NUMERICAL INVESTIGATION OF AIRFOILS FOR SMALL WIND TURBINE APPLICATIONS

by

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A detailed numerical investigation of the aerodynamic performance on the five airfoils namely Mid321a, Mid321b, Mid321c, Mid321d, and Mid321e were carried out at Reynolds numbers ranging from $0.5 \cdot 10^5$ to $2.5 \cdot 10^5$. The airfoils used for small wind turbines are designed for Reynolds number ranges between $3 \cdot 10^5$ and $5 \cdot 10^5$ and the blades are tend to work on off-design conditions. The blade element moment method was applied to predict the aerodynamic loads, power coefficient, and blade parameters for the airfoils. Based on the evaluate data, it was found that Mid321c airfoil has better lift to drag ratio over the range of Reynolds numbers and attained maximum power coefficient of 0.4487 at Re = $2 \cdot 10^5$.

Key words: *small wind turbine, blade element moment, low Reynolds number, airfoils*

Introduction

The fast depletion of fossil fuels made the people to look toward on the use of renewable energy resources. The differential heating of the earth's surface produces wind by the sunlight. A rough statistical estimation has been made that with the available wind energy as much as 10 million MW of power could be harnessed. It is clean, eco-friendly and prime national security at a time when the decreasing global reserves of fossil fuels are an eminent danger in the sustainability of global economy. Large scale wind turbines are usually placed in high potential wind resource regions, which are scarce in number. For fields of low wind potential, low cost, simple, portable, low interference, and maintenance free structured small wind turbines are of crucial influence in the rural and urban areas wind power extraction [1]. The approximate power coefficient of small and large scale wind turbines are 0.25 and 0.45, respectively. Nevertheless, the earlier scientific community conducted lot of the investigations on structural analysis than on aerodynamic optimization, but slowly the scientists are going towards the aerodynamic analysis of wind turbines [2].

In the middle of the 1980s, National Renewable Energy Laboratory (NREL) started to develop several families of airfoils for large wind turbine blades, and in the later years such development is continued especially for small wind turbines. The airfoils having good perfor-

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mance characteristics in the fluid flow with the Reynolds number range of less than $5\cdot10^5$ are the best for small wind turbines and their aerodynamic characteristics are listed [3, 4].

Simplifying the airfoil selection process for small wind turbines, a database was created with fifteen airfoils. These airfoils were tested in a wind tunnel at Re = $3\cdot10^5$ and parameters are given in [4]. The comprehensive wind tunnel tests conducted for the lift, drag, and moment characteristics of the six airfoils are E387, FX 63-137, S822, S834, SD2030, and SH3055 are used in small wind turbines at Reynolds numbers of $1\cdot10^5$, $2\cdot10^5$, $3.5\cdot10^5$ [5]. T. Urban 10/193 airfoil was designed based on the pressure load inverse method to perform at Reynolds number ranging from $3\cdot10^5$-$1\cdot10^6$ [6]. The bio inspired Seagull airfoil was designed and tested in CFD domain which shows better performance than its base airfoil NACA 4412 at the Reynolds number range of $1\cdot10^5$-$2\cdot10^5$ [7]. The new airfoil (SG 6043_EPPLER 422) developed from the set of existing low Reynolds number airfoils (SG6043, GOE15, E422, Eppler 560, and S1223) based on their aerodynamic performance, which are combined with each other to create a new one, in a Reynolds number range of $0.38\cdot10^5$, $0.28\cdot10^5$, and $2.05\cdot10^5$ [8]. The AF300 airfoil was optimized from the existing low Reynolds number airfoils, S1210 and S1223 were taken as base airfoil and increment in trailing edge thickness such as S1210 (3%) variant has given the best performance at Re = 0.55 and $1.48\cdot10^5$ through XFoil analysis [9].

