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Numerical Analysis of Scale Effect on Performance of DU84-132 Airfoil for Small Wind Turbine Blade

Labid Bin Bashar[1,*], *Shahria Arifin*[2] and, *Shadman Mahood Khan Pathan*[1]
[1] Department of Mechatronics Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6405, BANGLADESH
[2] Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka-1100, BANGLADESH

ABSTRACT
This paper presents a concise numerical investigation on DU84-132 airfoil based on a range of Reynolds numbers consistent with small wind turbines and low wind speed zones. It aims to find out the aerodynamic behavior of this airfoil under various wind speeds and angles of attack to ascertain the extent to which it is suitable for a small wind turbine blade. With the help of Qblade software, Panel code based numerical analysis shows that maximum glide ratio and stall point smoothly increases with the increase of Reynolds numbers. On the other hand, the design point and maximum lift coefficient decrease with the decrease of Reynolds numbers. Again, sensitivity to surface roughness on the performance of airfoil has been explored by forcing the boundary layer transition at 10% of the chord, which shows that it can be possible to avoid roughness effects by increasing the Reynolds number within the laminar limit. Finally, a comparative study with S2091 airfoil concludes that DU84-132 airfoil is suitable for a small wind turbine from the perspective of both blade performance ensured by maximum glide ratio and stability of energy production ensured by the smooth change of angle of attack. Still, there are a few limitations which can be eradicated by modification and redesign of the airfoil.

Keywords: Airfoil, Angle of Attack, Glide Ratio, Stall Point, Reynolds Number.

1. Introduction

Wind energy is one of the practical solutions to the issues the world is confronting today regarding energy scarcity along with environmental pollution. It is considered as the largest share-holder of all renewable energy sources across the globe, shooting up 44.2% in entire Europe [1]. Statistically wind power is the fastest-growing alternative energy source in the world over the last ten years [2]. Hence, maximizing the performance of wind turbines with the marginal cost is triggering scientist and engineers to continuously research on various related fields starting from airfoil design to electrical power generation systems.

Design, modification, or selection of the right airfoil is one of the first steps of designing a wind turbine blade. Though working on airfoils started with fixed airplane wings and helicopter rotors in 1884 [3], it was later (in 1980) maturated for wind turbine technology at an accelerated pace. The characteristics of wind turbine dedicated airfoils are quite different from that of wing airfoils. A considerably higher value of glide ratio is necessary as it causes a higher amount of the coefficient of torque with reduced bending moment. Again, product of lift coefficient and chord length ($C_l.c$) should be kept at an optimal value so that the power extracted from the rotor could be maximized. The relative thickness of airfoil is a factor that trades off between blade weight and drag force. Increasing the thickness of the blade reduces the blade weight which eventually increases the drag force. Another factor in choosing the right airfoil is surface roughness sensitivity. A highly sensitive airfoil would produce higher drag at a later portion of the lifetime of the blade, which ultimately would cause continuous performance degradation over its entire lifetime [4, 5].

The analysis of Reynolds number effect on the performance of airfoil is a necessary action for designing a wind turbine blade. It is a scale parameter describing the ratio of inertial force and viscous force, which represents the characteristic property of fluid flow. So, Reynolds number effect is also called scale effect [6]. Again, this dimensionless number is used for the transferability of model measurements in the wind tunnel to the flow conditions at the original object as a parameter of similarity. Elevating Reynolds number reduces the thickness of boundary layer resulting in lower drag. Increasing the number of Reynolds also has a destabilizing effect on the boundary layer movement, resulting in the transition position shifting to the leading edge, resulting in a turbulent boundary layer over a longer part of the airfoil surface. This results in lower drag but a smaller low-drag of angles of attack. Thus, the highest glide ratio will rise but the lift coefficient corresponding to the maximum glide ratio will have a minimum magnitude [4, 7].

In this paper, the performance analysis of DU84-132 airfoil has been taken into account. It is an airfoil designed by the Delft University of Technology with 13.6% maximum thickness at a 33.9% chord. The maximum camber is 3.1% at 45.3% chord. Robiul et al. have designed and validated a small turbine blade in which they ushered positive feedback about this despite being not a dedicated wind turbine airfoil [8, 9]. So, scale effect on lift coefficient, drag coefficient, glide ratio, maximum glide ratio, and stall point have been analyzed to ascertain its compatibility with a small wind turbine blade.

