NOVEL AIRFOIL DESIGN FOR SMALL HORIZONTAL AXIS WIND TURBINE: A PRELIMINARY RESULT

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ABSTRACT
Various research efforts have been directed towards the design and re-design of wind turbine systems. This is in order to have more efficient, better performing and cost effective turbine systems. Based on this, efforts have been focused on wind turbine rotor design with emphasis placed on its aerodynamics. This is because the important criterion of a wind turbine rotor is the airfoil. It is the element that produces the forces that makes the turbine rotate. This research builds on existing knowledge and aims to further deepen knowledge in the field of wind turbine rotor design. The study designed and analysed a new airfoil for use in a small horizontal axis wind turbine. It employed the flow stage airfoil behaviour together with analytical software tools that include XFLR5, AirfoilPrep_v2.02.01, WT_Perf, and MATLAB.. Three well known and tested airfoils were employed and the coordinates were interpolated to create a new, more efficient and better performing small wind turbine rotor airfoil. The outcome showed the new airfoil performs better with good glide ratio over longer angle range, chord distribution and blade twist among other things. The parameters of the new airfoil were such that 10.17%, 26.49%, 6.26% and 45.0% of the chord characterised the maximum thickness and its position, and the maximum camber and its position respectively.

INTRODUCTION
The desire to generate electricity from sources that are both clean and environment friendly has brought about various efforts at developing systems which can employ abundant renewable energy sources. One of such resources is the wind. It is well known that wind energy has the ability to supply a substantial amount of electrical power to communities, either as standalone and or grid connected power source [1-4].

Wind turbine design has gone through various developmental changes in the past years. These changes have focused on developing systems that would bring down the capital cost per kW of wind electricity. Various attempts have been made to develop wind turbine systems that are more efficient and cost effective. A good number of these attempts have focused on wind turbine blade design optimization [5-6]. More recently, efforts have been geared towards the design of turbine rotors that will operate with maximum aerodynamic performance. This is predicated on the fact that improvements in the aerodynamic design have associated benefits which include good efficiency and better economic performance [7]. Another major importance of having optimum aerodynamic performance is the associated ability to make wind turbine rotor blades produce at low cut-in wind speeds. This is because the airfoil is the most important and basic characteristic of a wind turbine blade. It is the element that produces the forces that make the turbine rotate. However, according to Singh and Ahmed [8], aerodynamic optimization of the rotor blades is associated with optimization of the chord and twist distribution, number of blades, choice of airfoil shape, and the tip speed ratio. With this in mind, research efforts have been directed towards determining the optimum rotor shape that produces desired electrical power at low cut-in wind speeds. This study focused on developing a new airfoil suitable for small horizontal axis wind turbine (HAWT) that will be more efficient with improved performance at low cut-in speeds.

There are several families of airfoil profiles in existence for different applications. For instance, there is the very popular National Advisory Committee for Aeronautics (NACA) series and the National Renewable Energy Laboratory (NREL), USA series. These are available for research purposes. NREL has some airfoils that are specifically available for small wind turbines (SWT). However, the strategy adopted in this study was to design/develop airfoils whose glide ratio is high at a range of angles of attack rather than just at one peak angle or few angles. This will enhance the performance of the designed blade better than others such as the NREL or NACA series. Some profiles of the NREL series that have gone through optimization process includes FX 63-137, S822, S834, SD2030, SG6043 and SH3055 [9-10].

RESEARCH METHODOLOGY

Rotor Characteristics

The most important component of a wind turbine rotor is the airfoil. This is because it is the element that produces the forces that make the turbine rotate. The forces are called the lift (L) and drag (D) forces and given by the equations (1) and (2) respectively. The parameters of utmost importance are the coefficients of lift (C_l) and drag (C_d).

$$L = \frac{1}{2}\rho v^2 C_1 s \qquad (1)$$

$$L = \frac{1}{2}\rho v^2 c C_d s \qquad (2)$$

$$\frac{L}{D} = \frac{C_1}{C_d} \qquad (3)$$

where: ρ = density, s = airfoil span, v = air velocity, c = airfoil chord.