Improvement on aerodynamic performance of wind turbine blades widely depends on the implementation of blade element momentum (BEM) theory. It is used to define the geometric parameters of the blade like chord and twist from root to tip. This is obtained by combining both momentum theory and blade element theory to calculate the aerodynamic torque and axial forces acting on each section of the blade [10]. Initially this approach was used for large wind turbines in 1980s and for small wind turbine according to the available literature in [11], it was initiated by Habali and Saleh [12] which designed and fabricated the blade with mixed airfoils such as NACA 63-621 and FX6-S-196 for root and tip sections, respectively. Small wind turbine designed for multipurpose with the dimension of 500 mm length blade using NACA 2404 pitch at 18° [1], NREL low Reynolds number airfoils S822 and S823 used in the tip and root of the blade operating at a tip speed ratio of 6 and angular velocity of 50 rpm [13], 3.5 m two bladed rotors designed with NACA 5317 airfoil [14], and two bladed rotor used AF300 as airfoil to work on the range of 3-6 m/s [15] were designed to maximize the power coefficient by using the BEM method.

This paper considers some new low Reynolds number airfoils for determining their aerodynamic characteristics, based on their performance implemented in small wind turbine blades whose geometric parameters were calculated by BEM approach.

Aerodynamics of wind turbine blade design

The BEM theory

In 1919, Albert Betz derived the equation for theoretical maximum possible energy generation from the available wind speed. He considered only axial momentum transfer and Glauert accounted the angular momentum transfer to derive the maximum energy generation (findings of Albert Betz and Glanert were referred from [10]). Finally BEM equations derived with correction factors used to design the blade. The BEM method used to determine the power coefficient, blade geometry parameters of wind turbine blade as per the flow chart available in fig. 1. In the blade design procedure, some values are assumed based on the wind condition at particular site.

