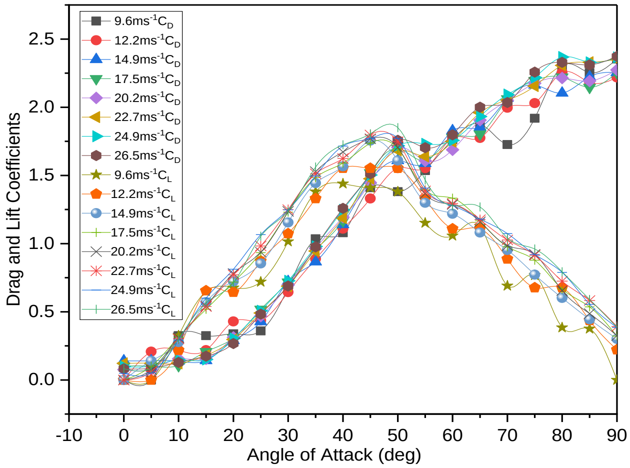

Figure 16a: Drag and Lift Coefficients of Fabricated Aerofoil Profile

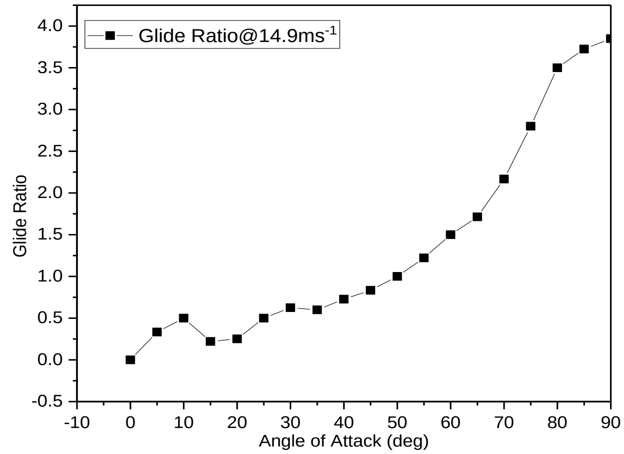

Figure 17b: Glide Ratio of Fabricated Aerofoil Profile

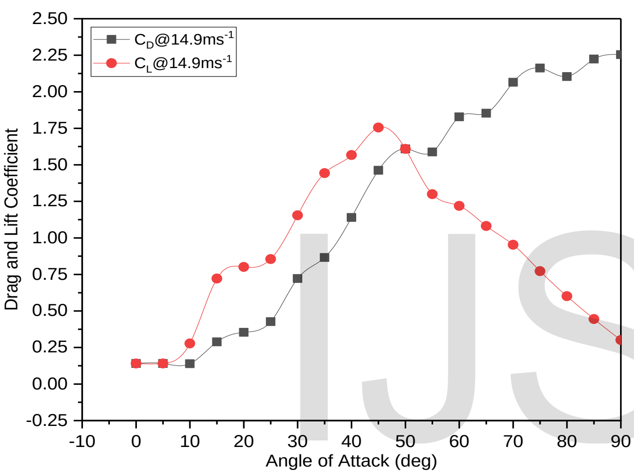

Figure 16b: Drag and Lift Coefficients of Fabricated Aerofoil Profile

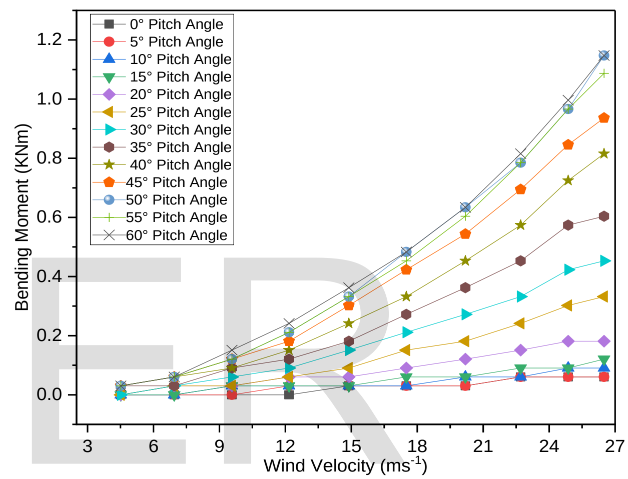

Figure 18: Bending Moment against Wind Velocity for Fabricated Aerofoil Profile

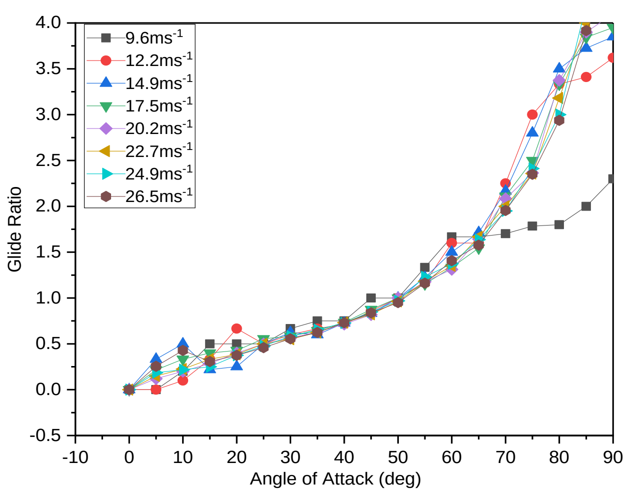

Figure 17a: Glide Ratio of Fabricated Aerofoil Profile

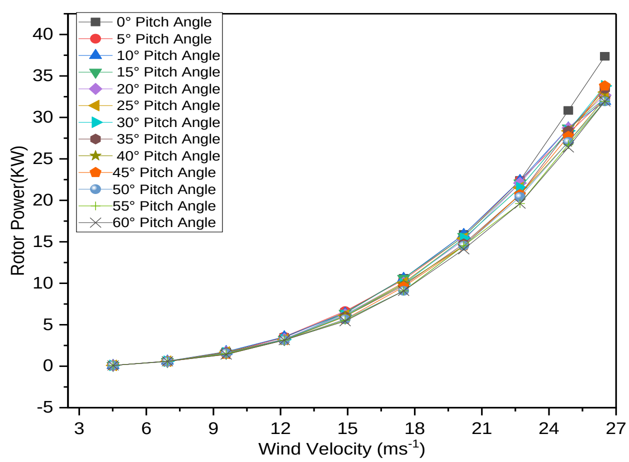

Figure 19: Power against Wind Velocity for Fabricated Aerofoil Profile

VI. Result Discussion

In consideration of the wind tunnel study with a design angle of attack of 15°; the corresponding lift and drag coefficients are obtained. The wind tunnel aerofoil sample produces 0.731 and 0.439 while in the simulation aerofoil, the values obtained are 0.711 and 0.2. Similarly, the fabricated aerofoil blade profiles produces 0.722 and 0.289 as presented in figures 6, 11 and 17 respectively. In all cases it is observed that the lift coefficients are higher than the drag. This is in conformity with an unveiled study that HAWT is a lift force based wind turbine with very noble performance. Thus, in order to achieve this phenomenon to obtain high value of lift force, the lift coefficient should be higher than the drag coefficient at a given design angle of attack [8], [9], [10]. These plot shows that for low angle of attack value, the aerofoil successfully produces a large amount of lift coefficient with little drag. This is a clear justification as confirmed in the reviewed literature. Similarly, at the same angle of attack, a phenomenon known as glide ratio, a ratio of lift and drag coefficients at constant wind velocity to the blade aerofoil is observed. According to scholarly research, high value of glide ratio for wind turbines is necessary for the enhancement of aerodynamic efficiency [6], [11]. Thus, the illustration of this scenario in figures 7, 12 and 18 gives clear indication of a graph plot of glide ratio against different angle of attack for the considered aerofoils. It is obvious that the glide ratio corresponding to the design point 15° angle of attack for the various graphs are less than their drag coefficients at the predefined wind velocity of 15ms^{-1}. Meanwhile, corresponding results of 0.333, 