Performance Analysis of a Small Capacity Horizontal Axis Wind Turbine using QBlade

Ali Said, Mazharul Islam, Mohiuddin A.K.M, Moumen Idres

Abstract--- In recent times, wind energy has become one of the leading renewable energy sources for generating electricity in prospective regions around the globe. Nowadays, researchers are conducting different research activities to develop and optimize the existing designs of wind turbines through experimental and diversified computational techniques. Among the computational techniques, one of the popular choices is Computational Fluid Dynamics (CFD). However, CFD techniques are hardware intensive and computationally expensive. On the other hand, freely available simple tools like QBlade is computationally inexpensive and it can be used for performance and design analyses of horizontal and vertical axis wind turbines. In the present research, an attempt has been made to use QBlade for performance analyses of a smaller capacity horizontal axis wind turbine using selected prospective airfoils. In this study, four airfoils (namely, NACA 4412, SG6043, SD7062 and S833) have been selected and investigated in QBlade. It has been found that the overall power coefficients (CP) of NACA 4412 at different tip speed ratios are superior to the other three airfoils.

Keywords: Airfoil; HAWT; NACA 4412; QBlade; S833; SG6043; SD7062; Wind Energy; Wind Turbine

1. INTRODUCTION

Small wind turbines (capacity <10 kW) can be installed in niche locations around the world to harness environment-friendly wind energies. Designing of small wind turbines is not trivial and involves detailed analyses of different components. At present, diversified research activities are routinely carried out by different research institutions to improve the aerodynamic performances of smaller capacity horizontal axis wind turbines (HAWTs).

The present research aims to conduct performance analyses of a smaller-capacity HAWT with selected prospective airfoils using QBlade [1]. QBlade is a freeware that has nice graphical user interface (GUI) to conduct different necessary steps for performance and design analyses of horizontal and vertical axis wind turbines as shown in Figure 1. The amount of time needed to conduct basic performance analysis, which is the prime focus of the present research, is significantly shorter than other computational tools like CFD. Interested reader can consult [2] for knowing more about different features of Qblade.

Revised Manuscript Received on March 10, 2019.

Ali Said, Department of Mechanical Engineering, Kulliyah of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia

Mazharul Islam, Department of Mechanical and Production Engineering, Ahsanullah University of Science and Technology, 141 & 142, Love Road, Tejgaon Industrial Area, Dhaka-1208, Bangladesh

Mohiuddin A.K.M, Department of Mechanical Engineering, Kulliyah of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia (mohiuddin@iium.edu.my)

Moumen Idres, Department of Mechanical Engineering, Kulliyah of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia

In this article, selected prospective airfoils have been identified and analyzed with the help of Qblade software. Results for a 3kW HAWT have also been validated with existing experimental results from Anderson et al [3]. The current research outcomes are expected to help the prospective researchers to design optimized smaller-capacity HAWT for different prospective locations.