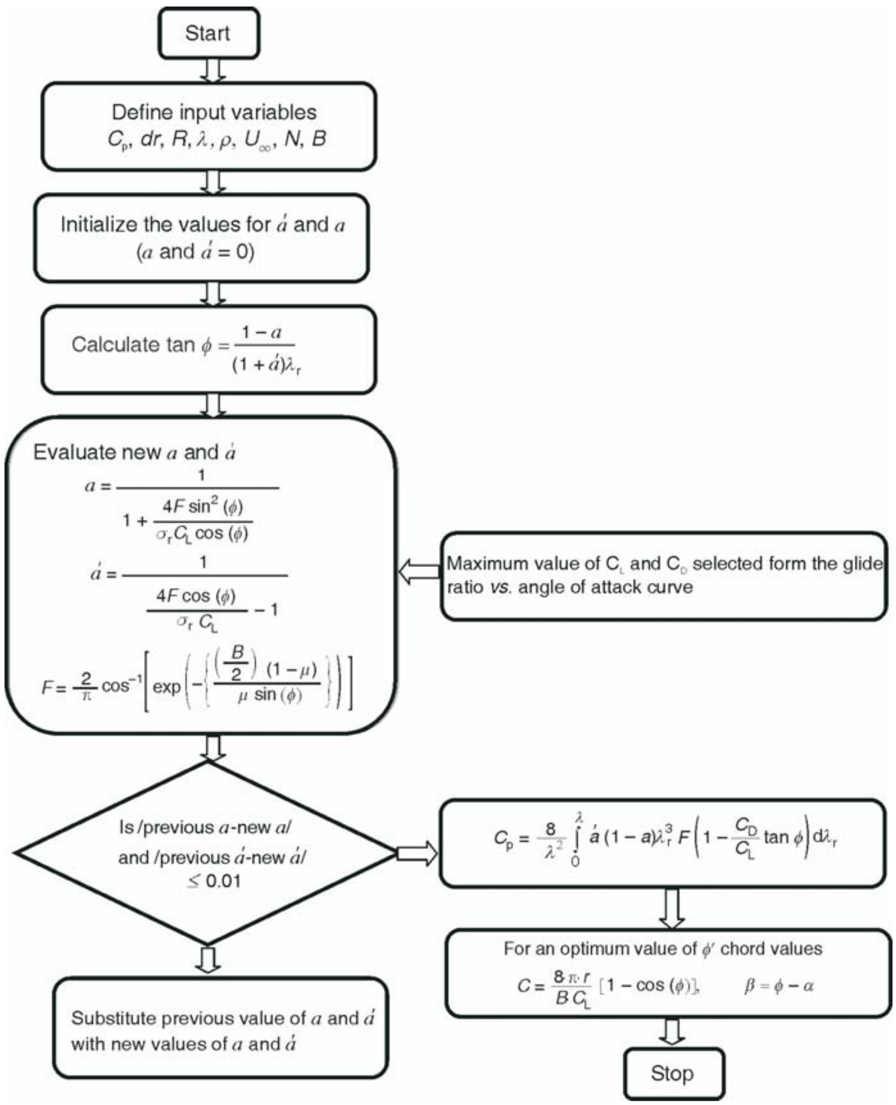

Figure 1. Flow chart for BEM equation for maximum power coefficient

Airfoil behaviour and selection

Small wind turbines are operating at very low wind speed, exposed to unsteady wind conditions like large wind turbines and most often fixed pitch blades. Airfoils are the basic elements in wind turbine blade, which plays the important role in an aerodynamic and structural performance in design and off design conditions. The anatomy of airfoils such as thickness and camber determines the structural stability and aerodynamic performance of the wind turbine blade. It is necessary to understand the Reynolds number and Mach number values to determine the aerodynamic characteristics of wind turbine airfoil performance:

$$\mathrm{Re} = U_\infty \frac{C}{\upsilon} \tag{1}$$

where Re is the Reynolds number, U_∞ – the velocity of the air, C – the chord of airfoil, and υ – the kinematic viscosity of air. The chord is defined as the straight line that connects the leading edge and trailing edge, which is always normal to blade span. Twist angle is defined as the angle between the chord lines to the plane of rotation of the blade. The Mach number is defined:

$$\text{Ma} = \frac{\text{object velocity}}{\text{sound velocity}} \tag{2}$$

The range of velocity ranges taken from 3-14 m/s, chord values ranging from 0.25-0.35 m, and υ consider the standard atmospheric condition is taken as $\upsilon = 16.5 \cdot 10^{-6}$ m^2/s.

The Reynolds number is calculated for various chord and velocity ranges, most of the Reynolds number values around $1 \cdot 10^5$ to $2 \cdot 10^5$. According to the literature [1], very few airfoils are designed with the Reynolds number value less than that $2.\ 5 \cdot 10^5$. So in most of the situation airfoils are subjected to off-design conditions, which shorten the annual energy output of small wind turbines. Proper determination of Reynolds number and suitable airfoil design could increase the annual energy production of small wind turbine. Airfoils listed in tab. 1 are subjected to the aerodynamic analysis and power coefficient of blade was calculated using the BEM method.

Airfoils are classified based their configurations like camber, thickness, leading edge radius, and trailing edge angle as shown in tab. 1.

Table 1. Airfoil details

Airfoil name	Thickness	Camber	r_{LE}	$\Delta\theta_{TE°}$
Mid321a	0.08998	0.03188	0.00530	6.40°
Mid321b	0.09450	0.03348	0.00580	6.71°
Mid321c	0.09997	0.03941	0.00656	7.12°
Mid321d	0.14998	0.03542	0.01474	10.68°
Mid321e	0.14998	0.04989	0.01486	10.64°

Computational study

The five airfoil co-ordinates obtained from [16] and surfaces smoothened and aerodynamic characteristics determined using Xfoil, which is the fortran based software, created by Derla [17] at the Massachusetts Institute of Technology, Cambridge, Mass., USA. This software simulate the airfoils based on the panel method, which is the combination of e^n laminar to turbulent transition method and the set of integral boundary layer formulations. For this method, airfoils geometery pre-requirments is the number of nodes that is constantly taken as 160 for all simulations and specific inflow condition that is N_{crit} value fixed as nine for the all cases. This software were very fast, in the order of milliseconds for one case, irrespective of computational resources [18].