0.134 and 0.221 are achieved from the experimentation for wind tunnel blade aerofoil, simulation and fabrication blade aerofoils respectively for glide ratio. However, a reviewed literature attests that aerofoil with higher glide ratio are more efficient than those with lower glide ratio [12]. Therefore, test result confirms the fabricated aerofoil as a better model against the simulation aerofoil using the wind tunnel aerofoil as the reference point model for the experimentation.

Consequently, the design rotor performance is evaluated by means of rotor power and bending moment with respect to wind velocity and are presented for discussion in figures 8, 13, 19 and 9, 14, 18 respectively. The importance of the rotor power of the wind turbine can not be over emphasized. It is proposed that the HAWT under study should be capable of producing upto 100 – 150watts for a minimum wind velocity of 3.8ms^{-1} at its design point. Thus, results from aerofoil blade study gives 0.1346KW, 0.125kw and 0.09986KW at a design wind velocity of 3.8ms^{-1} for the wind tunnel aerofoil blade sample which is used as the bench mark, simulation and fabricated aerofoil blade profiles respectively at a pitch angle of 5°. However, the value for the obtained bending moment is zero for the three samples. This means the aerofoils are symmetric in nature thus, the aerodynamic moment about the aerodynamic center is zero for all angles of attack. This attest a balance and stable aerofoil at the design point of 5° pitch angle. By close observation, the bending moment across the design wind speed for the HAWT blade for both wind tunnel, simulation and fabricated aerofoils at different pitch angles appears to be constant and having value as zero. This is a clear validation as confirmed in a scholarly study conducted both experimentally and theoretically that an applied aerodynamic force at a location one – quarter chord backward from the leading edge on most low speed aerofoils have the tendency of constant aerodynamic moment [13]. Though, the rotor power and bending moment seems to increase as the wind velocity increases with rise in pitch angle as can be verify in the figures for tunnel sample aerofoil profile and fabricated aerofoil model. The results confirm that pitching occurs after the designed rotor power is achieved. This helps and controls the speed of the turbine, protecting it from damage at high speed.

