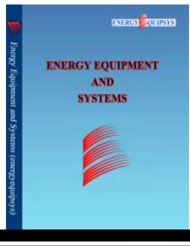
energyequipsys/ Vol 2/No2/AUG 2014/ 185-193

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
http://energyequipsys.com



Aerodynamic optimal design of wind turbine blades using genetic algorithm

Mojtaba Tahani[a]*
Tahmine Sokhansefat[a]
Kiana Rahmani[a]
Pouria Ahmadi[b]

[a] Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran

[b] Department of Mechanical Engineering, University of Ontraio Institute of Technology, Toronto, Ontario, Canada

Article history:

Received 29 June 2014
Accepted 14 September 2014

ABSTRACT

Wind power has been widely considered and utilized in recent years as one of the most promising renewable energy sources. In the current research study, aerodynamic analysis of the upwind three-bladed horizontal axis turbine is carried out using blade element momentum theory (BEM), and a genetic algorithm (GA) is applied as an optimization method. Output power generation is considered as an objective function, which is one of the most common choices of objective function. The optimization variables also involve chord and twist distribution variations and the placement of the airfoil sections along the blade length. The optimal blade shape is investigated for the maximum output power at a specific wind speed, rotor diameter and airfoil profile. The modified BEM results are compared with an experimental measurement indicating reliable results. The results show that considering placement of the airfoils as design variables in addition to chord and twist rate has a significant effect on the optimal output power. Finally, the objective function (output power) is improved by 10% compared to the base function.

Keywords: Aerodynamic, BEM & GA, Optimization, Output Power, Wind turbine blade.

1. Introduction

Recently, the wind power growth rate has been investigated. Wind turbine technology is one of the methods to apply this renewable resource in order to generate environmentally friendly electrical energy. These technologies are complex systems whose design requires the integration of many engineering disciplines, including aerodynamics, structures, controls and electrical engineering. The main aim of most wind turbines is to capture maximum energy from the wind energy. Therefore, it is necessary to know what the best design parameters for each component of the wind turbine would be [1]. Generally, wind turbine design techniques try to emphasize and address the optimal blade shape and optimal control, and increase site-specific performance to improve wind turbine efficiency and life cycle. Aerodynamic design and structural design are two stages of a wind turbine blade design process, which can both be seen as optimization problems. Typically, the design goal is maximum aerodynamic efficiency at a specific wind speed. Aerodynamic design optimization includes the selection of an airfoil family and its placement, and the chord and twist distributions along the blade length [1]. There are different aerodynamic methods that have been developed for wind turbines, such as blade element momentum (BEM), vortex methods [2], dynamic stall models [3], CFD [4] and experimental methods. BEM method, presented by Glauert [5], enables the calculation of the steady loads and power.

*Corresponding author:
Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran.
E-mail address: m.tahani@ut.ac.ir (Mojtaba Tahani)

This method with some modifications often predicts the performance of wind turbines with acceptable accuracy, and also has a cheap computational run time. Many studies have been conducted on BEM method for the design and evaluation of wind turbine rotor performance [6-11].

Furthermore, genetic algorithm (GA) has been successfully implemented in aerodynamic optimization problems for horizontal axis wind turbines [12]. Liu et al. [13] investigated the linearization of the chord and twist angle radial profiles for a fixed-pitch, fixed-speed horizontal axis wind turbine using the BEM theory to calculate the power performance of the blade. They considered the highest AEP for a particular wind speed as the optimization criterion with constraints on the upper limit of power output of the wind turbine. Ceyhan [14] developed an aerodynamic design and optimization tool for horizontal axis wind turbines using both the BEM theory and GA. Blades were optimized for the maximum power output for a given wind speed. Chord, twist angle and a fixed number of sectional airfoil profiles were considered as design variables. Polat and Tuncer [15] developed an aerodynamic shape optimization methodology based on genetic algorithm and blade element momentum theory for rotor blades of horizontal axis wind turbines. They studied the maximization of power production at a specific wind speed, rotor speed and rotor diameter. The sectional chord length, twist and blade profiles at the root, middle and tip regions of the blade were considered as design variables. Liu et al. [16] studied an optimization model using the extended compact genetic algorithm (ECGA) for rotor blades of a 1.3 MW stall-regulated wind turbine with an objective function to satisfy the maximum annual energy output on specific winds. Mendez and Greiner [17] illustrated the optimal wind blade shape using a genetic algorithm. This work focused on optimization of wind turbine application in particular wind conditions, which might differ from the standard classes according to the IEC classification.

