Aerodynamic Design of a Horizontal Axis Micro Wind Turbine Blade Using NACA 4412 Profile

Sandip. A. Kale*‡, Ravindra N. Varma*

*Mechanical Engineering Department, Trinity College of Engineering and Research, Pune, Kondhawa - Saswad Road, Bopdev Ghat India-411 048

(sakale2050@gmail.com, ravindra6859@gmail.com)

‡ Corresponding Author; Sandip A. Kale, 511 Ganesh Nakshtram, Dhayari, Pune, India – 411 041, +91 888 882 1160, sakale2050@gmail.com

Received: 04.12.2013 Accepted: 09.02.2014

Abstract- Wind turbine blade is a key element to convert wind energy in to mechanical power. This work presents functional design and aerodynamic design of an eight hundred mm long blade of a six hundred W horizontal axis micro wind turbine using NACA4412 profile. Functional design of blade is carried out by considering use of electrical appliances to meet need of a rural house for low wind speed region. Various theories are available and used by designers for blade design. The chord and twist angle distributions of the preliminary blade design are determined. The preliminary blade design does not necessarily provide the best power performance under practical operation conditions and needs to follow further modifications and calculations. Also, a reasonable compromise between high efficiency and good staring is expected. The optimization with the objective of enhancement of power performance and low speed starting behavior is carried out. Though, hub region contributes little to overall power production, its optimization plays important role for good starting and low wind performance. In this work analysis is carried out for coefficient of performance of the blade and for starting behavior of the wind turbine blade. MATLAB programming is developed for the blades. The power coefficients curves are drawn for the optimized wind turbine.

Keywords- Coefficient of Power; Aerodynamics; Optimization; Blade

1. Introduction

Wind energy is most of the promising renewable energy source. Harnessing wind energy has gained significance. Deployment of wind energy in the world has been increasing steadily [1, 16]. In many developing countries, off-grid small wind power is an efficient and key solution to solve problems of power supply in remote regions of electricity shortage. Small wind energy is also increasing insistently and it has shown annual 35 % increase in the global installed capacity for the past years [2]. Small wind turbines are classified as micro, medium and small wind turbines. Micro wind turbine has the potential to fulfil electricity need of rural homes. With highly efficient, solid and reliable micro wind turbine, wind power offers a solution to meet energy needs and environmental care.

The blade is key element of micro wind turbines which converts the kinetic energy of the wind and in electricity through generators [17]. Aerodynamic shape optimization is one of the main research fields which is directly related to power production of a wind turbine. The optimum distributions of the chord length and the pitch angle in each section can be acquired according to the design parameters, which include the rated wind speed, number of blades, design tip speed ratio and design angle of attack [3]. Operating at low cut-in wind speeds has been made possible through aerodynamic optimization of the rotor blades which is the most important part of a wind turbine [4, 5]. 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 (TSR) [6]. C. J. Bai, et al. [3] presented design of horizontal-axis wind wurbine blade and aerodynamic investigation using numerical simulation using BEM theory for S822 aerofoil.

BEM theory usually is uses for evaluating the forces on the wind turbine in its design and optimization[15]. Ozge Polat and Ismail H.Tuncer has present parallel genetic algorithm to optimize blade shape at prescibed wind speed, rotor speed, rotor diameter and number of blades of four digit NACA profile of a wind trubine [1].

There are three main factors that must be considered for blade design. First, power extraction occurs mainly on the outer part of any turbine blade. Second, starting torque is generated mainly near the hub. Thirdly, thick aerofoil sections are not to be used for small turbine blades as their low-Re performance is generally very poor at high angles of attack. The first two factors are encouraging as they suggest that a reasonable compromise between high efficiency and good starting is possible. The third result is cause for concern because thick sections are used near the hub of large blades for structural strength (in combination with the circular root attachment that allows pitch adjustment). It is for these reasons that the biggest difference between the shape of optimal blades for large and small turbines will occur in the hub region [9].

A low Reynolds number airfoil was designed for applications in small horizontal axis wind turbines to achieve better startup and low wind speed performances. The dimension of wind turbine blades for a defined size, always involves research including calculations, modeling and experimentation. The calculations of blade geometry parameters like chord length, thickness and angle of attack is a most noteworthy ingredient of any blade design procedure for required profile, length and rated wind speed [7, 8, 17].

