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Computational studies on small wind turbine performance characteristics

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Abstract: To optimize the selection of suitable airfoils for small wind turbine applications, computational investigation on aerodynamic characteristics of low Re airfoils MID321a, MID321d, SG6040, SG6041, SG6042 and SG6043 are carried out for the Reynolds number range of $(0.5- 2)\times10^5$. The BEM method is used to determine the power coefficient of the rotor from the airfoil characteristics; in addition, the blade parameters like chord and twist are also determined. The newly designed MID321a airfoil shows better aerodynamic performance and maximum power coefficient as compared with other investigated airfoils for wider operating ranges.

1. Introduction

Wind is a cost effective, efficient source of energy and is abundant in nature and roughly 10 million MW of power can be harnessed from it. Wind turbines convert the energy in the flowing air to mechanical energy without the use of fossil fuels. Compared to other renewable energy extracting devices, wind turbine efficiency is significantly higher. Large wind turbines are installed at places where there are favorable wind condition, is referred as commercial wind turbines. Such turbines attain power coefficient of 0.45, whereas small wind turbines have power coefficient of around 0.25 and are generally installed any places irrespective of wind conditions. These turbines are classified into three types namely micro (1 kW and >1.5m), midrange (5 kW and > 2.5m) and mini (20+, > 5m) [1] based on the power and rotor radius.

Small wind turbines usually operate at Reynolds number less than 5×10^5. In this Reynolds number range, laminar flow gets separated at the upper surface of the airfoil and is reattached to the surface as turbulent causing laminar separation bubble, which increases the drag of the airfoil. The aerodynamic behavior of the airfoil is affected by laminar separation bubble significantly. The wind tunnel study was conducted on 15 low Reynolds number airfoils for free and fixed conditions to establish the database for small wind turbine applications [2]. In a continuing effort to improve the aerodynamic properties of airfoils at these Reynolds number range four airfoils were developed, one root and three primary airfoils namely SG6040 and SG6041, SG6042, and SG6043[3].

Further studies have been conducted [4] on these airfoils and the results were validated against previous airfoils. Thus SG6043 airfoil was combined with GOE15, E422, Eppler560 and S1223, the performance of SG6043_Eppler422 was found to be better than the other combinations at Reynolds number of 0.38×10^5, 1.28×10^5 and 2.05×10^5. To improve the roughness sensitivity of airfoil at the tip

section of blade, USPT2 airfoil was designed with implication of multi-objective genetic algorithm and it reached a maximum lift to drag ratio of 72 at Re of 2×10^5, modified airfoil was better than its base SG6043 airfoil [5]. AF300 airfoil was designed by modifying the trailing edge of high lift airfoils S1210 and S1223, which are taken as base airfoils and new airfoil attained the C_{lmax} of 1.72, 1.81 and 1.86 at Re 0.7×10^5, $1.28\times10^5$and 2.05×10^5respectively for angle of attack of 14° [6].

   This investigation focuses on the performance prediction of low Reynolds number airfoils for small wind turbine applications and the blade parameters are determined using BEM approach. The literature studies are explained in Introduction, determination of Reynolds number and aerodynamic characteristics are described in Aerodynamic design section and the subsequent sections deal with the Computational methodology and the outcome of numerical simulations.

2. Aerodynamic Design
Many parameters play vital role on the design of wind turbine blade that includes aerodynamic behavior, generator characteristics, blade strength, rigidity and noise levels. The main objectives of small wind turbine design are maximizing its energy extraction and improving its starting characteristics at low wind speed; rotor aerodynamics plays a crucial role in the minimization of cost of energy generation. However, the total energy produced depends on both the behavior of the power output and wind's probability distribution [7, 8]. The diameter is determined by the following equation (1),

$$P = c_p \frac{1}{2} \rho \eta_{all} \left(\frac{\pi}{4} d^2 \right) V_o^3 \qquad (1)$$

where, P-power, c_p-power coefficient, ρ-density of air, η_{all}-overall efficiency of generator, V_o-free stream velocity of air and d -the diameter of rotor.

   Most of the wind turbine analyses are determined by the common design and analysis method, which is known as blade element momentum method (BEM) and it was proposed by Glauert [7, 8].
The outline of BEM is given below.