The BEM method is solved by using MATLAB tool. The blade is divided into ten elements and aerodynamic loads are calculated for each elements. The overall blade power cofficient determined from elemental section of blade using trapezium formula of numerical integration. Finally blade parameters such as chord and twiste angle have been calculated.

Result and discussion

Aerodynamic analysis of airfoils

Aerodynamic characteristics of selected airfoils at the Re = $0.5 \cdot 10^5$, $1 \cdot 10^5$, $1.5 \cdot 10^5$, $2 \cdot 10^5$, and $2.5 \cdot 10^5$ for an angle of attack (AOA) at 0-18 º given in the fig. 2. At Re = $0.5 \cdot 10^5$,

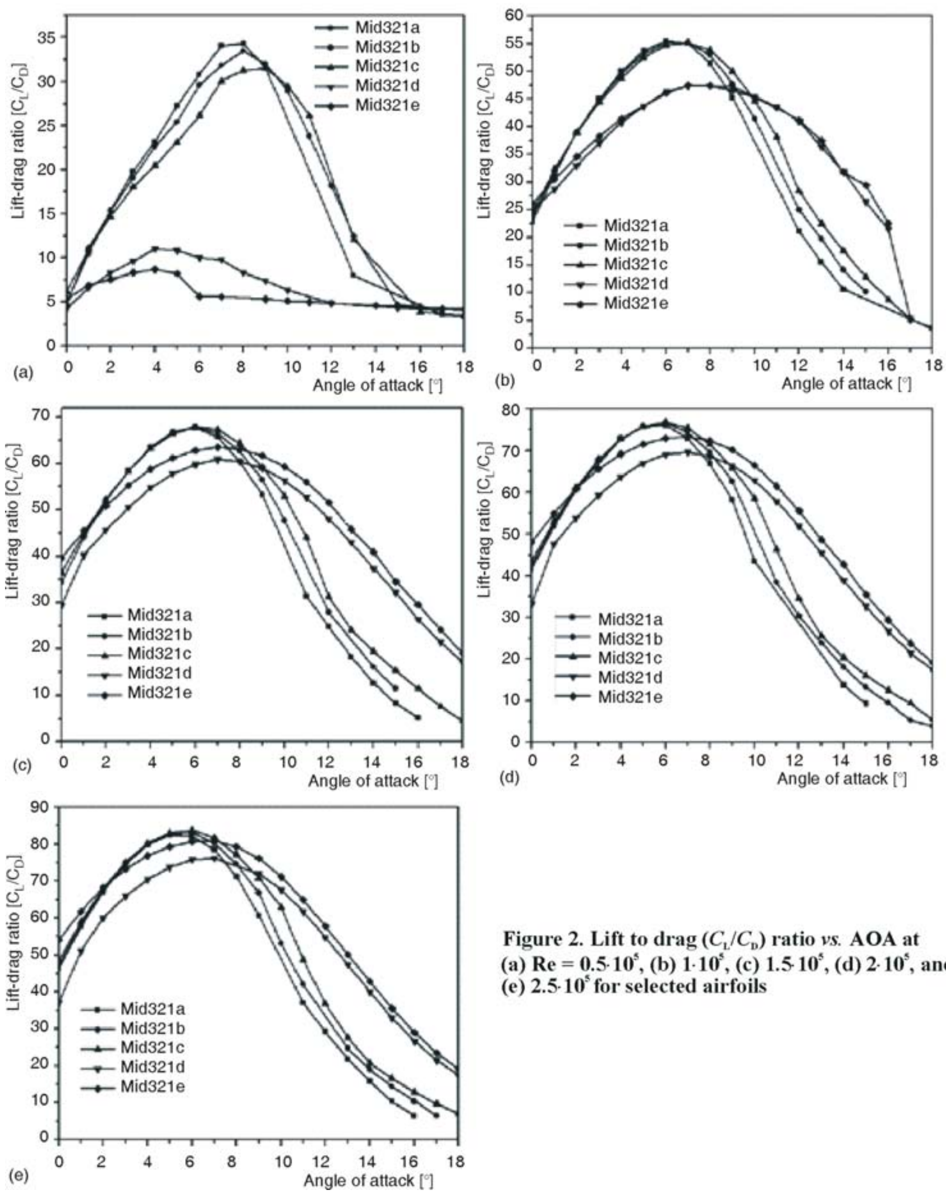

Figure 2. Lift to drag (C_L/C_D) ratio *vs.* AOA at (a) Re = $0.5 \cdot 10^5$, (b) $1 \cdot 10^5$, (c) $1.5 \cdot 10^5$, (d) $2 \cdot 10^5$, and (e) $2.5 \cdot 10^5$ for selected airfoils

Mid321a and Mid321b airfoils reached the maximum lift to drag ratio of 35 at 7 º of an AOA, in addition Mid321c reached its maximum lift to drag ratio of 30 at 9 º of AOA. The airfoils Mid321d and Mid321e produces very low lift to drag ratio. Moreover, Mid321d performed better than Mid321e at lower AOA shown in fig. 2(a).

First three airfoils working narrow AOA and Mid321d airfoil performing wider AOA. At Re = $1 \cdot 10^5$, Mid321a, Mid321b, and Mid321c airfoils attained lift to drag ratio of 55 at 6º, unlikely these airfoils working narrow AOA. The Mid321d and Mid321e airfoils reached the lift to drag ratio of 46 at 7º then increasing the Reynolds number, the lift to drag ratio tends to increase by 40% from the initial position and operating wider AOA compared to former airfoils as shown in fig. 2(b). So these airfoils do not affected by the laminar separation bubbles at this case.