* Corresponding author. Tel.: +88-01743078796
E-mail addresses: labid.bashar@gmail.com

2. Methodology

The analysis of the airfoil under concern has been done following different steps chronologically. Firstly, the airfoil geometry has been imported to the panel code section where the airfoil dimension and number of the panel have been assessed with the ideal value. Then, a proper range of Reynolds number has been chosen based on wind speed and the expected size of the blade. Thirdly, polar analysis parameters have been set up based on different flow conditions. After executing the algorithm, polar data have been compared and represented. Finally, the extracted data out of DU84-132 airfoil has been compared with a known data from the literature. Fig.1 illustrates the hierarchal step in the form of a block diagram.

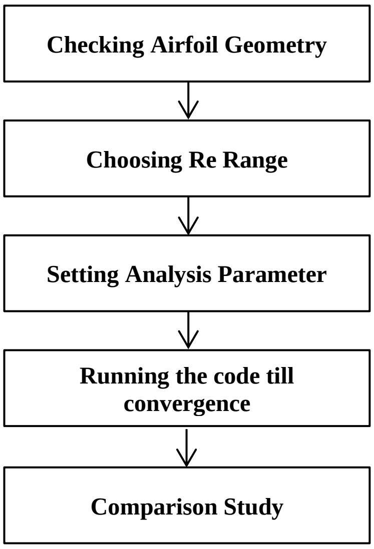

Fig.1 Evaluation Methodology

Before running the algorithm, the first and foremost task is to assess the airfoil geometrical data and compare it to the original dimension of the airfoil designed by Delft University. In this case, the thickness of airfoil fully complied with the real value, but the maximum camber deviated by 1.6% of the original value. Again, the number of panels is to be such that it should make a symmetrical pattern over the airfoil, and it should cross at least a minimum value so that minimum convergence criteria are met. In this case, the number of panels has been taken as 100. Finally, the given airfoil is entirely suitable for the second step.

As Re varies with the wind speed and length of the chord directly shown by equation (1), it is necessary to select the range accordingly. Here, the selected range is from 0.8E+05 to 5.0E+05 with an interval of 1.0E+05. The evaluation roughly fluctuated between 4 m/s to 20 m/s of wind speed [10].

$$Re = \frac{\rho v c}{\eta} \tag{1}$$

There are a couple of polar analysis parameters that need to be chosen. The angle of attack (α) has been taken between -10^0 to 25^0 [6]. In this context the Mach number, another parameter for XFOIL direct analysis [11], has been considered as zero. This is done since the velocity of rotor blade is far less than that of the sound [12]. The value of Critical Number (Ncrit) has been taken as nine, which is a default value of free transition in a general wind turbine [13, 14]. Finally, in the case of force transition, the value of both top tip location and bottom tip location has been 10% of the chord. This parameter helps to determine the roughness effect on the airfoil performance [6]. Table 1 shows the analysis parameters for the code.

Table 1 Parameters for Numerical Analysis

Parameters	Value.
Starting α	-10
Ending α	25
Mach Number	0
Ncrit	9
Free Transition	(1, 1)
Forced Transition	(0.1, 0.1)

For each α, the code runs a maximum of 100 iterations. Within these numbers of iterations, the code has to extract each polar data. If the code fails to extract data even after 100 iterations, it skips for that given α and proceeds to the next one. In this way, the outputs are generated either through single analysis, batch analysis, or multithreaded batch analysis.

The final step in the process of numerical analysis is comparing the data attained from simulation with the best airfoil for small wind turbine and that is S2091 [13]. This step works as a passive validation process. The comparison criteria in this case are seven in number shown in Table 2 with their respective labels introduced for the easier data representation.

Table 2 Comparison Criteria

Criteria	Label
GR_{max} at 1.0E+05 Re	C-1
GR_{max} at 3.3E+05 Re	C-2
Deviation of α_{design}	C-3
Maximum Percentage Deviation of GR_{max} at 1.0E+05Re	C-4
Maximum Percentage Deviation of GR_{max} at 3.3E+05Re	C-5
Roughness sensitivity at 1.0E+05 Re	C-6
Roughness Sensitivity at 3.3E+05 Re	C-7

3. Results

Figure 2-3 demonstrate the scale effects on the lift and drag properties of the airfoil. Figure 2 displays that, with increasing Re, the lift curves are steeper. Nonetheless, this shows a quite different scenario than that of the thicker airfoils. Keeping in touch with the variation of C_l presented by figure 3, the laminar bucket region with very low C_d also gets broader. Again, the point of α, where C_d starts to rise, increases with the increase of Re.