Most of the research has reported on and studied the optimization of twist and chord rate. In the current research study, the placement of different types of airfoil along the blade is considered. Blade optimization of the Vestas 660 kW wind turbine is investigated from an aerodynamic point of view. The methodology is implemented within an integrated GA method and modified BEM developed by computer code for this complex wind turbine blade. The optimization is focused on maximizing power generation, determined by optimal chord and twist rates and the optimal placement of the airfoils along the blade length.

Nomenclature

a	Axial Induction Factor
a'	Tangential Induction Factor
C	Chord (m)
C_D	Drag Coefficient
C_L	Lift Coefficient
C_N	Normal Force Coefficient
C_T	Tangential Force Coefficient
$f(x)$	objective function
$g_j(x)$	inequality constraint
m	number of constraints
n	number of design variables
P	Power (KW)
r	Radial distance from root (m)
T	Twist (deg)
V_0	Wind Speed (m/s)
V_a	Axial Induced Velocity (m/s)
V_{rot}	Rotational Induced Velocity (m/s)
x	design variable
x_i^L	Lower limits
x_i^U	Upper limits

Greek Symbols

α	Angle of Attack (deg)
α_{pitch}	Pitch Angle (deg)
Φ	Inflow Angle (deg)
Σ	Solidity
Ω	Rotational Velocity (rpm)

2.Methodology

The methodology is described in two main sections. In the first, the computational code (i.e., BEM theory) is presented for aerodynamic analysis of the wind turbine blade, and in the other optimization and details of the integration of the optimization algorithm and BEM code are described.

2.1 Blade Element Momentum Theory

BEM combines blade element and one-dimensional momentum theory. In this method, the wind turbine blades are divided into a number of independent elements along blade length. At each section, two-dimensional force balances are applied by considering torque and thrust produced by the section. At the same time, the momentum balance for the annular element is applied. Finally, a set of equations are derived that can be solved for each blade section [18]. Because of the rotational flow, the angle of attack at each section of blade is determined as follows:

$$\alpha = \alpha_{pitch} - \varphi \tag{1}$$

φ is inflow angle of attack that is calculated from the below:

$$\varphi = \arctan\frac{V_a}{V_{rot}} \tag{2}$$

where α_{pitch} is pitch angle, V_a and V_{rot} are induced velocities in rotor plane that are determined by means of axial and tangential induction factor, as follows:

$$V_a = (1 - a)V_0 \tag{3}$$

$$V_{rot} = (1 + a')\Omega r \tag{4}$$

The normal and tangential force coefficients are determined by projecting lift and drag coefficients in those directions.

$$C_N = C_L \cos(\varphi) + C_D \sin(\varphi) \tag{5}$$

$$C_T = C_L \sin(\varphi) - C_D \cos(\varphi) \tag{6}$$

Finally, the following relations are obtained by the use of mathematical computation for axial and tangential induction factors:

$$a = \frac{1}{\frac{4\sin^2\varphi}{\sigma C_N} + 1} \tag{7}$$

$$a' = \frac{1}{\frac{4\sin\varphi\cos\varphi}{\sigma C_T} - 1} \tag{8}$$

where σ is solidity and is defined as the fraction of the annular area in the control volume that is covered by the blades. Prandtl [18] derived a correction factor F to the axial and tangential induction factor to correct the assumption of an infinite number of blades. With regard to the initial BEM assumptions, for each section of blade the following algorithm is applied independently:

1. Initial guess for a and a'
2. Calculate inflow angle (Eq. 2)
3. Calculate local angle of attack (Eq. 1)
4. Read lift and drag coefficient from tabulated data
5. Calculate axial and tangential induction factor (Eq. 7 and 8)
6. If error of a and a' are more than tolerance considered, go to step 2, otherwise go to next step
7. Calculate aerodynamic forces

2.2 Optimization

In this section, we try to formulate the aerodynamic optimization of the blade. Optimization problems are made up of a set of design variables, an objective function and a set of constraints. The focus of optimization is to determine the values of the design variables that lead to either minimizing or maximizing the objective function while satisfying the constraints. From this point of view, the nonlinear, constrained optimum design problem can be expressed mathematically as follows:

Find $x = [x_1, x_2, x_3, \dots\dots]^T$

To minimize $f(x)$

Subjected to

$$g_j(x) \le 0 \qquad j = 1,2,\dots m$$

$$x_i^L \le x_i \le x_i^U \qquad i = 1,2,\dots n \tag{9}$$

where x represents the design variable vector, n is the number of design variables and m is the number of constraints. $f(x)$ is the objective function which depends on the values of the design variables. $g_j(x)$ denotes the inequality constraint. x_i^L and x_i^U are the lower and upper limits of the design variables, respectively, and they simply limit the region of search for the optimization.