   BEM is the combination of momentum and blade element theory. In this theory some assumptions are made such that the blade is divided into strips along the radial location and no interaction between the strips is considered. The momentum theory estimates the thrust and torque at different locations of the rotor. The blade element theory determines the forces on the blade elements by using sectional lift and drag data from the performance of airfoils corresponding to the angle of attack. The BEM relationship was developed by balancing the local blade forces with momentum forces and relations. The BEM is usually implemented in a convergence scheme, starting with assumed values of a and a'. By summing the contributions of each annulus, the rotor thrust and torque are found through the iterative process.

2.1 Iterative method summary
The following procedure can be used to predict the power coefficient of rotor for specified tip speed ratio by iterative process [8]:

1. Initialize a and a', typically set $a = a' = 0$;

2. Calculate the relative wind angle φ with the equation (2), and angle of attack α with equation (3),

$$\phi = \tan^{-1} \left[\frac{1-a}{1+a'} \right] \qquad (2)$$

$$\phi = \theta + \alpha \qquad (3)$$

3. Get C_l and C_d at the appropriate and Reynolds number.

4. Recalculate a and á with equations (4) and (5),

$$a = \cfrac{1}{\cfrac{4 F \sin^2 \phi}{\sigma C_l \cos \theta} + 1} \qquad (4)$$

$$a' = \cfrac{1}{\cfrac{4 F \sin \phi \cos \phi}{\sigma C_l} - 1} \qquad (5)$$

5. Repeat steps 2-4 until a and a' converge to stable values. Repeat process for each element, saving the final from each element.

6. Calculate c_p using equations (6).

$$c_p = \frac{8}{\lambda^2} \int \lambda_r^3 F a' (1-a) \left[1 - \frac{C_d}{C_l} \tan \phi \right] d\lambda_r \qquad (6)$$

where, a - Axial reduction factor, a' - Angular reduction factor, σ - Solidity ratio, ϕ - Relative wind flow angle, λ - Tip speed ratio, θ - Pitch angle, C_l - Lift coefficient, C_d - Drag co-efficient, λ_r - local tip speed ratio and F - Tip loss factor.

2.2 Airfoil selection and Reynolds number prediction
Airfoils are the basic elements (shapes) in the wind turbine blade cross sections, which convert the kinetic energy in wind to mechanical energy effectively. Aerodynamic behavior such as lift and drag characteristics changes due to angle of attack and Reynolds number. Appropriate selection of Reynolds number would improve the annual energy production.

$$Re = V_0 c / \nu \qquad (7)$$

Where, Re is Reynolds number, V_0 is free stream velocity, c is chord and ν is kinematic viscosity of air. Range of velocity is taken from 3 to 14m/s, chord values ranging from 0.25 to 0.35m and ν is taken as $= 16.5 \times 10^{-6}$ m^2/s at Standard atmospheric condition.

Based on the atmospheric conditions, predicted Reynolds number comes under the range of 6×10^4-2×10^5. Selected airfoils for an investigation are given in table 1.

Table 1. Airfoil name and geometrical characteristics

Airfoil Name	Thickness (t/c %)	Camber(%c)
MID321a	0.08	0.031
MID 321d	0.14	0.035
SG6040	0.16	0.025
SG6041	0.10	0.020
SG6042	0.10	0.038
SG6043	0.10	0.055

3. Computational study
In this study, aerodynamics performance of the airfoil is predicted through the Xfoil tool, which was developed by Mark Derla in 1986 at the Massachusetts Institute of Technology (MIT). This tool is specially tailored for subsonic airfoil design and analysis purpose. It is built with panel code algorithm which is the combination of e^n laminar to turbulent transition method and the set of integral boundary layer formulations.

The airfoil co-ordinates are obtained from the airfoil database website [9, 10]. The basic geometrical requirements of the airfoil for carrying simulation in this tool are panel number and specific inflow condition (Ncrt) values [11]. Thus the minimum paneling parameter and Ncrt values are maintained at 160 and 9 respectively.

The iterative procedure is used to solve the BEM relationship by using Matlab tool. Before initializing the iteration process some parameters needed to be assumed. The blade is divided into ten strips and aerodynamic loads are calculated for each strip along the span of rotor. Then the overall blade power cofficient is predicted from the individual strips of blade using trapezium formula of Numerical Integration. Finally blade parameters such as chord and twiste angle have been calculated.