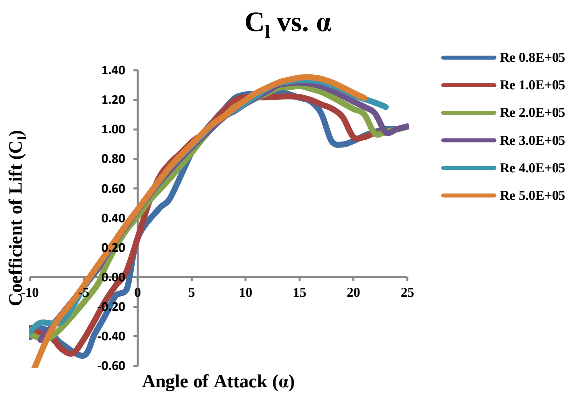

Fig.2 Reynolds Number Effect on Coefficient of Lift Force

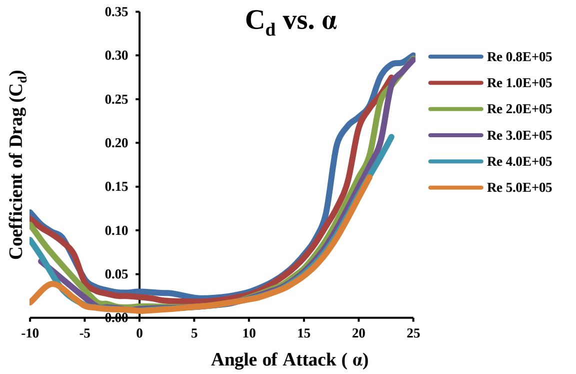

Fig.3 Reynolds Number Effect on Coefficient of Drag Force

Fig.4 depicts the variation of pressure drag coefficient, a coefficient corresponding to pressure drag arising out of pressure difference between the leading and trailing edge of an airfoil. The pattern of the curves exactly follows that of C_d.

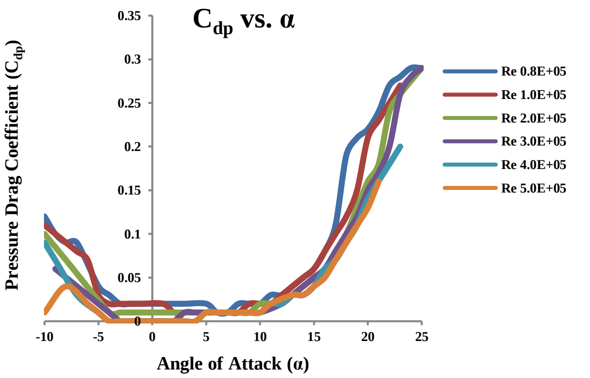

Fig.4 Reynolds Number Effect on Coefficient of Pressure Drag Force

Figure 5 illustrates the variation of GR over a wide range of α in different Reynolds numbers. Here, the curves surge with the increase of Re. Besides, the upward slopes are steeper for higher Re, but the downward ones plateaued more or less equally.

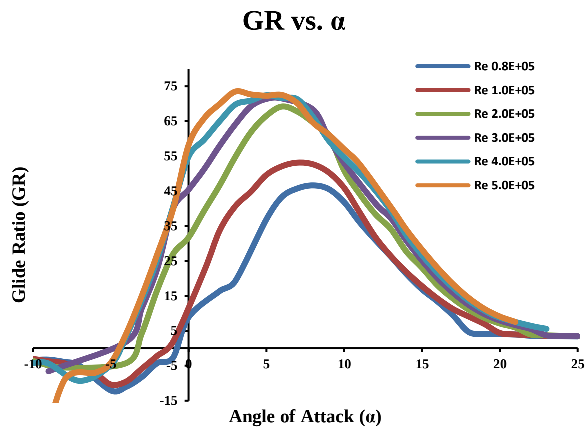

Fig.5 Reynolds Number Effect on Glide Ratio

The airfoil design performance and off-design performance generally assume the efficiency and fatigue load-bearing capacity of the rotor blade. Figure 6-7 illustrates the scale effects on the airfoil design performance parameters as GR_{max}, α_{design}.