Objective function

The output power is one of the important objectives for aerodynamic optimization of the wind turbine blade. In the current work, output power is applied as the outputs of BEM code for calculating the objective functions.

Design variables

Distribution of the chord and twist along the blade length is shown in the following equations.

$$C = ar + b \tag{10}$$

$$T = ce^{dr} + e \tag{11}$$

where r is distance from root and a, b, c, d and e are coefficients. Placement of the airfoils along the blade length of the wind turbine in this case study is illustrated in Fig. 1. Each type of airfoil is placed at a specific distance from root of blade.

In this study, chord and twist rates and the placement of the airfoils along blade length are considered as a design variables, and are shown in Table 1.

Constraint

In the optimization, lower and upper value limitations for twist and chord rate and the placement of the airfoils along the blade length are considered as constraints. Chord and twist constraints are shown in Figs 2 and 3. Additionally, a lower limitation (300) is considered for output power.

2.2.1 Optimization Method

Genetic algorithms are based on natural selection mechanisms and use only the values of the objective function. In the other words, they do not use gradients of the objective function. The genetic algorithm is based on a collection or population of candidate solutions to the optimization problem. The algorithm works in an iterative manner. At each iteration, three operators (selection, crossover and mutation) are applied to the entire population of designs. The iteration and the population values used for this paper are set to 100 and 500, respectively.

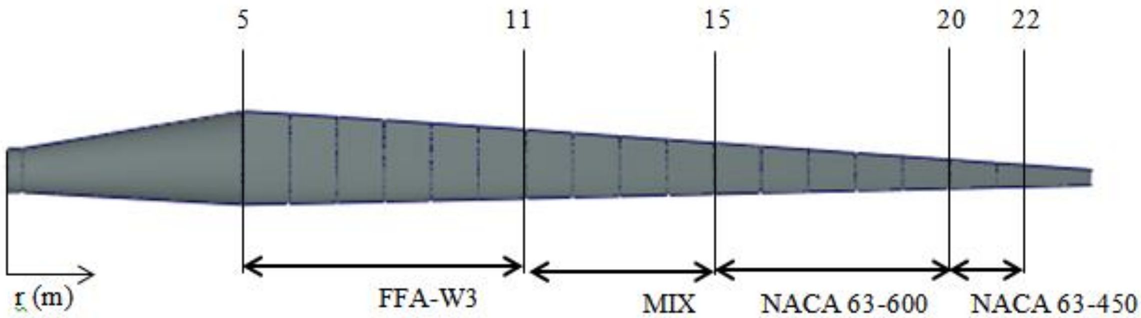


Fig. 1. Placement of the airfoils along the blade distribution

Table 1. Design variables of the problem

Notation	Design variables	Lower bounds	Upper bounds	Unit
x_1	coefficient (a)	-0.1	-0.09	-
x_2	coefficient (b)	2	3	-
x_3	coefficient (c)	27	33	-
x_4	coefficient (d)	-0.19	-0.13	-
x_5	coefficient (e)	-1	1	-
x_6	Placement of the FFA-W3	10	14	m
x_7	Placement of the MIX	14	16	m
x_8	Placement of the NACA 63-600	19	21	m
x_9	Placement of the NACA 63-450	21	22.5	m

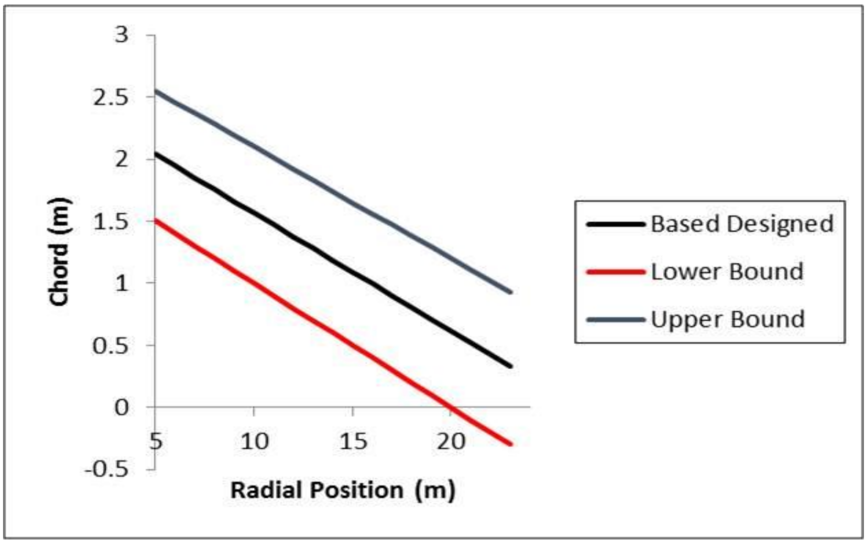


Fig. 2. Lower and upper limitation of chord distribution

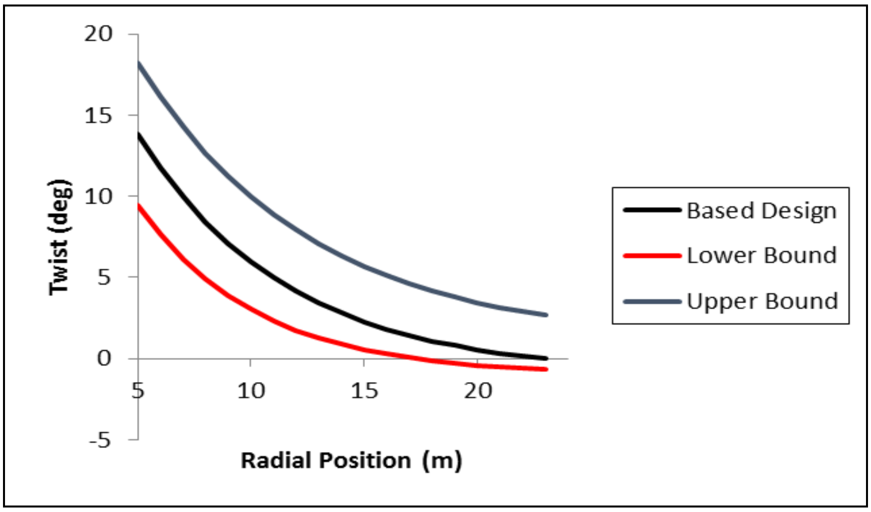


Fig. 3. Lower and upper limitation of twist distribution

2.3. Integration of GA Algorithm and BEM Code

The initial value of the design variables is inputted to the BEM code from the optimization program; then, the output power is evaluated as an output of the BEM code. The GA algorithm modifies the design variables in the input file and runs the BEM code again. This process continues until optimization convergence conditions are satisfied. The flowchart of this process is shown in Fig. 4.

3.Result and discussion

3.1. Validation

To validate the aerodynamic analysis of the wind turbine, the only available data are manufacturer's measurements that are reported in [19]. In order to show the accuracy of the BEM results, output power is compared with reported data in different wind speeds. Rated speed, through which maximum output power is determined, is one of the most important wind speeds, and for this turbine it is almost equal to 14 m/s. Figure 5 shows the comparison between BEM results and reported data for different wind speeds. According to the BEM results, there is a 5 % average error for output power.

3.2. Optimum design point

Unlike in most recent studies, the challenge that has been discovered in the aerodynamic analysis and optimization process here relates to the complexity of geometry. In spite of this difficulty, the results of optimization can satisfy the constraints well.

The optimum design variables are

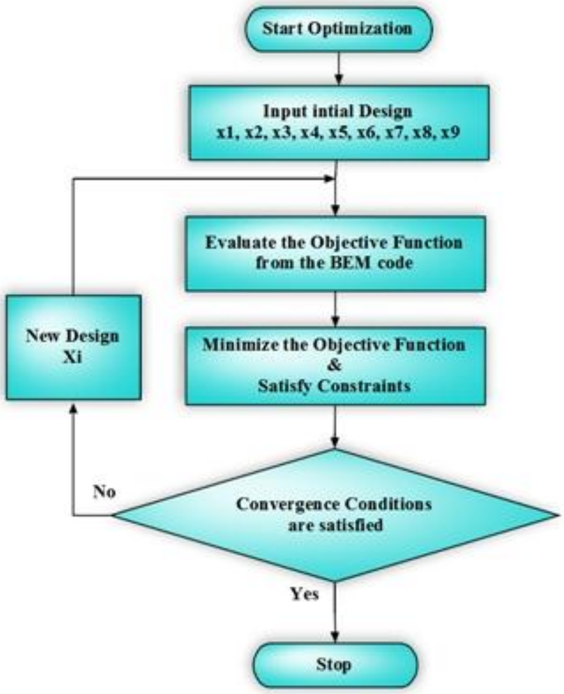


Fig. 4. Integrated diagram of GA and BEM code

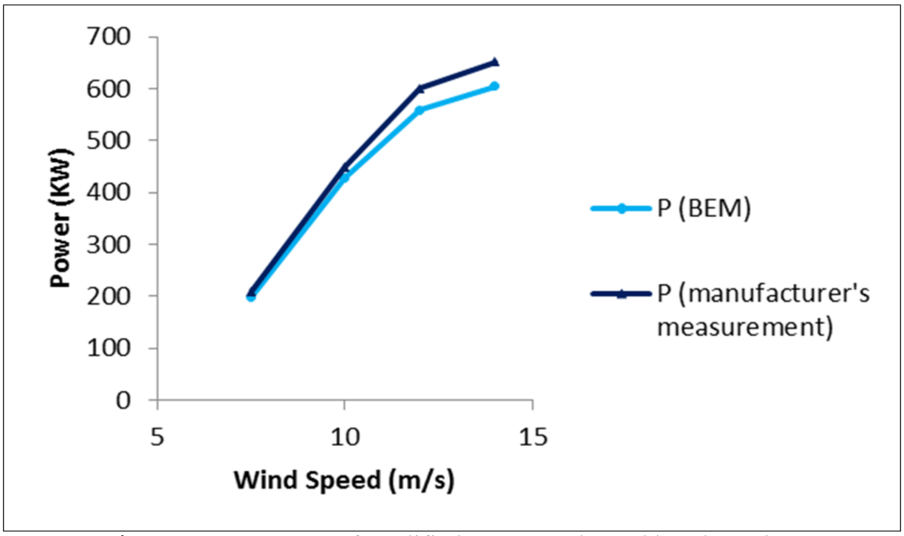


Fig. 5. Output power of modified BEM results and brochure data

demonstrated in Table 2. We can observe that most of the optimal design points are between their lower and upper bound. This table illustrates that the optimum values for chord distribution are -0.091969 and 2.463606, and for twist are 27.111365, -0.188605 and -0.319621. The optimal placements of airfoils (FFA-W3, MIX, NACA 63-600, NACA 63-450) are 13.2706, 14.9901, 20.7983 and 22.3966 m, respectively.

The optimal chord and twist distributions are shown in Figs. 6 and 7. Figure 6 shows that the chord distribution of the optimal design is almost identical to the preliminary design. According to these figures, the twist rate variation in the optimized shape is more than that of the chord rate along the blade. Figure 7 shows that the difference between the new design twist and the old one is higher near the root than in the rest of the blade length. Figure 8 illustrates the placement of the airfoils along the blade length.

Finally, the output power is improved by 10 % in the optimum design point compared to the base design at rated speed.

Table 2. Optimum values of design variables and objective function

Design variables	Lower bounds	Upper bounds	Optimal
x_1	-0.1	-0.09	-0.091969
x_2	2	3	2.463606
x_3	27	33	27.111365
x_4	-0.19	-0.13	-0.188605
x_5	-1	1	-0.319621
x_6	10	14	13.2706
x_7	14	16	14.9901
x_8	19	21	20.7983
x_9	21	22.5	22.3966

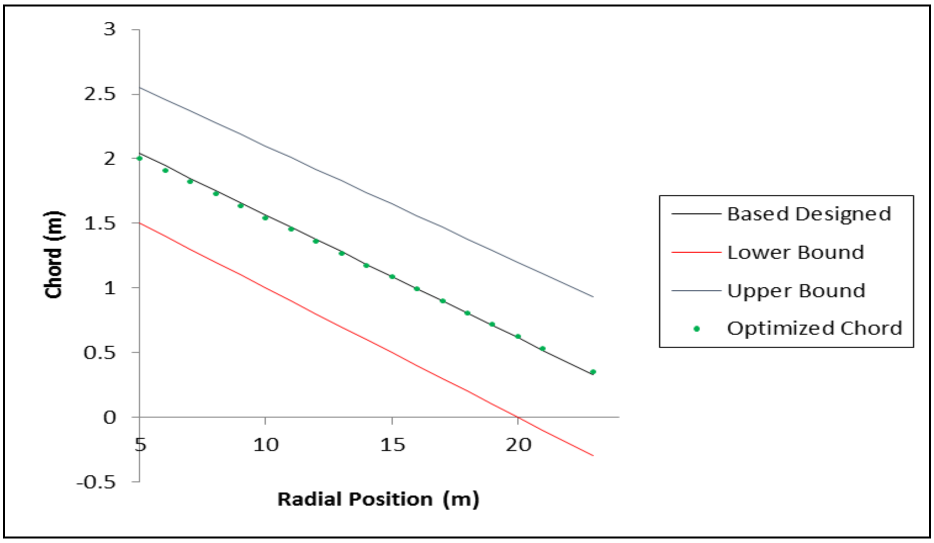


Fig. 6. Optimal chord rate

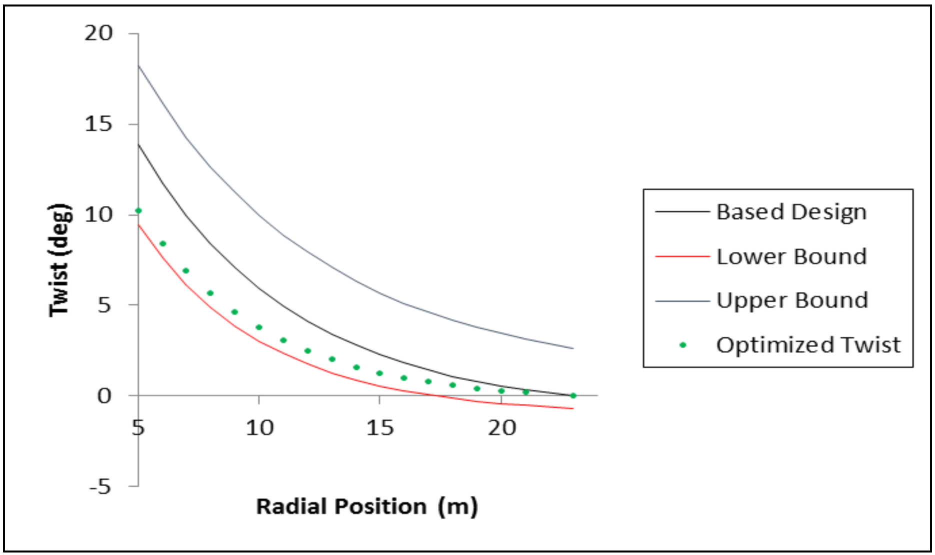


Fig. 7. Optimal twist rate

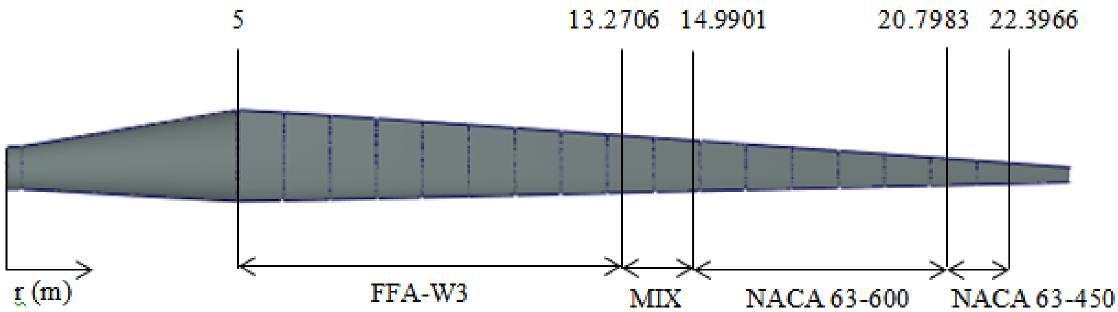


Fig. 8. Optimal placement of the airfoils along the blade length

4. Conclusion

The aerodynamic optimization of the wind turbine blade is investigated by integrated GA algorithm and modified BEM code. In order to improve output power in the same blade length, the GA algorithm was chosen as an optimization method, and for this purpose chord and twist distribution and placement of airfoils are considered as design variables. Aerodynamic analysis of the wind turbine was also carried out by the use of BEM theory, which is a well-known method in aerodynamics of rotary wings, especially in wind turbines. One of the challenges facing this study related to the aerodynamic analysis of the case study. Unlike most aerodynamic studies, which are of wind turbines with a simple geometry, this turbine has been designed with more complexity, so that it included different types of airfoils that were also twisted and tapered along the blade length. Never the less, the BEM code determined acceptable results compared to the manufacturer's measurements. Results show that by choosing optimized variables, output power can be increased by 10 % compares to the base design in a specific wind speed.

Reference

[1] Burton T., Sharpe D., Jenkins N., Bossanyi E.: Wind energy handbook, John Wiley & Sons, 2001.

[2] Abedi H.: Aerodynamic load on rotor blade, Master Thesis, Chalmers University of Technology, 2011.

[3] Hansen M. H., Gaunaa M., Madsen H. A.: A Beddoes-Leishman type dynamic stall model in state-space and indicial formulations. Risø-r-1354(en), Risø National Laboratory, Roskilde, Denmark, 2004.

[4] Tahani M., Moradi M.: Numerical investigation of airflow around a horizontal axis wind turbine, 13th International Conference on Clean Energy, Turkey, 2014.

[5] Glauert H.: The elements of aerofoil and airscrew theory, Cambridge University Press, 1948.

[6] Vaz J. *et al.*: An extension of BEM method applied to horizontal-axis wind turbine design, Renewable Energy, 36, pp. 1734-1740, 2011.

[7] Dai J.C. *et al.*: Aerodynamic loads calculation and analysis for large scale wind turbine based on combining BEM modified theory with dynamic stall model, Renewable Energy, 36:3, pp. 1095–1104, 2011.

[8] Lanzafame R., Messina M.: BEM theory: How to take into account the radial flow inside of a 1-D numerical code, Renewable Energy, 39:1, pp. 440–446, 2012.

[9] Kim B. *et al.*: Aerodynamic design and performance analysis of multi-MW class wind turbine blade, Mechanical Science and Technology, 25:8, pp.1995-2002, 2011.

[10] Yang H. *et al.*: Prediction of the wind turbine performance by using BEM with airfoil data extracted from CFD, Renewable Energy, In print, 2014.

[11] Monteiro J.P. *et al.*: Wind tunnel testing of a horizontal axis wind turbine rotor and comparison with simulations from two blade element momentum codes, Wind Engineering and Industrial Aerodynamics, 123, pp. 99-106, 2013.

[12] Fuglsang P., Madsen H.A.: Optimization method for wind turbine rotors, Wind Engineering and Industrial Aerodynamics, 80, pp. 191-206, 1999.

[13] Liu X., Wang L., Tang X.: Optimized linearization of chord and twist angle profiles for fixed-pitch fixed-speed wind turbine blades, Renewable Energy, 57, pp. 111-119, 2013.

[14] Ceyhan O.: Aerodynamic design and optimization of horizontal axis wind turbines by using BEM theory and genetic algorithm. Master Thesis. Aerospace Engineering Department, METU: Ankara; 2008.

[15] Polat O., Tuncer I.H.: Aerodynamic shape optimization of wind turbine blades using a parallel genetic algorithm, Procedia Engineering, 61, pp. 28-31, 2013.

[16] Liu X., Chen Y., Ye Z.: Optimization model for rotor blades of horizontal axis wind turbines, Frontiers of Mechanical Engineering in China, 2:4, pp. 483-488, 2007.

[17] Mendez J., Greiner D.: Wind blade chord and twist angle optimization by using genetic algorithms. In: Proceedings of the fifth international conference on engineering computational technology, 2006.

[18] Hansen M.O.L: Aerodynamics of wind turbine, second edition, Earthscan Publication, 2008.

[19] General specification 660 kW variable slip wind turbine, Item no.: 943111.R4, Denmark.