VII. Conclusion

The study is justifiable since obtained results have close march to the proposed design point performance mostly for the rotor power yielding 134.6W, 125W and 99.86W for the wind tunnel, simulation and fabricated aerofoil respectively against 100 – 150W design value of power. This is an indication that if small amount of wind energy about 3.8ms^{-1} can produce optimum electric power of approximately 100W from deplayed fabricated aerofoil result; then sourcing into wind renewable energy will enhence energy sustainabilty in the region where study is carried out. Established results also validates the position of HAWT as a lift force based turbine with high efficiency in power generation because analyzed results attest low drag coefficient than lift coefficient at a given angle of attack. Thus, this assures preferable good design parameters for the blade because it is obvious that the achieved low glide ratio will match the design requirements of the aerofoil. Therefore, the proposition of the study in the coastal and hilly regions of Nigeria with abundant uncultivated naturally endowed wind renewable energy is not out of place.

REFERENCES

[1] T.G, Wang, L. Wang, W. Zhong, B.F Xu and L. Chen, "Large-scale wind turbine blade design and aerodynamic analysis", *Chin Sci Bull, Vol.*57, No.5, pp. 446 – 472, 2012.

[2] D. Sale, J. Jonkman, and W. Musial, "Development of a hydrodynamic optimization tool for stall-regulated hydrokinetic turbine rotors", *ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering*, pp. 901–906, 2009.

[3] P.J. Schubel, and R.J. Crossley, "Wind turbine blade design", *Energies, Vol. 5, No.*9, pp.3425-3449.

[4] D.G. Hull, "*Fundamentals of Airplane Flight Mechanics*", Springer: Berlin, Germany, 2007.

[5] N.S. Farha Khanam, "Performance Improvement of Horizontal Axis Wind Turbine by Using Modified Blade of NACA 5510", *International Journal of Advanced Research in Science, Engineering and Technology (IJARSET)*, Vol. 3, No.2, 1575-1580. 2016.

[6] A.J. Balasem, and S. Narsimhulu, "Design and Modeling of Horizontal Axis Wind Turbine Blade", *National Conference on Recent Advances in Mechanical Engineering*, 16-17th March, 2012. MED, UCE, OU, Hyderabad, AP-500007, 1-6, 2012.

[7] GUNT Hamburg, "*HM 170 Educational Wind Tunnel Manual.* Unpublished Instructional Manual", GUNT-Gerätebau GmbH, Barsbűttel, Germany, 1997.

[8] T.J. Ajoko, "Horizontal Axial Wind Turbine Blade Design Using Ansys Fluent. *Journal of Multidisciplinary Engineering Science Studies (JMESS),* Vol. 2, No. 8, pp.798-803, 2016.

[9] P. Hardik, and D. Sanat, "Performance Prediction of Horizontal Axial Wind Turbine Blade", *International Journal of Innovative Research in Science, Engineering and Technology*, Vol. 2, No. 5, pp.1401 – 1406, 2013.

[10] T.V. Miguel, V.D.C. Marcelino, A.F. Juan, A.M.P. Luis, and T.E. Guilibaldo, "Design and Experimentation of a 1 MW Horizontal Axial Wind Turbine", *Journal of Power and Energy Engineering*, Vol. 2, No. 1, 9-16, 2014.

[11] K. Krzysztof, "High Performance Sailplane Design Strategy Using Inverse Design and Optimization Techniques", *Inverse Problems, Design and Optimization Symposium Miami, Florida, U.S.A., April 16-18. 2007*

[12] K. Emrah, and Y. Nadir, "HAWT Rotor Design and Performance Analysis", *ASME 2009 3rd International Conference on Energy Sustainability,* San Francisco, California, USA, July 19–23, Vol. 2, pp.1019-1029, 2009.

[13] T. Vogeltanz, "Application for Calculation of Mean Aerodynamic Chord of Arbitrary Wing Planform", *American Institute of Physics*, doi: 10.1063/1.4951901, pp. 120018-1 - 120018-4, 2016,