4. Result and discussion

The proposed design of small wind turbine configurations are 3 bladed, 2.25m radius, TSR 7, fixed pitch-variable speed with design wind speed of 7 m /s for the power of 1kW. These values were given as an input to the BEM calculations.
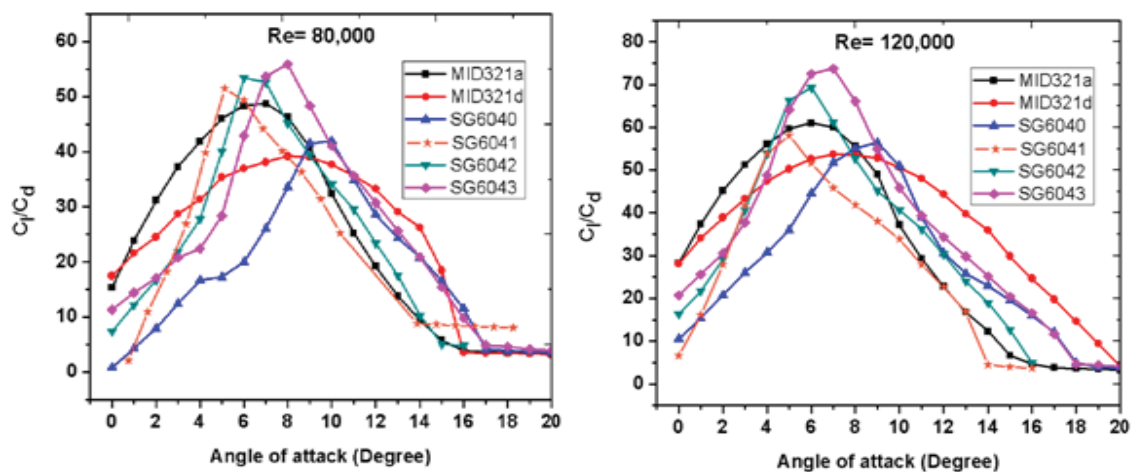

Figure 1. C_l/C_d versus Angle of attack for Reynolds number of 0.8×10^5 and 1.2×10^5.

The aerodynamic behavior of the airfoils at the Reynolds number of 0.8×10^5 and 1.2×10^5 with angle of attack ranging from 0 to 20º is shown in figure 1. At the Reynolds number of 800,000, MID321a and MID 321d airfoils shows a better performance for wider range of angle of attack compared to the other four airfoils whereas SG6040, SG6041, SG6042 and SG6043 airfoils performed at narrow angle of attack with maximum lift to drag ratio of 40,45, 55and 58 respectively. At Reynolds number of 120,000, MID321a and MID321d produces lift to drag ratio of 60 and 55, while SG6040, SG6041, SG6042 and SG6043 airfoils attain the maximum lift to drag ratio of 56, 59, 70 and 75 those are operated at narrow angle of attack.
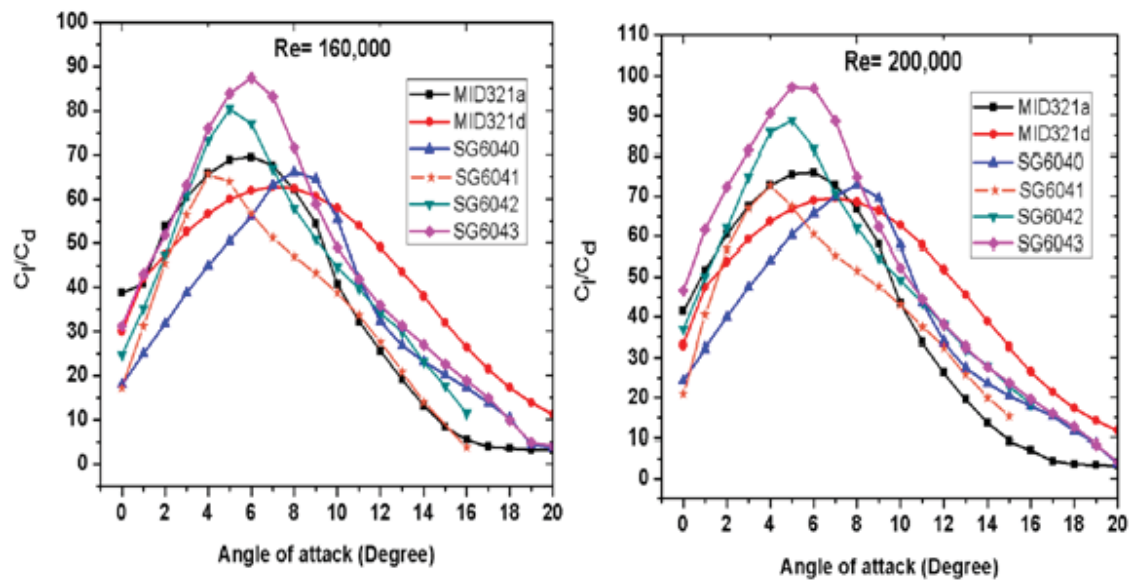
Figure 2.C_l/C_d versus Angle of attack for Reynolds number of 1.6×10^5 and 2×10^5.