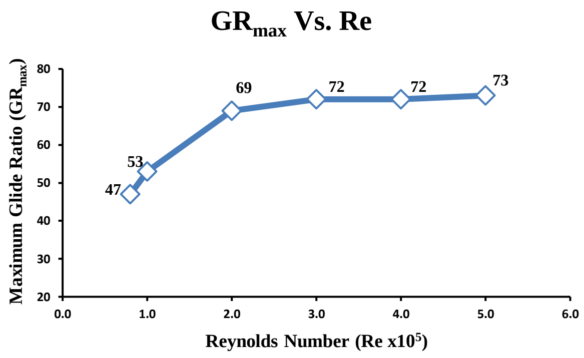

Fig.6 Reynolds Number Effect on GR_{max}

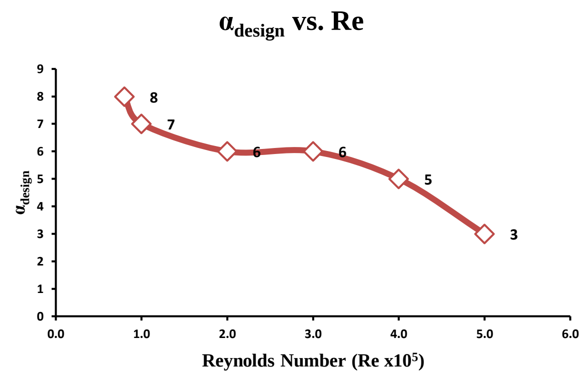

Fig.7 Reynolds Number Effect on Design Angle of Attack

In the case of design performance parameters depicted by Fig. 6-7, GR_{max} increases with the increase of Re, but the rate of increase of that gets slower. Again, α_{dsign} decreases with the increase of Re.

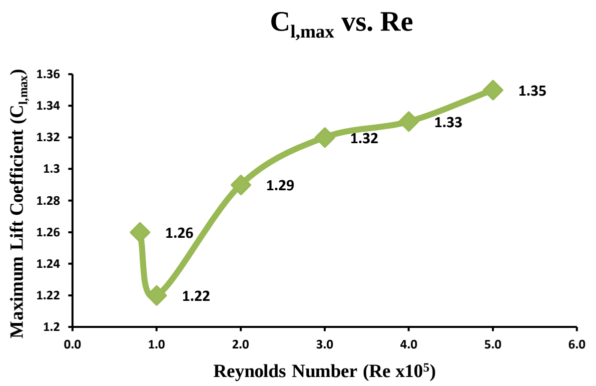

Fig.8 Reynolds Number Effect on Maximum Lift Coefficient

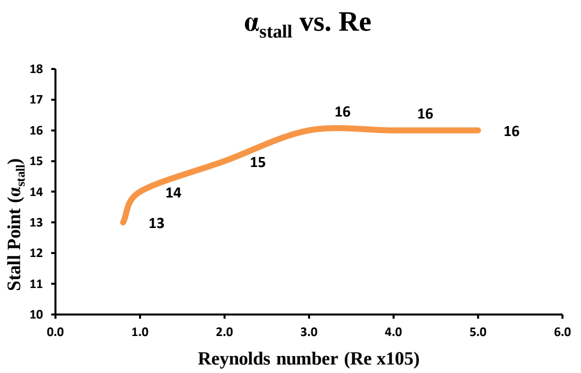

Fig.9 Reynolds Number Effect on Stall Angle of Attack

In the case of off-design performance parameters, in Fig. 8-9 $C_{l,max}$ decreases till 1.0e+5 Re and after that it increases at different rates. Again, α_{stall} increases with the increase of Re but plateaus down at higher values.

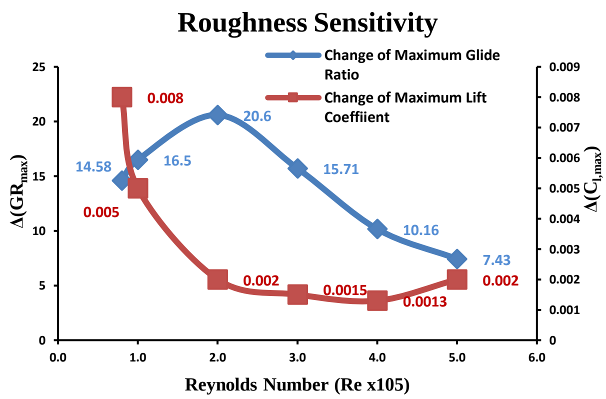

Fig.10 Roughness Sensitivity Effect

The aftermath of Re on the roughness sensitivity of airfoil performance was also explored by protruding the boundary layer at a position discussed at the methodology. Figure 10 clarifies the end-result of surface roughness on the $C_{l,max,}$ and GR_{max} as a difference (ΔGR_{max} and $\Delta Cl_{,max}$) of their values at various Re. It is also obtained from Figure 10 that raising Re can eliminate the impact of surface roughness on airfoil's performance, which is consistent with previous investigation [6].

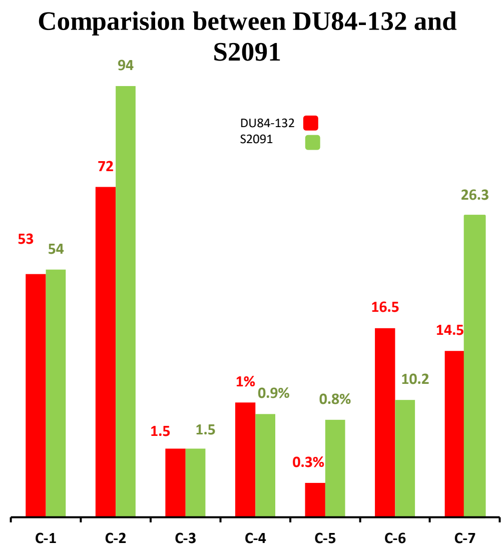

Fig.11 Comparative Study between DU84-132 and S2091

Finally, Figure 11 depicts how DU84-132 is adaptable in the field of small wind turbines. In C-1, C-3, and C-4, the values are quite close. In C-2 and C-7, S2091 performs better while reverse incident occurs in C-5 and C-6. The discussion part describes it more elaborately.

4. Discussion

In this scenario, analysis of performance parameters, stability parameters and roughness sensitivity parameters give a picture of the overall stand of the airfoil. Here, Reynolds number effects on GR_{max} certify the optimum wind turbine cut in of the considered airfoil despite having limitations over producing peak power. Again, scale effects on off-design performance parameter conclude that storm loading and fatigue loading effect of the designed rotor would be less due to possessing benign stall characteristics along with moderate $C_{l,max}$ [15]. The roughness sensitivity curves predict the possibility of eradicating roughness effect by fairly increasing Re.

Now, coming to the traits of Figure 11, both of the airfoils have good cut in performance as given by the label C-1. The elaboration of each axis label has been given in Table 2. As depicted by C-2, S2091 exceeds in generation of peak power and marks that the airfoil under consideration of this paper needs a bit modification. Criteria labeled by C-3, C-4, and C-5 are the stability criteria of an airfoil. Corresponding to C-3, as both airfoils have value less than 2.0, turbines are able to generate stable power. Again, turbine with DU84-132 has lower GR smoothness at Lower Re and vice versa. Finally, the airfoil of interest tends to be more roughness sensitive at lower Re than that of higher Re.

5. Conclusion

The main effort of this paper is to find out the effectiveness of DU84-132 airfoil to design a small wind turbine blade in low wind speed region. The numerical study of performance of this airfoil has been shown over six different low Reynolds number. Significance of design performance and off-design performance parameters has been described in the context of the given airfoil. Finally, comparative study has concluded that DU84-132 airfoil would be suitable for small wind turbine suggesting a small modification.

6. References

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NOMENCLATURE

Re : Reynolds Number
GR : glide Ratio
GR_{max}: maximum Glide Ratio
$C_{l,max}$: maximum lift coefficient
α : angle of attak
α_{design}: design angle of attack
α_{stall} : stall point
C_d : coefficient of drag
ρ : density, kg.m^{-3}
v : wind speed, m.s^{-1}
c : chord length of airfoil, m
η : kinematic viscosity, m^{2}s^{-1}
C_{dp} : coefficient of pressure drag
$Ncrit$: critical number