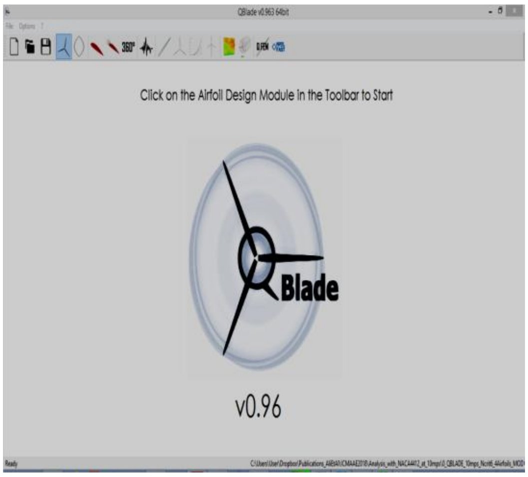

Fig. 1: Graphical User Interface of QBlade

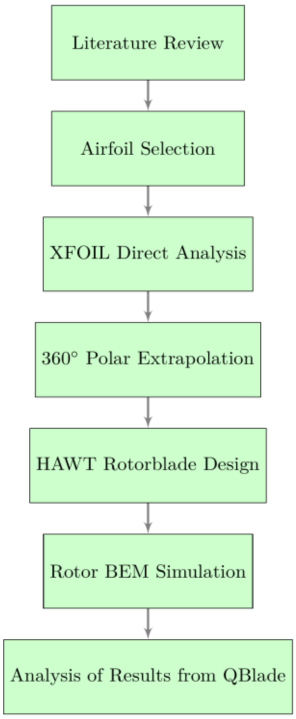

Figure 2: Methodology of the Research

*Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication*

2. METHODOLOGY

Figure 2 illustrates the methodology to conduct performance analysis of a 3kW HAWT using QBlade. Different steps shown in this figure are briefly described under the subsequent headings in this section

2.1. Computational tools

For performance and design analysis of HAWTs, increasingly researchers are using CFD software like Ansys Fluent and Open-FOAM). However, it has already been mentioned that CFD techniques need considerable hardware resources (often they are executed in High Performance Computing or HPC clusters) and time consuming. Alternatives to the CFD tools are the computational models based on BEM. In his dedicated book on small wind turbines, Professor Wood included MATLAB codes for conducting performance prediction of HAWTs. However, it is preferred to have a freely available computational tool with user-friendly GUI that can incorporate diversified airfoils with ease. QBlade is one such freeware and thus chosen for the present research work.

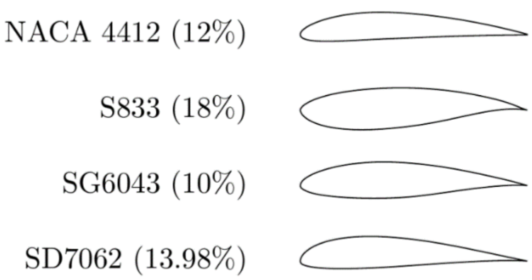

Figure 3: Geometry of Selected Airfoils

2.2. Experimental results

To validate the results obtained from any computational tool, there is need for experimental data. Several experimental works are available in the literature. For the present research, the valuable work conducted by Anderson et al. [3] has been considered.

2.3. Prospective airfoils for small-capacity HAWTs

To find out prospective airfoils for the current research, extensive literature review was required. Several institutions, like NREL [4,5] and UIUC [6], have design airfoils specifically for small-capacity HAWT. The following special-purpose airfoil serieses have been identified:

- S-series: Developed by Selig (S) from the University of Illinois Urbana-Champaign (UIUC) in thin and thick shapes for different types of wind turbines [7,8]. It can be found from [4] that S833 is suitable for wind turbines with rotor diameters between 1 and 3 meters. The diameter of the HAWT used by Anderson et al [3] was 3 meters. So, S833 has been selected as one of the prospective airfoils for the present study.
- SD-series [7]: designed by Selig (S)/Donovan (D) and particularly SD 7062 was used extensively by the Wind Energy Group at University of Newcastle in Australia. According to [9], SD7062 has a 14% thickness, which gives it extra strength to withstand the high centrifugal loads on small blades. Under this backdrop, SD 7062 has been considered in this study for further investigations.
- SG-series [8]: Designed by Giguere and Selig from UIUC specifically for small wind turbines [9] According to Professor Wood, they were probably the first aerofoils designed specifically for small wind turbines. The maximum lift-drag ratios of SG 6043 at different Reynolds number were higher than some other prospective airfoils like SD 7062 and SG 6041. Due to this fact, SG 6043 was also chosen as one of the prospective airfoils for the present study.

2.4. Airfoil selection

The airfoil used by Anderson et al [3] was NACA 4412 and thus chosen for the present research work as well for validation. Apart from this airfoil, three other airfoils from S, SD and SG serieses have also been investigated in this study.