Equation (3) is called the glide ratio. It is the most important factor that affects the performance of the wind blade.

The pitching moment coefficient (C_m)

This is another important parameter, apart from the coefficients of lift and drag that affects the Reynolds number. It is derived from (Manwell *et al*. [11]:

$$C_m = \frac{M}{\frac{1}{2}\rho V^2 s c^2} \qquad 4$$

where: M = pitching moment

The airfoil behaviour

There are basically three flow stages of airfoil behaviour. These are the attached flow stage, the high lift/stall development stage and the flat/fully stalled stage. However, small wind turbines are generally designed in the attached flow stage. This study therefore employed the attached flow stage.

Blade radius and size

This is determined from equation (5):

$$R = \sqrt{\frac{P}{\frac{1}{2}\rho\pi v^2 C_p}} \qquad (5)$$

where: R = radius, P = power extracted from the wind, ρ = density, v = wind velocity and C_p = coefficient of power.

Chord distribution

The wind blade solidity is affected by chord distribution. The chord specification at the blade tip determines the magnitude of energy lost as a result of the wind vortices. Equation (6) [12] was employed to determine the chord distribution.

$$c = {}^{16\pi}/_{9C_l N\lambda^2 r} \qquad (6)$$

where: λ is tip speed ratio, N is the number of blades (= 3), C_l is the maximum coefficient of lift and r is radius.

The chord distribution is important in the determination of starting time and also the stresses at the connection of the blade to the hub. The closer the chord distribution is to the tip of the blade, the faster the blade moves through the air. Hence, the relative velocity of the wind increases with increase in radius.

Blade twist (Ø)

This is a significant determination of the coefficient of power obtained at each segment of the blade. Equation (7) was used to determine the designed blade twist [12] as:

$$\tan Ø = \frac{2}{3\lambda + 2/\lambda} \qquad (7)$$

where, λ is tip speed ratio at a particular radius r.

Wind speed, rotational speed and blade pitch

In the design, the operating conditions were assumed to be the following:

- Operating wind speed = between 3 and 15 m/s
- Blades' rotational speed = between 200 and 600 rpm
- Blade pitch was taken to be zero.

Tools used

The rotor characteristics are the foundation of SWT blade design. Therefore, before the process of creating a wind blade begins an airfoil must be envisaged and selected. This is because the airfoil is the most important and fundamental aspect of creating a wind turbine's blade. The airfoils are then analysed for suitability and adaptability. Based on this, this study employed the XFLR5 tool to analyse and study the characteristics of different airfoils with the view to select the best airfoil design that optimally meet the desired goal. XFLR5 is a program that analyses airfoils using the Xfoil code developed by Professor Mark Drela of the Massachusetts Institute of Technology. In order to understand and validate the results from the XFLR5, a set of different airfoils were selected and examined so as to be able to determine the benefits of the airfoil to be created. The selection was based on the criteria that they must have data with which comparisons could be made. Airfoils employed in this study, and their characteristics are presented in Table 1. Further to this, the XFLR5 was used to find the aerodynamic parameters of the airfoils E214, S1210 and NACA 7409 and thereafter used to create a novel airfoil called "*OP 2-3 airfoil"* and also determine its aerodynamic parameters. The results from this served as input for the Microsoft Excel tool, AirfoilPrep_v2.02.01. This excel tool was used to prepare and process the aerodynamic parameters of the novel OP 2-3 airfoil for use in the program WT_Perf (Wind Turbine Performance). WT_Perf was developed by NREL. It uses the Blade Element Momentum (BEM) theory in computing the performance of a wind turbine.

MATLAB codes were used to generate the chord distribution and twist of the wind turbine blades. The codes were written by Professor David Wood of the Department of Mechanical and Manufacturing Engineering, University of Calgary, Canada.