Maximum efficiency is only one of the parameters to be optimized on many blades. It is generally not possible to derive analytic expression for multi-dimensional optimization. There are a vast number of multi-dimensional optimization methods available for blade design, a number of which are available as MATLAB functions. The strategy described here produces optimum results, easy to code, easily extended to higher dimensional optimization, and computationally very fast.

2. Functional Design

Functional design is carried out by the considering the use of the electrical appliances to meet the need of the household purposes in the rural sectors. The rotor diameter (*d*) is calculated from the basic Eq. (1) of wind power (*P*) at rated wind speed (*v*) [12, 13],

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

For 600 W power output required blade length calculated as 800 mm by considering various efficiencies of the system components.

3. Aerodynamic Design

All the parameters which are related to the Aerodynamic such as the Chord Length(C), Relative angle (Φ), Local Radius (r), Angle of attack (α), Reynolds Number (R_e), Coefficient of lift (C_L), Coefficient of drag (C_D) (Corresponding to the R_e), Solidity (σ), Axial Induction Factor (a), Radial Induction Factor (a') and Coefficient of power (C_p) by using the Blade Element Momentum Theory [9, 11, 14]. Blade is divided in ten elements. The relative angle is calculated from Eq. (2),

$$\phi = \tan^{-1}\frac{2}{3\lambda_r} \qquad (2)$$

The chord length at each station is calculated by Eq. (3)

$$C = \frac{16\pi}{9N\lambda\sqrt{4}/9 + [\lambda_r + 21(9\lambda_r)]^2} \qquad (3)$$

Reynolds Number is given by Eq. (4),

$$R_e = \frac{v \times \lambda_r \times C}{1.5\times10^{-5}} \qquad (4)$$

Coefficient of Lift and Coefficient of Drag are taken from the chart and by using interpolation for corresponding Reynolds Number and angle of attack calculated the values of the same. The solidity is calculated from Eq. (5),

$$\sigma = \frac{B \times C}{2\pi r} \qquad (5)$$

The axial induction factor (*a*) and radial induction factor (*a'*) are givrn by Eq. (6) and Eq. (7) respectively.

$$a = \frac{1}{1 + \frac{1 + 4F\sin^2\phi}{\sigma C_L \cos\phi}} \qquad (6)$$

$$a' = \frac{1}{\frac{4F\cos\phi}{\sigma C_L} - 1} \qquad (7)$$

After calculating the axial and radial induction factor, relative or blade in-flow angle is again calculated by Eq. (8),

$$\tan\phi = \frac{1-a}{(1+a')\lambda_r} \qquad (8)$$

Then, through multiple iterations calculates the Axial and Radial Induction Factors, blade inflow angle for the greater accuracy and to get small change in the angle of attack. It is further used to calculate the Coefficient of Power (C_p) by Eq. (9)

$$C_p = \frac{8}{\lambda}\left[F\sin^2\phi\left(\cos\phi - \lambda_r\sin\phi\right)\left(\sin\phi + \lambda_r\cos\phi\right)\left(1 - \frac{C_D}{C_L}\cot\phi\right)\lambda_r^2\right] \qquad (9)$$

Following these steps, through multiple iterations aerodynamic parameters can determined.

4. Optimization of the Wind Turbine

The optimization with the objective of enhancement of power performance and low speed starting behavior is carried out. For Optimization we have used the Betz-Joukowsky Limit Theory. Reynolds number and solidity are calculated by Eq.4 and Eq.5. The axial force coefficient (C_a) and tangential force coefficient (C'_a) are given by Eq. (10) and Eq. (11)

$$C_a = C_L \cos\phi + C_D \sin\phi \quad (10)$$

$$C_a^{'} = C_L \sin\phi - C_D \cos\phi \quad (11)$$

For Tip Loss Correction, two intermediate factors Y_1 and Y_2 are given by Eq. (12) and Eq. (13),

$$Y_1 = \frac{4F\sin^2\phi}{\sigma C_a} \quad (12)$$

$$Y_2 = \frac{4F\sin\phi\cos\phi}{\sigma C_a^{'}} \quad (13)$$

Axial and Radial Induction Factors are determined by Eq. (14) and Eq. (15)

$$a = \frac{2 + Y_1 - \sqrt{\left[4Y_1(1-F) + Y_1^2\right]}}{2(1+FY_1)} \quad (14)$$

$$a' = \frac{1}{\frac{2(1-aF)Y_2}{(1-a)} - 1} \quad (15)$$

Relative angle is given by Eq. (8) and twist angle of blade element is given by Eq. (16),

$$\theta_p = \phi - \alpha \quad (16)$$

The coefficient of power is given by Eq. (9). Blade optimization is achieved through multiple iterations.