Geometry of the four selected airfoils are shown in Figure 3. Selection of airfoils in QBlade is quite easy. Figure 4 shows the QBlade's interface for airfoil design. The NACA 4- or 5-digit airfoils can readily be generated inside QBlade. The coordinates of other airfoil geometries can be imported and analysed in QBlade as well. One of the best websites to find coordinates of diversified airfoils is the UIUC Airfoil Coordinates Database [6].

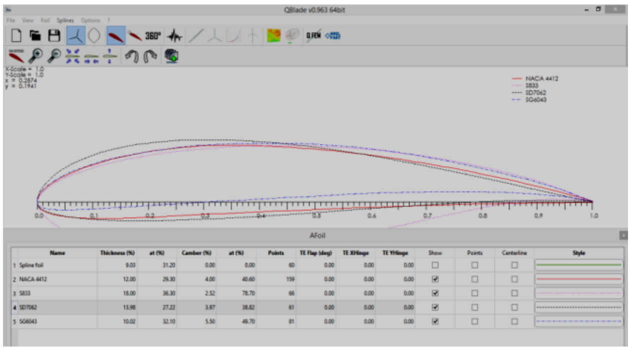

Figure 4: User interface for airfoil design

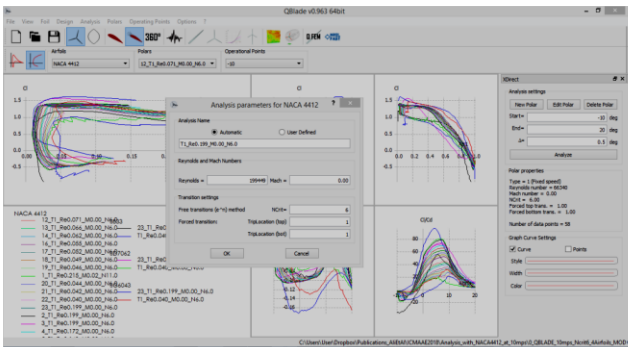

Figure 5: User interface for XFOIL direct analysis

2.5. XFOIL direct analysis

XFOIL [10-12] was originally developed by MIT and it is extensively used by the research communities around the world. One of the advantageous features of QBlade is that it has incorporated XFOIL Direct Analysis as shown in Figure

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

5. To manage the transition from laminar to turbulent boundary layer around the airfoils, the popular e^N method is used in XFOIL.

To conduct the performance analysis of HAWT in QBlade, XFOIL is used mainly for generating pre-stall aerodynamic coefficients. For the present study, XFOIL direct analyses were done to generate aerodynamic coefficients for -10°≤α≤20°. The boundary layer transitions are controlled by the N_{crit} value in XFOIL which is a function of turbulence intensities. It was reported by Anderson et al. [3], that the turbulent intensities for their experiments with HAWTs were between 3 and 4%. To account for such higher magnitudes of turbulence intensities, the value of N_{crit} was chosen as 6 for the plots (shown in Figures 10 - 14) required for validation.

2.6. 360° Polar extrapolation

To conduct performance analysis of a HAWT, the lift and drag coefficients are needed. To achieve this, the lift and drag coefficients (for the range of -10° ≤ α ≤ 20°. obtained from XFOIL should be modeled for 0° ≤ α ≤ 360° using a suitable model. At present, QBlade has two post-stall model (as shown in Figure 6), which are:

1. Montgomery Extrapolation
2. Viterna-Corrigan Post-Stall Model according to the QBlade Guidelines [2] - "firstly, the sophisticated Montgomery extrapolation can be chosen. Secondly, the Vitera- Corrigan post stall model which is favored in industrial environments is disponible, too". For the present research, the Montgomery extrapolation have been used.