Table 1: Small Wind turbines airfoil in literature

Airfoil	Airfoil Characteristics	Blade Characteristics	Reference
NACA 63-415	Max thickness 15% at 34.9% chord. Max camber 2.2% at 50% chord	Rated power 20kW, design wind speed 10m/s, rotor diameter 10m, blade number 3.	[13]
SD 7062	Max thickness 13.98% at 27.2% chord. Max camber 3.97% at 39% chord	Rated power 600W, design wind speed 10m/s, rotor diameter 2m, blade number 3.	[14]
SG 6043	Max thickness 10.02% at 32.1% chord. Max camber 5.5% at 49.7% chord	Rated power 2kW, rotor diameter 3m, blade number 3.	[15]
S 809	Max thickness 21% at 38.3% chord. Max camber 1% at 82.3% chord	Rated power 19.8kW, cut-in wind speed 6m/s, rotor diameter 10.06m, blade number 3.	[16]
DU 96-W-180	Max thickness 18% at 35.2% chord. Max camber 2.5% at 36.3% chord	Frequently used in combination with other airfoils on large wind turbines.	[17]

RESULTS AND DISCUSSION

When the airfoils in Table 1 were inputted into the XFLR5 and their performances were analysed based on different criteria such as their coefficients of lift, coefficients of drag, pitching moment coefficients and the most important, the lift to drag ratio, Fig. 1 results.

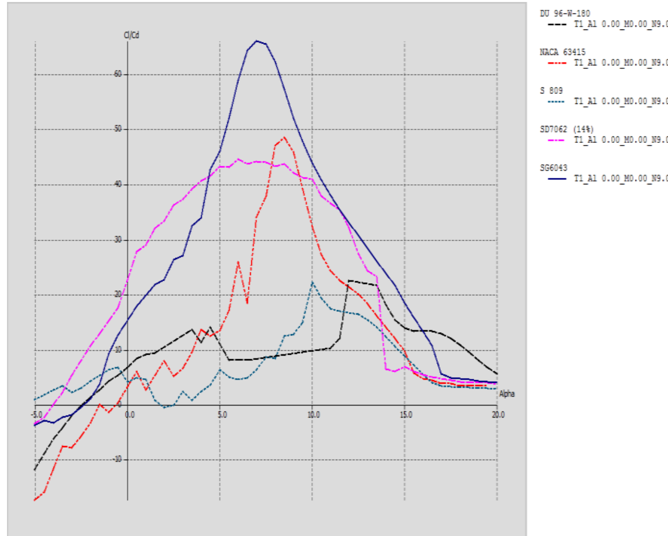

Fig. 1: Graph of Glide ratio against angle of attack

These results were compared to the airfoils' respective data in literature and a close correlation was obtained, thus validating the application of the XFLR5. In order to create a novel and more efficient airfoil, three airfoils (S1210, E214, and NACA 7409; see Table 2) widely considered as some of the most efficient [18, 19], were selected and used to create a new airfoil. In addition to their aerodynamic characteristics, airfoil E214 and NACA 7409 were chosen for their relative thickness in order to make the resulting airfoil (OP 2-3) easy to manufacture.

Table 4.2: Interpolated airfoils and their characteristics

Airfoil	Characteristics	By
S1210	Max thickness 12% at 21.51% chord. Max camber 7.2% at 51.11% chord	Michael Selig
E214	Max thickness 11.1% at 33.1% chord. Max camber 4.03% at 52% chord	Richard Eppler
NACA 7409	Max thickness 9% at 29.1% chord. Max camber 7% at 39.5% chord	NACA

Moreover, there are two methods of designing airfoils [20]. These include using an inverse design code (e.g. Eppler code) to prescribe flow parameters and come up with a desired geometry. The second method uses a trial and error approach in combination with a numerical optimisation (iterative) technique/code. However, the method employed for the creation new airfoil in this study was to carry out an interpolation between E214 and S1210 airfoils. The resultant airfoil was further interpolated with NACA 7409. The outcome led to the development of a new airfoil designated the *OP 2-3* airfoil. This designation was just for the purpose of identification. The configuration of *OP 2-3* airfoil is shown with Fig. 2