5. Results and Discussion

Through multiple iterations aerodynamic parameters are calculated and given in Table 1.

Table 1. Calculated parameters for Normal Blade

Element No.	r (mm)	Φ (^{0})	C (mm)	t (mm)	θ_p (^{0})	C_P
1	160	23.1	166.22	16.20	17.10	0.2122
2	224	17.62	139.48	13.50	11.62	0.2904
3	288	14.35	113.45	11.00	8.35	0.3797
4	352	12.05	95.07	9.12	6.05	0.4654
5	416	10.31	81.60	7.86	4.31	0.4729
6	480	9.32	71.37	6.84	3.82	0.4932
7	544	8.23	63.36	6.12	2.73	0.5012
8	608	7.44	57.16	5.50	1.94	0.5239
9	672	6.79	51.68	5.00	1.29	0.6048
10	736	6.14	47.30	4.5	0.64	0.6592
11	800	5.66	43.60	4.2	0.16	0.8042

The optimized aerodynamic parameters along with power coefficients ate presented in Table 2.

Table 2. Calculated parameters for Optimized Blade

Element No.	r (mm)	Φ (^{0})	C(mm)	t (mm)	θ_p (^{0})	C_P
1	160	23.66	135	11.25	17.66	0.1945
2	224	17.04	112	9.33	11.04	0.2833
3	288	13.88	91	7.58	7.88	0.3709
4	352	11.73	76	6.33	5.73	0.4559
5	416	10.06	65.5	5.46	4.06	0.5358
6	480	9.17	57	4.75	3.67	0.6233
7	544	8.08	51	4.25	2.58	0.6964
8	608	7.32	46	3.83	1.82	0.7674
9	672	6.64	41.5	3.46	1.14	0.8405
10	736	6.04	38	3.17	0.54	0.9048
11	800	5.58	35	2.92	0.08	0.9696

Graphs are plotted for chord length, thickness, Coefficients of power at various non-dimensional radii as shown in Fig.1, Fig.2. and Fig. 3 respectively for normal and optimized blade. Final optimized profiles are shown in Fig. 4.

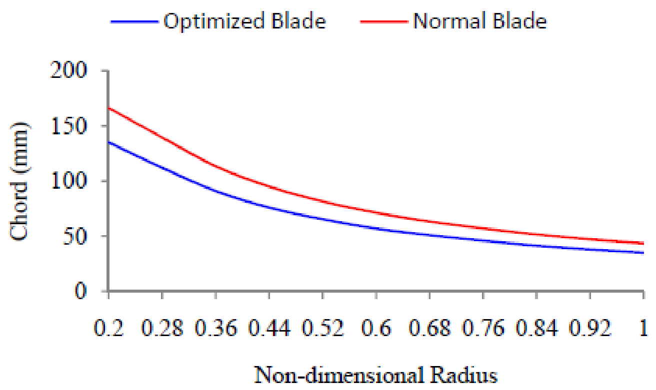

Fig. 1. Blade chord at various stations.

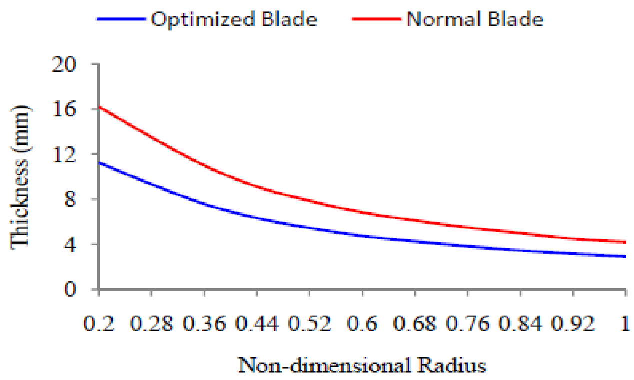

Fig. 2. Blade thickness at various stations.