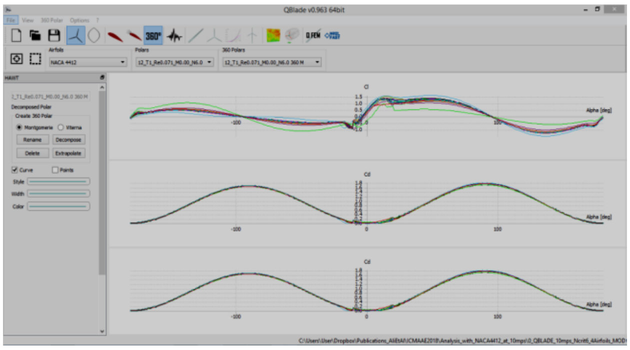

Figure 6: QBlade interface for post-stall aerodynamics coefficients.

2.7. HAWT rotor blade design

QBlade has graphical interface, as shown in Figure 7, to enter the information to generate the shape of the three-dimensional HAWT rotors. The three-dimensional blade is divided into number of elements and the users must specify the following parameters for each element of the blade:

1. position
2. chord length
3. the twist angle
4. airfoil
5. polar containing lift and drag coefficients for 0 ≤ α ≤ 360°

It should be noted that different blade elements are encountering different magnitudes of Reynolds numbers (known as local Reynolds numbers) based on variable relative wind speed and induction factors (axial and radial) as outlined in the QBlade manual. However, a simpler approach has been adopted in the present study and a single value of Reynolds number has been applied for all the blade elements. For validation purpose, the information shown in Table 1 has been used in the current research to provide the geometry of the blades for further analysis.

Table 1: Geometry of the Blades from Wood [9]

Element	Radius(m)	Chord(m)	Twist°
1	0.1333	0.2502	24.21
2	0.2325	0.2318	21.06
3	0.2975	0.1998	15.87
4	0.3625	0.1732	11.92
5	0.4275	0.1512	8.96
6	0.4925	0.1333	6.77
7	0.5515	0.1186	5.18
8	0.6225	0.1067	4.02
9	0.6875	0.0971	3.16
10	0.7525	0.0892	2.49
11	0.8175	0.0826	1.93
12	0.8825	0.0771	1.44
13	0.9475	0.0723	0.99
14	1.0125	0.068	0.59
15	1.0775	0.0641	0.25
16	1.1425	0.0604	-0.06
17	1.2075	0.057	-0.36
18	1.2725	0.0538	-0.67
19	1.3375	0.0508	-0.98
20	1.4025	0.0484	-1.28
21	1.4675	0.0466	-1.59
22	1.5	0.046	-1.74

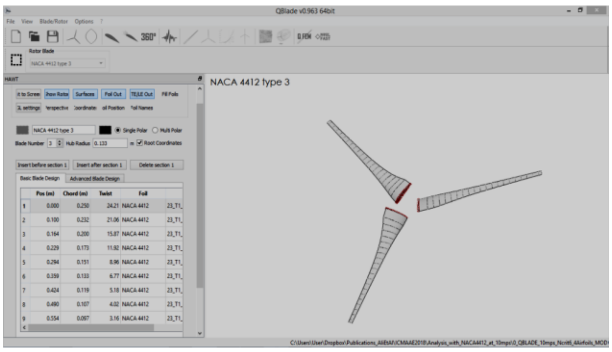

Figure 7: HAWT blade design and optimization submodule.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

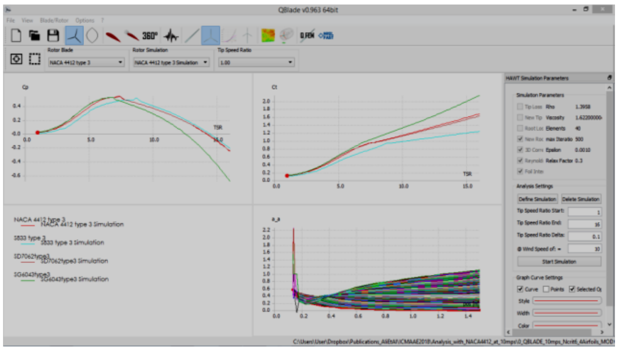

Figure 8: HAWT rotor simulation

2.8. Rotor BEM simulation

QBlade uses the Blade Element Momentum (BEM) method for conducting performance analyses of HAWTs. In Figure 8, the QBlade's interface for rotor BEM simulation is shown. For the present research, the following options have been enabled in Qblade:

- New root loss
- 3D correction
- Reynolds drag correction
- Foil interpolation

2.9. Analysis of results from QBlade

As mentioned earlier, four airfoils (namely NACA4412, S833, SD7062, and SG6043) have been investigated in the present study at different Reynolds numbers. QBlade can supply valuable data related to the performances of HAWTs. However, in the next section mainly the following two parameters are analyzed for the selected airfoils.

2.9.1. Power coefficient (C_P)

It is one of the most critical factors for wind turbines and defined by the following formula:

$$C_p = \frac{P_{out}}{\frac{1}{2}\rho V_\infty^3 \pi R^2} \quad (1)$$

2.9.2. Tip speed ratio (λ)

This is a non-dimensional parameter which is used for generating wind turbine performance curves along with Cp or Ct. It is defined by the following expression.

$$\lambda = \frac{\omega R}{V_\infty} \quad (2)$$

3. RESULTS

All the computational models for HAWTs should be meticulously validated with experimental results before under taking any serious study. As mentioned in Section 2.9, results obtained from QBlade for NACA 4412 at 10 m/s (i.e. Re = 199,449 based on maximum chord length at 20°C) have been compared with Anderson et al. [3] and illustrated in Figure 9. Apart from NACA 4412, three other prospective airfoils (which are S833, SD7062 and SG6043) have also been investigated at the same operating condition for comparative assessment. It can be seen from this figure that the results obtained from QBlade are over-predicting the Cp values up to λ ≈ 9 and then under-predicting for the subsequent tip speed ratios. Both SD 7062 and SG 6043 are performing better than NACA 4412 up to λ ≈ 6.5.

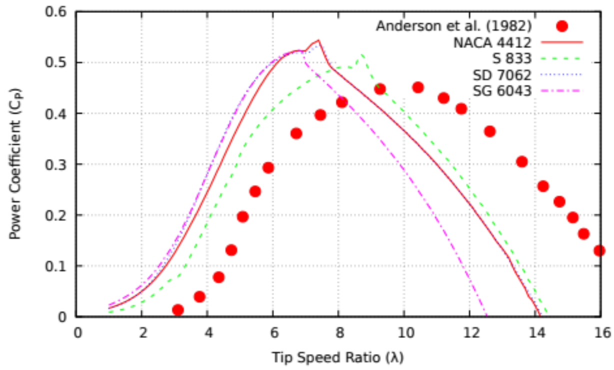

Figure 9: Variation of power coefficients with tip speed ratios

3.1. Performances of the four airfoils at different Reynolds numbers

Typically, a small-capacity HAWT operates at Re ≤ 500,000 which can be considered as low Re regime. Modelling of HAWTs at low Re is quite challenging due to diversified factors including laminar separation bubbles [13]. In this section, five C_P-λ curves (Figures 10 - 14) for the four selected airfoils are presented at 100,000 ≤ Re ≤ 500,000 for comparative study. Unlike Figure 9, the N_{Crit} value for all these curves is 9.

Figure 10 depicts that the overall performance of NACA 4412 is quite impressive even at low Re value of 100,000. Though C_P values for SG 6043 is quite close to that of NACA 4412 up to λ ≈ 7, but at λ ≥ 7, the C_P values are significantly lesser than that of NACA4412. C_P values for SD 7062 are not impressive at λ ≤ 7.5 and at λ ≥ 7.5 its C_P values are almost similar to that of NACA 4412. It can also be seen that the CP values for S 833 is not impressive in comparison to NACA 4412 for all the λ values.