The Mid321a, Mid321b, and Mid321c airfoils attained the maximum lift to drag ratio of 68 at 6º of AOA for a Reynolds number of $1.5 \cdot 10^5$ whereas Mid321d and Mid321e airfoils attained slightly short value of lift to drag ratio of 61 and 63 at 7º. Similarly, in this case also later two airfoils performing broad range of AOA, among the first three airfoils Mid321c operates well compare to remaining two airfoils. After reached the maximum glide ratio former three airfoils suddenly decreases, later two airfoils operated well over the investigated range and Mid321e produced much better glide ratio than Mid321d airfoil given in fig. 2(c).

For the Reynolds number of $2 \cdot 10^5$, Mid321a, Mid321b and Mid321c airfoils reached the lift to drag ratio of 76 at 6º of AOA. The Mid321d and Mid321e airfoils produced the lift to drag ratio of 67 and 72 at 7º AOA and these two airfoils performances are lesser than the former airfoils and Mid321e airfoil operated well over the range of AOA compared to remaining airfoils available in fig. 2(d).

The Mid321a, Mid321b, and Mid321c airfoils attained the lift to drag ratio of 82, 83, and 84 at 6º of AOA and Re = $2 \cdot 10^5$ where as Mid321d and Mid321e airfoils attained 76 and 80 at 7º of AOA given in fig. 2(e). The flow separation of former three airfoils occurs very earlier and later two airfoils working better over the broad range of AOA. All over the investigated Reynolds number, Mid321c airfoil arrive the maximum lift to drag ratio and works better in range of AOA than Mid321a and Mid321d likewise Mid321e airfoil produced considerably higher glide ratio and performed wide range of AOA. The Mid321c airfoil was selected for the further blade design studies.

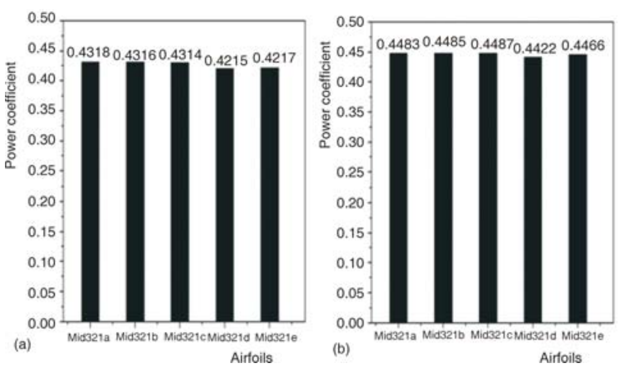

Figure 3. Power coefficient of various airfoils

The BEM simulation

The proposed design of small wind turbine configurations is three bladed, 4.50 m diameter, tip speed ratio 7, fixed pitch-variable speed, design wind speed of 7 m/s, and power of 1 kW, these values given as an input to the BEM calculations. The power coefficient calculated and compared with the all five airfoils, Mid321c and Mid321d airfoil operating well over the broad range of AOA, but Mid321c reached the maximum glide ratio thus gave higher C_p values of 0.4314 and 0.4487 at Re = $1 \cdot 10^5$ and $2 \cdot 10^5$ as shown in fig. 3. The Mid321c airfoil was subjected to further analysis based on the overall performances.

The optimal geometric parameter (chord and Twist distribution) of the wind turbine blade is determined though the equation available in the flowchart for different radial locations and the results are shown in the fig. 4.

The chord is higher in root section and lower in the tip section to provide structural stability to the blade as shown in fig. 4. The inflow angle is obtained larger at root section and smaller at tip section. To maintain the maximum lift to drag ratio along the blade, the airfoilis pitched at the optimum AOA along the span of blade subsequently twist angle can be determined.

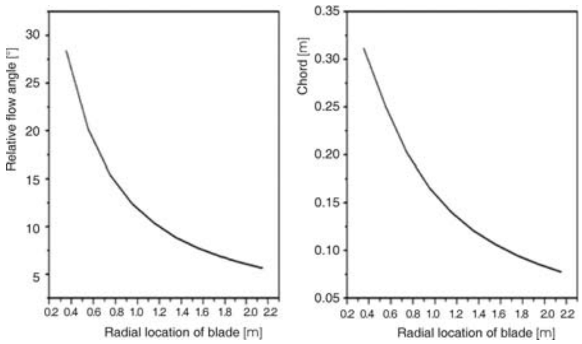

Figure 4. Relative flow angle and chord values *vs.* radial locations along the span

Conclusion

This paper presents the optimal aerodynamic blade design procedure for small horizontal axis wind turbine by using BEM theory. For the proposed design parameters, blade operating Reynolds number ranges are determined and airfoils are subjected to aerodynamic analysis. The Mid321a, Mid321b, and Mid321c airfoils are attaining maximum lift to drag ratio, whereas Mid321d and Mid321e airfoils operating at a wider range of AOA. The Mid321c airfoil shows good lift to drag ratio for various Reynolds numbers, this is extended to BEM analysis. Optimal blade geometry parameters like chord and twist were calculated. The chord values varied from 0.31 m to 0.07 m and relative inflow angle varies from 28° to 5°. For this optimal geometry, maximum power coefficient value of 0.4472 has been attained at the Reynolds number of $2 \cdot 10^5$.

Nomenclature

a – axial induction factor, [–]
$\acute{a}$ – angular induction factor, [–]
B – number of blade, [–]
C – chord, [m]
C_D – drag coefficient, [–]
C_L – lift coefficient, [–]
C_p – power coefficient, [–]
dr – elemental radius of the blade, [m]
F – correction factor, [–]
N – number of blade element, [–]
R – radius of the blade, [m]
r_{LE} – leading edge radius
U_∞ – free stream wind velocity, [ms^{-1}]

Greek symbols

α – angle of attack, [°]
β – twist angle, [°]
$\theta_{TE°}$ – trailing edge angle
λ – tip speed ratio, [–]
λ_r – local tip speed ratio, [–]
μ – ratio of various radial locatons (r) on the span of rotor to radius of rotor (R)
ρ – density of air, [kgm^{-3}]
σ_r – local blade solidity, [–]
ϕ – relative wind angle, [º]

Acronyms

AOA – angle of atack
BEM – blade element momentum, [–]

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