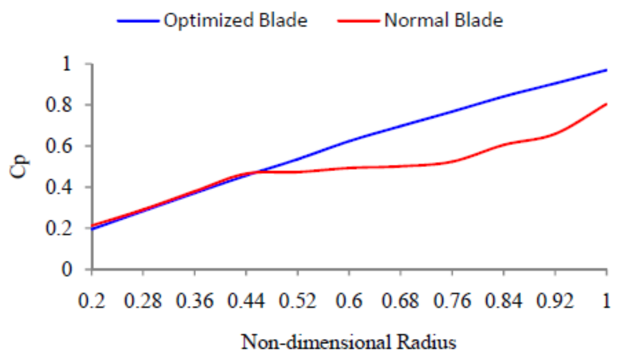

Fig. 3. Coefficient of power at various stations.

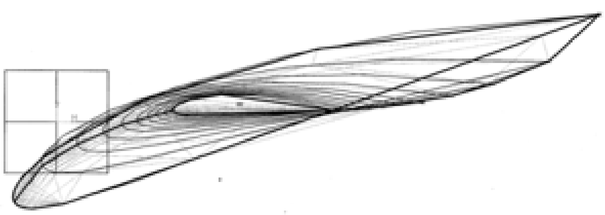

Fig. 4. Optimized blade profiles.

6. Conclusion

Blade of 800 mm length is successfully developed for a horizontal axis micro wind turbine of 600 W power output through multiple iterations to enhance its performance. The chord of optimized blade is reduced by 24% and thickness is reduced by 44%. Coefficient of power of optimized blade is increased significantly up to 30% than that of normal blade.

References

[1] Ozge Polat, Ismail H.Tuncer,“Aerodynamic shape optimization of Wind Turbine Blades using a parallel Genetic Algorithm”, Procedia Engineering, 61, 2013, pp. 28-31

[2] Small Wind Energy Report, World Wind Energy Association, March 2012, pp.5-15

[3] C. J. Bai, F. B. Hsiao, , M. H. Li, G. Y. Huang, Y. J. Chen, “Design of 10 kW Horizontal-Axis Wind Turbine (HAWT) Blade and Aerodynamic Investigation Using Numerical Simulation”, Procedia Engineering 67, 2013, pp 279 – 287

[4] Habali SM, Saleh IA. , “Local design, testing and manufacturing of small mixed airfoil wind turbine blades of glass fiber reinforced plastics. Part I: design of the blade and root”, Energy Conversion & Management 2000;41:249-80.

[5] Ahmed MR, Narayan S, Zullah MA, Lee YH. , “Experimental and numerical studies on a low Reynolds number airfoil for wind turbine blades”, Journal of Fluid Science and Technology 2011;6:357-71.

[6] Badr MA, Maalawi KY. , “A practical approach for selecting optimum wind rotors”, Renewable Energy 2003;28:803-22

[7] Ronit K. Singh, M. Rafiuddin Ahmed, , Mohammad Asid Zullah, Young-Ho Lee, “Design of a low Reynolds number airfoil for small horizontal axis wind turbines”, Renewable Energy 42 (2012) 66-76

[8] P. D. Clausen and D. H. Wood, “Research and development issues for small wind turbines”, Elsevier Academic Press, *Renewable Energy Journal* 16, 1999, pp.922-927.

[9] David Wood, Small Wind Turbine – Analysis, Design and Application , Springer ,2011.

[10] Eastman N. Jacobs, Kennetit E. Ward, Report -460 by NACA, 1948, pp-56

[11] Grant Ingram, Wind Turbine Blade Analysis using the Blade Element Momentum Method, 2011

[12] J. F. Manwell, J.G. McGowan, A.L. Rogers, Wind Energy Explained: Theory, Design and Application, John Wiley and Sons, Ltd, 2002, pp 247-317

[13] L. L. Freris, Wind Energy conversion systems, PHI (UK) Ltd. , 1990, pp. 282-284

[14] Martin O. L. Hansen, Aerodynamics of Wind Turbines, Earthscan, Uk, Second Edition ,2008.

[15] M.H. Djavareshkian, A. Latifi Bidarouni, M.R.Saber, “New Approach to High-Fidelity Aerodynamic Design Optimization of a Wind Turbine Blade”, International Journal of Renewable Energy Research, Vol.3, No.3, 2013, pp. 725-735

[16] Ali Hajiah, M. Sebzali , “Optimal Sizing of Wind Power Systems in Three High Wind Potential Zones in Kuwait for Remote Housing Electrification”, International Journal of Renewable Energy Research, Vol.3, No.1, 2013, pp. 167-171

[17] Xu Baoqing, Tian De, “Simulation and Test of the Blade Models’ Output Characteristics of Wind Turbine”, Energy Procedia 17 , 2012 , pp. 1201 – 1208