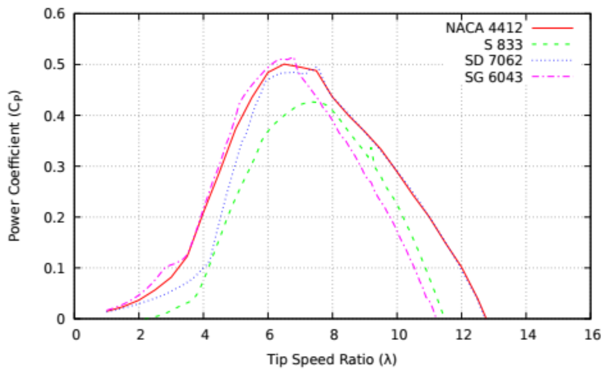

Figure 10: Variation of power coefficients with tip speed ratios at Re=100,000

It can be seen from Figure 11 that the overall performance of SD7062 is the best. The C_P values for NACA 4412 is quite close to that of SD 7062 for all the λ values. The C_P values for SG 6043 are almost similar to that of SD 7062 at λ ≤ 7 and beyond that the values are significantly lower. The C_P values for S833 have improved at λ ≥ 7.75 and quite close to that of NACA 4412, SD 7062 and SG 6043. Almost similar trends can be observed in Figure 12. However, the C_P values for

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

S833 are higher than the rest of the airfoils at Re values of 400,000 and 500,000 as illustrated in Figures 13-14.