The aerodynamic behavior of the airfoils at the Reynolds number of 1.6×10^5 and 2×10^5 with angle of attack varying from 0-20° is shown in figure 2. At Reynolds number 1.6×10^5, MID321a and MID321d
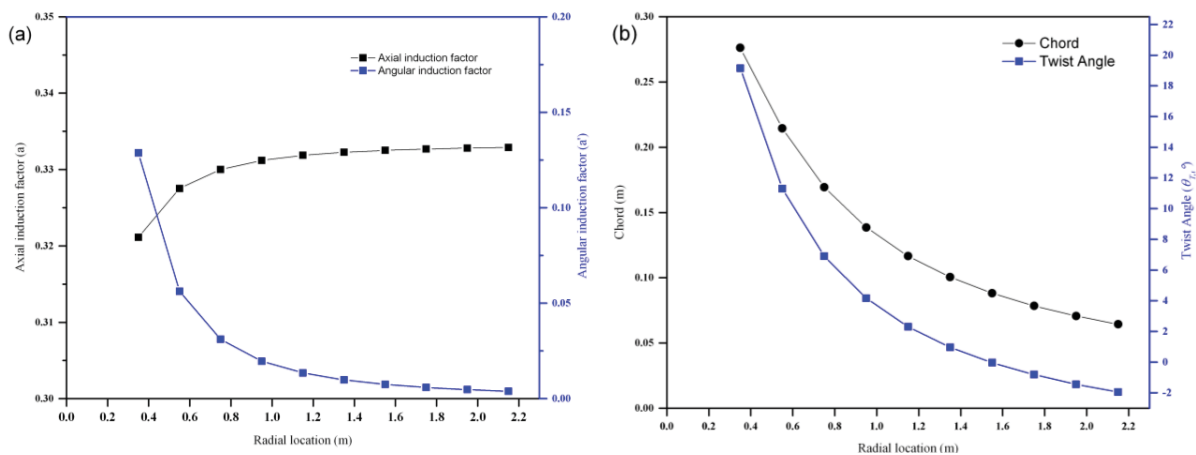

Figure 3. (a) Axial, Angular inductions factors, (b) Chord and Twist values of MID321a airfoil at Re=0.8×10^5.

produced limited glide ratio (C_l/C_d) compared to the remaining airfoils. SG6042 and SG6043 airfoils attained lift to drag ratio of 80 and 90 at short range of angle of attack. At higher Reynolds number of 2×10^5, MID321a and MID321d airfoils produced very limited glide ratio, while SG6043 airfoil attained a glide ratio of 100.

From the above results, MID321a and MID321d airfoils generate quite better lift to drag ratio for wider angle of attack compared to other four airfoils. The aerodynamic properties of Mid321a airfoil lift to drag ratio at 0.8×10^5 Reynolds number is selected. Thus it is used to BEM approach; the maximum

achievable power coefficient is determined through the iterative procedure. For the maximum power coefficient, chord and twist values are derived as shown in figure 3. The axial and angular induction factors are plotted in the figure 3(a), which is attained from the BEM method. The chord and twist values are higher at root section and lower at tip section is shown in figure 3(b).

5. Conclusion

 The operating characteristics of a small wind turbine having 3 blades and of 2.5 m diameter are estimated and aerodynamic properties of the concerned airfoils are determined using Xfoil tool. Subsequently the airfoil that shows the best performance is subjected to BEM calculations. Based on the obtained results, MID321a and MID321d airfoils are showed quite better lift to drag ratio at wider range of angle of attack for entire Re range whereas SG6042 and SG6043 airfoils are attained maximum glide ratio with narrow angle of attack. Optimal blade geometry parameters like chord and twist are calculated using aerodynamic characteristics of MID321a airfoil at 0.8×10^5 Reynolds number. The blade parameters such as chord values are varied from 276mm to 64mm and twist angle are varied from 19 ° to -1.95°. The maximum power coefficient value of 0.4 is attained by MID321a airfoil for Re 0.80×10^5.

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