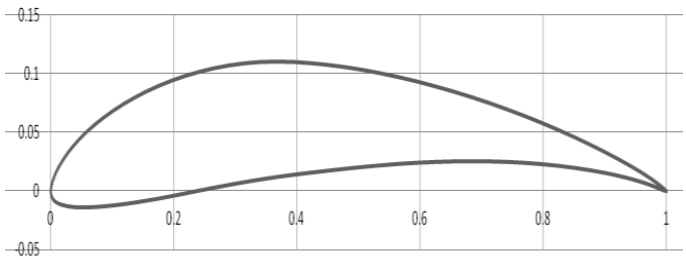

Fig. 2: The configuration of OP 2-3 airfoil

Table 3 shows the characteristics for the resulting airfoil while Fig. 3 shows the glide ratio to angle of attack for the interpolated airfoils and the resulting airfoil.

Table 3: Characteristics of the new airfoil (OP 2-3)

Name	Characteristics
Airfoil designation	OP 2-3
Max Thickness	10.17% of Chord
Position of Max Thickness	26.49% of Chord
Max Camber	6.26% of Chord
Position of Max Camber	45% of Chord

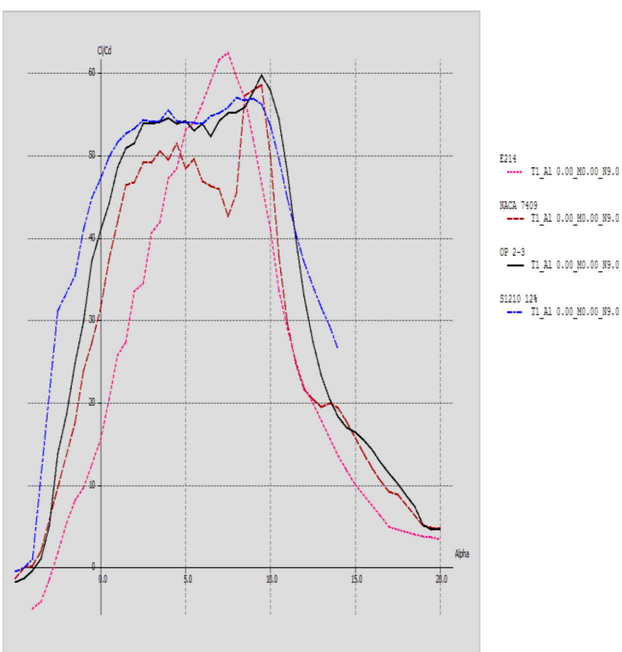

Fig. 3: Glide Ratio of airfoil E214, NACA 7409, S1210, OP 2-3

Fig. 3 shows that airfoil E214 has the highest glide ratio. However, it has its optimum angle for which the glide ratio is greatest at one angle point (7°). Also from the graph, airfoil S1210 has a large range at which its glide ratio is high (above 40° from -1.5° to 10.5°), although it does not possess the highest glide ratio. Likewise airfoil NACA 7409 has a good range though not as high as S1210. Comparing these characteristics with that of the developed airfoil, *OP 2-3* shows that *OP 2-3* airfoil has a good blend of all three. It has the second highest glide ratio and the second highest range, thereby ensuring that it has the best of all sides. The Table 4 shows the coordinates of the airfoil OP 2-3.

Table 4: *OP 2-3* Airfoil Coordinates

X coordinate	Y coordinate	X coordinate	Y coordinate	X coordinate	Y coordinate
1	0	0.17538	0.08979	0.19789	-0.00396
0.99298	0.00334	0.15523	0.08495	0.21988	-0.00166
0.9804	0.00845	0.13608	0.07974	0.24274	0.00074
0.9642	0.01427	0.11798	0.07423	0.26641	0.00317
0.94524	0.02033	0.10099	0.06846	0.29086	0.00559
0.92414	0.02658	0.08515	0.06248	0.31602	0.00794
0.90128	0.03295	0.07052	0.05633	0.34186	0.01017
0.87699	0.03935	0.05715	0.05006	0.36832	0.01226
0.85151	0.04573	0.04512	0.04368	0.39535	0.01416
0.82504	0.052	0.03448	0.03727	0.42289	0.01591
0.79775	0.05811	0.02526	0.03095	0.4509	0.01762
0.76979	0.064	0.01747	0.0248	0.47932	0.01925
0.74131	0.06965	0.01111	0.01894	0.50807	0.02078
0.71242	0.07504	0.00627	0.01346	0.53711	0.02216
0.68323	0.08013	0.00285	0.00845	0.56636	0.02333
0.65385	0.08491	0.00069	0.00393	0.59575	0.02429
0.62437	0.08934	-0.00007	-0.00003	0.6252	0.025
0.59488	0.09342	0.00072	-0.00341	0.65464	0.02543
0.56545	0.09711	0.00295	-0.00629	0.68398	0.02558
0.53616	0.1004	0.00664	-0.00861	0.71311	0.02542
0.50708	0.10326	0.0119	-0.01029	0.74195	0.02495
0.47828	0.10567	0.01857	-0.01161	0.77038	0.02415
0.44982	0.10762	0.02656	-0.01271	0.79827	0.02302
0.42177	0.10909	0.03594	-0.01343	0.82549	0.02158
0.39418	0.11006	0.04671	-0.01376	0.85189	0.01983
0.36711	0.11041	0.0588	-0.01376	0.87729	0.01777
0.34061	0.11005	0.07216	-0.01347	0.90149	0.01544
0.31474	0.10896	0.08676	-0.01288	0.92424	0.01285
0.28955	0.10718	0.10256	-0.01201	0.94525	0.01004
0.26509	0.10477	0.11951	-0.01088	0.96412	0.00704
0.24139	0.10177	0.13756	-0.00951	0.9803	0.00397
0.21851	0.09824	0.15668	-0.00791	0.99297	0.00119
0.19649	0.09423	0.17681	-0.00606	1	0

Analysis of Rotor Parametric Characteristics

Based on the new airfoil, a SWT was designed with the characteristics shown in Table 5.

Table 5: Wind Turbine Blade Characteristics

Number of Blades	Three bladed
Rotor Radius	1 metre

Airfoil Type	*OP 2-3*
Approximate Tip Speed Ratio	6
Rated Wind Speed	11m/s
Cut In Wind Speed	3m/s
Cut out Wind Speed	25m/s
Type of Wind flow	Upwind
Hub radius	0.1 metres

A radius of 1.0 m and 3 number blades were chosen so as to make the wind turbine as compact as possible. The purpose of adapting the created airfoil to a wind turbine blade was to be able to further the analysis and to ascertain its applicability and efficiency.

Chord Distribution and Twist

The chord distribution and twist of the blade were decided using equations 6 and 7 respectively together with values of 0^{o} for overall blade pitch angle and 0.1 m for radius of the hub. A MATLAB code developed by Wood [12] was employed for the analyses. The results of the analyses of the chord distribution and blade twist are given in Figs. 4 and 5 respectively.

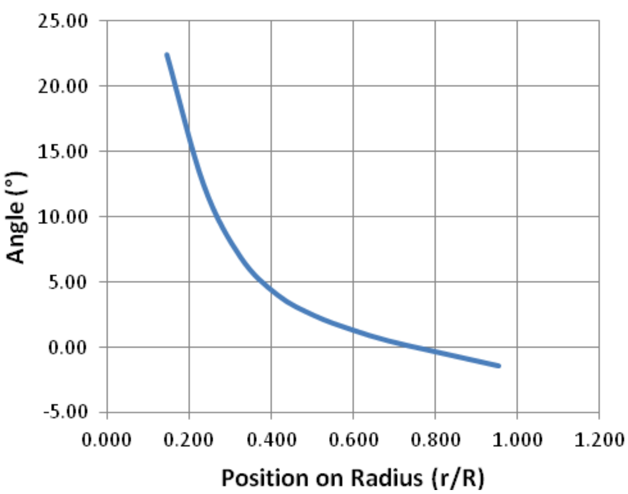

Fig 4: Blade Twist Distribution

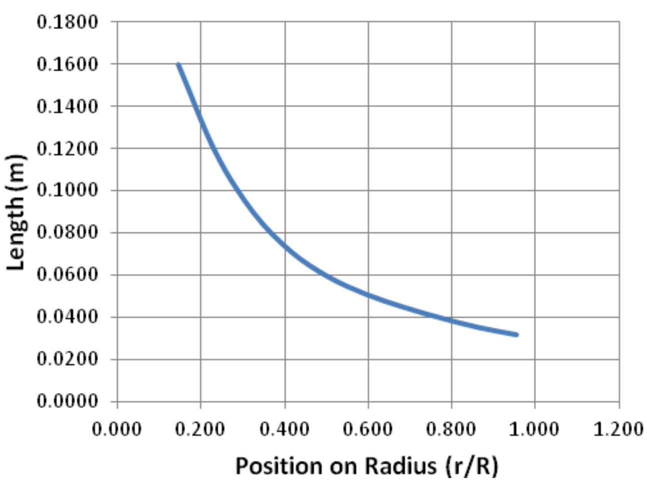

Fig 5: Blade Chord Distribution

The figures show that an inverse relationship exists between radial distance from the centre and twist angle as well as with chord distribution.

Using the chord distribution and blade twist from the MATLAB codes by Wood [12], a solid model of the blade design was created as shown in Figs. 6 and 7.

Fig. 6: Model of Wind Blade

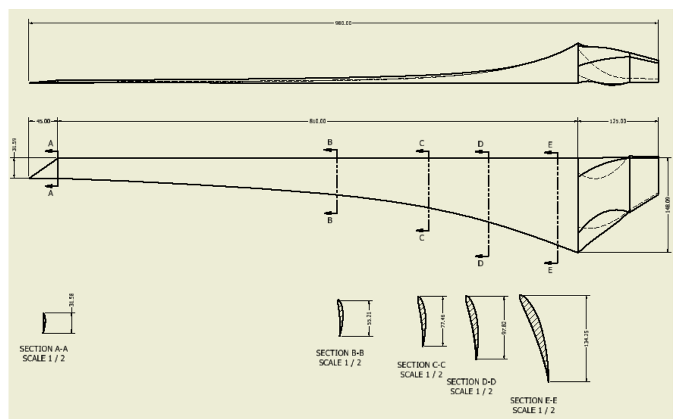

Fig. 7: The blade plan form and section cuts

CONCLUSION

The preliminary result showed that the novel airfoil OP 2-3 is more efficient with better performance criteria. When the aerodynamic parameters of the airfoil, generated with AirfoilPrep_v2.02.01, were employed with WT_Perf, the outcome showed that the torque, bending moment and optimum generation increased with rotor revolutions per minute (rpm). The maximum coefficient of power (C_p) was 0.45 and the torque varied between 6 Nm at 200 rpm and 26 Nm at 600 rpm. The bending moments, at these rotor speeds, were also between 11.5 and 35.0 Nm. The wind speed that produced the maximum C_p, torque and bending moment ranged between 11.0 and 12.0 m/s. The power curve is shown with Fig. 8

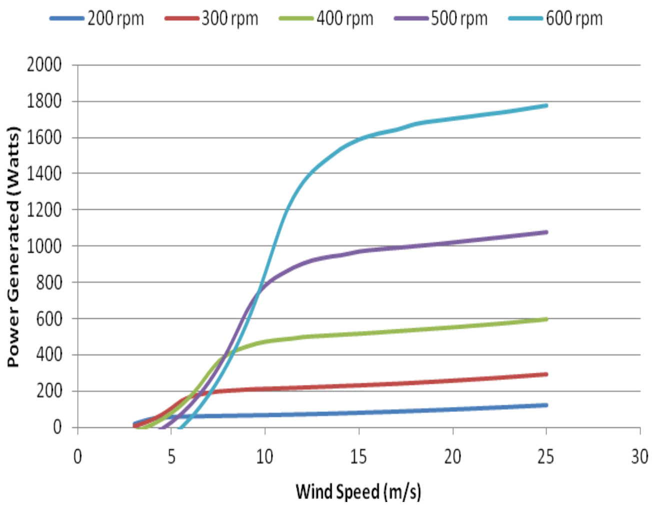

Fig 8: Graph of Power Generated against Wind Speed (power curve)

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