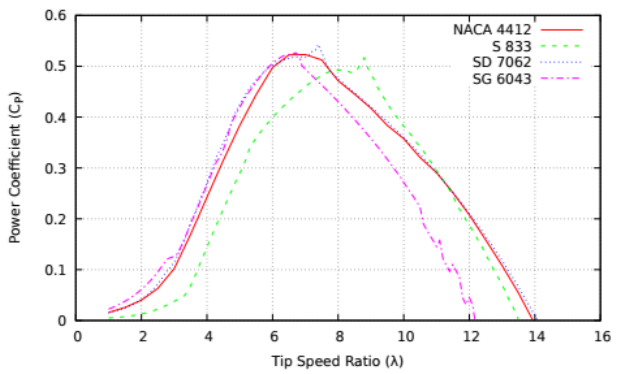

Figure 11: Variation of power coefficients with tip speed ratios at Re=200,000

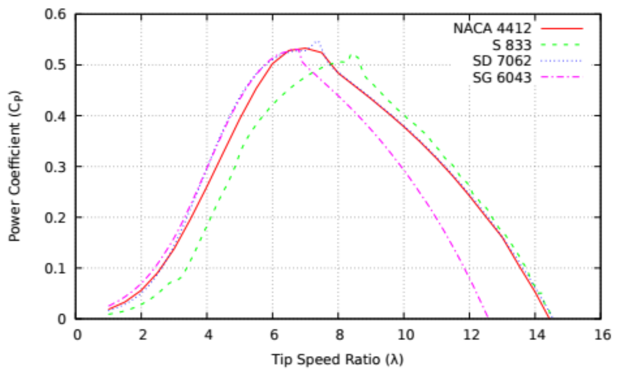

Figure 12: Variation of power coefficients with tip speed ratios at Re=300,000

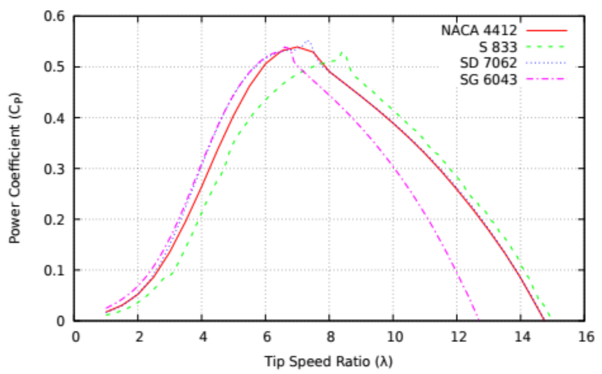

Figure 13: Variation of power coefficients with tip speed ratios at Re=400,000

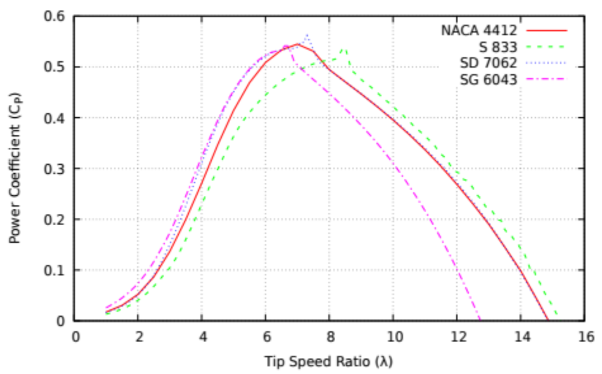

Figure 14: Variation of power coefficients with tip speed ratios at Re=500,000

4. CONCLUSION

Performance analysis of a 3 kW HAWT has been conducted in the present research using four prospective airfoils, which are NACA4412, SD7032, SG6043, and S833. A freely available open source software called QBlade, was used to conduct the performance analysis of the 3 kW HAWT, designed by Anderson et al. [3], with these four airfoils. It has been found that the QBlade has user friendly GUI to execute different stages of the performance analyses of a HAWT.

The results obtained from QBlade is conforming reasonably with the experimental data obtained from Anderson et al. [3] at 10 m/s. A comparative study has been presented in this article at five different Re which are typical for smaller-capacity HAWTs. It can be said that the overall performance of NACA 4412 is the best in terms of C_P values. However, the thickness of NACA 4412 is only 12%, whereas maximum thickness of SD 7062 is about 14% which is advantageous from structural point of view.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided by RIGS Project of International Islamic University Malaysia (IIUM) to carry out this work.

REFERENCES

1. QBlade, URL: http://www.q-blade.org (28/8/2018)
2. Marten D & Wendler J (2013). QBlade Guidelines. http://qblade.org/project_images/files/guidelines_v06.pdf
3. Anderson, M., Milborrow, D., & JN, R. (1982). Performance and Wake Measurements on a 3m Diame-ter Horizontal Axis Wind Turbine. *4th International Symposium on Wind Energy Systems* (pp. 113–136).
4. Wind Turbine Airfoil Families, URL: https://wind.nrel.gov/airfoils/AirfoilFamilies.html
5. NREL’s S833 Airfoil Graphic and Coordinates, URL: https://wind.nrel.gov/airfoils/Shapes/S833_Shape.html
6. UIUC Airfoil Coordinates Database, URL: http://m-selig.ae.illinois.edu/ads/coord_database.html
7. Selig MS, Donovan JF & Fraser DB (1989), Airfoils at Low Speeds, Spartech.
8. Giguere P & Selig MS (1998), New Airfoils for Small Horizontal Axis Wind Turbines. *Journal of Solar Energy Engineering* 120 (2), 108–114.
9. Wood D (2011), *Small Wind Turbines: Analysis, Design, and Application*, Springer-Verlag London Limited.
10. XFoil,URL:http://web.mit.edu/drela/Public/web/xfoil
11. Drela M (1989) “XFOIL: An analysis and design system for low Reynolds number airfoils”, *Conference on Low Reynolds Number Airfoil Aerodynamics*, Vol.54, pp.1–12
12. XFLR5, URL: http://www.xflr5.com
13. Islam M (2008). Analysis of fixed-pitch straight-bladed VAWT with asymmetric airfoils. (Order No. NR42382, University of Windsor (Canada)). ProQuest Dissertations and Theses.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication