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AERODYNAMIC SHAPE OPTIMIZATION OF WIND TURBINE BLADES USING A PARALEL GENETIC ALGORITHM

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ABSTRACT

An aerodynamic shape optimization methodology based on Genetic Algorithm is developed for rotor blades of horizontal axis wind turbines. Optimization studies are performed for the maximization of power production at a specific wind speed, rotor speed and rotor diameter. Power calculations for the rotors are carried out with the tool based on Blade Element Momentum theory. The potential flow solver with a boundary layer model, XFOIL, provides necessary sectional aerodynamic loads. The chord length distribution, the twist distribution and the blade profiles at root, mid and tip regions of the blade are taken as design variables. Blade sections are defined by the NACA four digit airfoil series. The power calculations required by Genetic Algorithm, which is inherently parallel, are performed in a parallel computing environment. Message Passage Interface library is employed in the parallel computations. After validating the Blade Element Momentum tool and XFOIL against the wind turbine and airfoil test data, optimization studies are performed on NordTank wind turbine. Finally, design optimization is carried out for a 1MW wind turbine.

INTRODUCTION

The wind turbine technology has been significantly growing due to the world's primary energy needs and the potential in wind energy. Being one of the promising renewable energy sources, harnessing of wind energy has gained importance and the deployment of wind turbines in the world has been steadily increasing. In recent years people has chasen after wind turbines being fascinating in a way of capturing invisible force of wind which is clean and free. A huge rise in global installed capacity has taken place. Annual wind power installations in the European Union Heads of State have increased from 3.2 GW in 2000 to 11.9 GW in 2012 [EWEA,2013]. It is aimed to obtain %20 of energy from renewables by 2020 and 33% by 2030 [2]. Also in Turkey, increase in usage of wind energy has been achieved with an installed wind power which has been reached to 2300 MW by the end of 2012 [EWEA,2012].

Wind turbines convert the kinetic energy of wind into electrical or mechanical energy. They are mainly categorized as vertical axis and horizontal axis wind turbines based on the axis of rotation. Vertical Axis Wind Turbines (VAWT) are relatively modest in power generation. Their main advantage is the simplicity in design and construction with housing the generator and gearbox at ground level. On the other hand, they achieve lower power capacity compared to Horizontal Axis Wind Turbines (HAWT). Consequently, HAWT are utilized more extensively for electricity generation and this type of wind turbines is within the scope of the conducted study. Typical HAWT are composed of rotor, rotor shafts

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and bearings, gearbox, control system, generator, yaw system and tower. A rotor is the main component of a wind turbine which converts the kinetic energy of the wind into the mechanical energy and it is directly related to the power capacity of the wind turbine. Rotor blades are airfoil-shaped bodies which create lift and drag. These forces are decomposed into tangential and thrust forces. Tangential forces acting on blades create rotation torque which acts in the power generation. The geometrical shape of a rotor blade is essential in terms of the mechanical power captured from the wind and the main parameters dominating are; blade section profiles, chord length distribution and twist distribution.

Wind turbine design is a multi-disciplinary topic which involves aerodynamics, structures, electricity, noise, cost and manufacturing. Among all the other aspects, aerodynamic shape optimization of the turbine blades is one of the main research fields, which is relevant to the power production of a wind turbine. In this study, a new methodology is developed for the aerodynamic optimization of HAWT rotor blades [Ceyhan,2008] [Polat,2011], which is based on Genetic Algorithm (GA) [Carroll,1996] and Blade Element Momentum theory (BEM). The aerodynamic shape optimization of the blades is done at the prescribed wind speed, rotor speed, rotor diameter and number of blades. The BEM tool calculates the objective function, which is the power production of the turbine. The open source potential flow solver, XFOIL [Drela,1989], supplies necessary aerodynamic data including viscous effects at the blade sections for given flow conditions. Optimization variables are selected as the sectional chord length, the sectional twist and the blade profiles at root, mid and tip regions of the blade. The blade sections are defined by the NACA four digit airfoil series and are represented by design variables such as geometrical properties; maximum thickness, maximum camber position and maximum camber. Utilizing the GA the computations are performed in a parallel computing environment with 8 nodes, where each node is equipped with 64 cores in 2.3 GHz 4 AMD Opteron CPUs and connected to a 10 Gb/s Ethernet network. Firstly, validation studies for the aerodynamic analysis tools are performed with the airfoils and the wind turbines having experimental data. Then, optimization studies are performed on the NordTank [Bak,1999][Hansen,2000] wind turbine rotor. Finally, a wind turbine having 1 MW power capacity is designed.

METHODOLOGY

In this study, Genetic Algorithm is coupled with the Blade Element Momentum tool and the Potential Flow Solver, XFOIL, in order to develop a design optimization methodology. The BEM tool calculates the objective function, which refers to the power generation, for optimization process. XFOIL supplies necessary aerodynamic data including viscous effects at the blade sections for given flow conditions. To start with, utilized tools for airfoil and wind turbine aerodynamic analyses are validated against the available test results. Then, they are embedded to the GA optimization tool.

Airfoil Aerodynamic Evaluations

The airfoil data that the BEM tool necessitates are obtained with XFOIL, which is used for the design and analysis of airfoils at subsonic flows. It has the capability of calculating both inviscid and viscous flows. The linear-vorticity stream function Panel Method is implemented for inviscid flow calculations. Airfoil flowfield is constructed by the superposition of a freestream flow, a vortex sheet on the airfoil surface and a source sheet on the airfoil surface and wake. The Kutta condition is used. In order to obtain viscous solutions a model is built up on this potential flow theory. The friction drag on the airfoil is analyzed with modeling boundary layer and wake with a two equation lagged dissipation integral boundary layer formulation. It is based on the velocity distribution derived by the Panel Method. The thickness of the boundary layer changes with Reynolds number. Additionally, to compute the viscous and inviscid coupling the envelope type transition formulation using a global Newton method is implemented. The turbulence level of the flow is supplied to the tool and the transition from laminar flow to turbulent flow is modeled.

In current study, XFOIL is coupled with BEM tool and provides the airfoil aerodynamic data at each section for corresponding angle of attack and Reynolds number. NACA four and five digit airfoil series are defined parametrically in XFOIL. Thus, there is no need to provide the coordinates of NACA four digit airfoil series which is employed throughout the optimization process. Viscous flow solutions are obtained. XFOIL has an ability to mirror compressibility effects by integrated Karman-Tsien correction. However, incompressible flow solutions are obtained since wind turbines are subjected to low speeds and also the BEM theory is constructed on the assumption of incompressible flow.

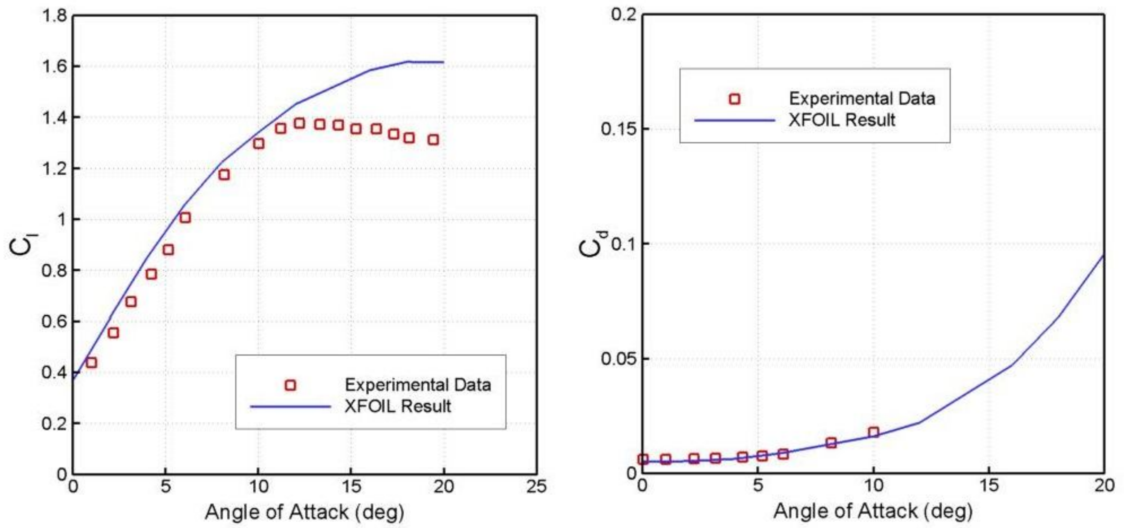

Figure 1: *Aerodynamic Coefficients of NACA63418 at Re=3x10^6*

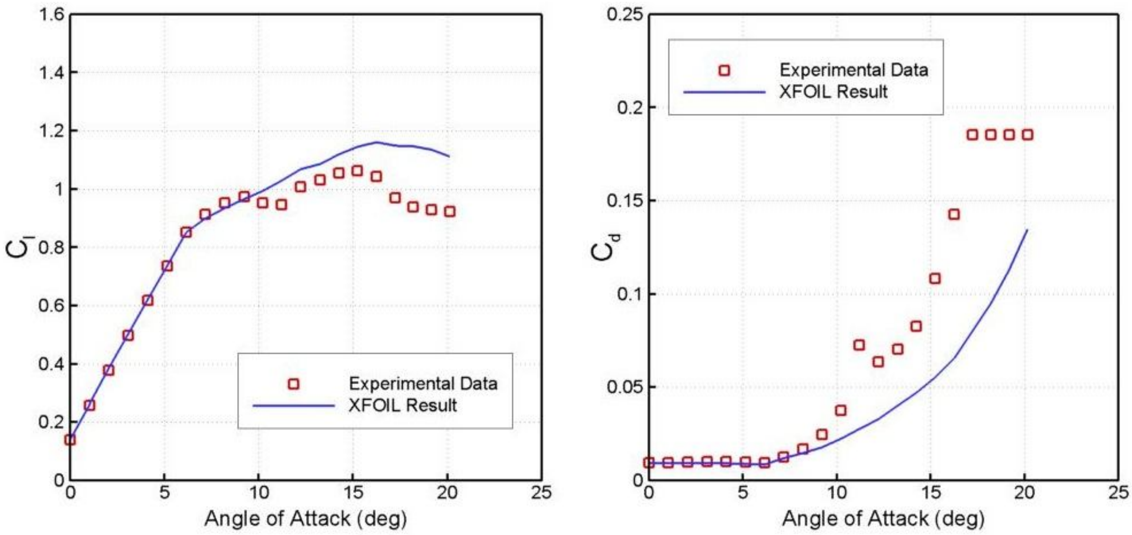

Figure 2: *Aerodynamic Coefficients of S809 at Re=10^6*

In order to check the validity of the aerodynamic data gathered from the potential flow solver, NACA63418 and S809 airfoils are analyzed and the results are compared with experimental data [Abbott,1959] [Sorense,2001] as shown in Figure 1 and Figure 2. According to the comparisons, it is assessed that XFOIL gives satisfactory results for small angle of attacks in the attached flow regime. However, the prediction of stall region is poor. It is an expected result since the prediction of stall behavior is challenging even though with higher order methods. Usage of XFOIL in the optimization tool is feasible considering the short computation time. The optimization tool is built up for the first phase of design and recalculations on the designed turbines can be done with higher order methods which require more computation time.

Wind Turbine Performance Evaluations

Wind turbines extract mechanical energy from the kinetic energy of the wind and there is a theoretical limit for this extraction. The Betz limit, depicted in Figure 3, stands for the ideal case. If rotational effects are added, energy extraction will be lower than the case without rotation. A wind turbine rotor causes the flow behind rotate in the opposite direction from that of the blades. Thus, the rotational kinetic energy in the wake results in less power extraction.

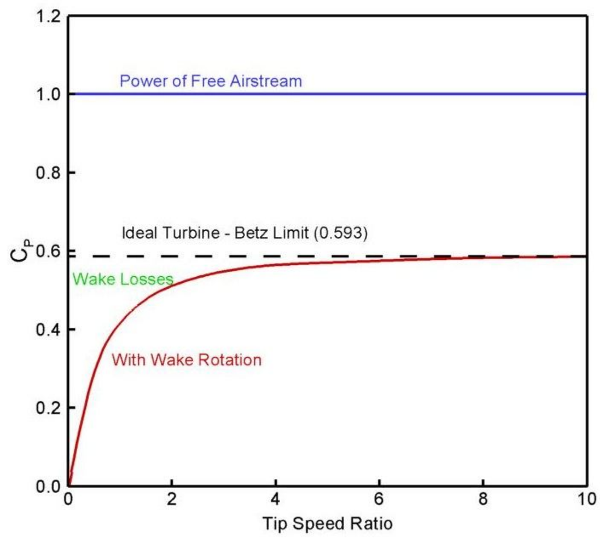

Figure 3: *Power Coefficient of an Ideal Wind Turbine with and without Wake Rotation*

The Blade Element Momentum theory is a widely used method to perform aerodynamic analyses of rotors. In this method, the blade is divided into elements and each element is examined independently from each other by using corresponding airfoil profile aerodynamic data.

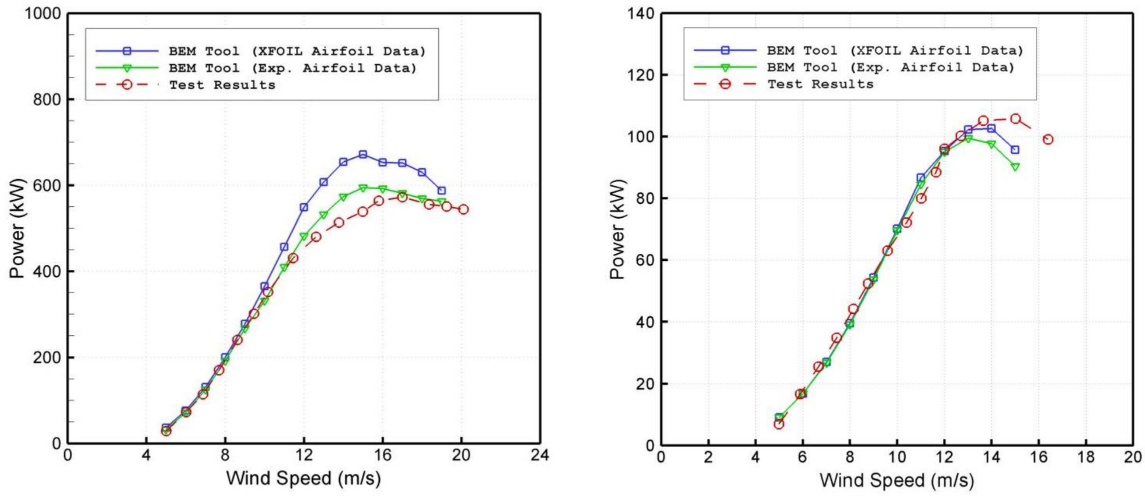

Figure 4: *Power Curves Comparison for NordTank (leftside) and Risoe Wind Turbines*

The BEM tool, which evaluates the aerodynamic performance, is the key point of the optimization process since it is the objective function calculator. In order to decide whether the calculation method is appropriate or not for design process, the validation studies are conducted. The power estimations of Risoe [Schepers,2002] and NordTank are well-matched with the experiment results up to the wind speeds at which the area of stall region increases as depicted in Figure 4. Employing the XFOIL data instead of the experimental data do not make considerable difference up to high wind speeds, whereas at the stall region results alter. This drawback is not significant in terms of the usage of these tools in design optimization process since the rotor blades are never designed at the stall region. In accordance with all of these facts, the accuracy of the aerodynamic performance calculation method is sufficient and it is proper to use it in the optimization algorithm.

Genetic Algorithm Overview

The Genetic Algorithm is a stochastic optimization method that is inspired by the biological evaluation process. Components of a GA are encoding technique, initialization procedure, evaluation function, selection of parents and genetic operators such as mutation, crossover and elitism. Individuals are composed of chromosomes which carry the properties of individuals as variables of the problem. Chromosomes are represented with different encoding types like binary coding, permutation encoding, value encoding, etc. The evolution starts with a population that is created randomly. Thus, an initial condition is not required. The objective function is calculated for each individual. According to the values of the objective function, two individuals are selected and the crossover takes place with recombining the genetic material from the two parents. The mutation occurs by causing a change in the chromosome pattern to ensure the diversity of the population. The GA operates on the principle of survival of the best. The elitism refers to the process that the best solution survives to the next generation and it increases the performance of the optimization process by preventing the loss of the best individual. A new generation is created and the same procedure is carried out until a satisfactory solution is found or until the maximum generation limit is reached.

In this study, the GA optimization tool developed by D. Carroll is employed. Binary coding, in which the variables are discretized into the number of possibilities, is applied. Thus, the chromosome length is related to the number of possibilities in the binary format. Tournament selection for choosing random pairs for mating is implemented. Fitter individual in each pair mates and one child which has mixed chromosomes of the two parents as a result of crossover is created. Two types of crossover, single-point and uniform, are applied. In the single-point crossover, the chromosome set of one parent overwrites the chromosome set of the other parent at a randomly chosen crossover point. On the other hand, in the uniform crossover any combination of chromosome sets of each parent can be obtained. Jump and creep mutations are included in order to ensure the diversity of the population. A randomly picked chromosome is placed in the chromosome set with the jump mutation and it is independent from the parent values. In the creep mutation, a randomly picked chromosome is kept between the variables values of parents. The elitism operator replicates the best individual to the next generation.

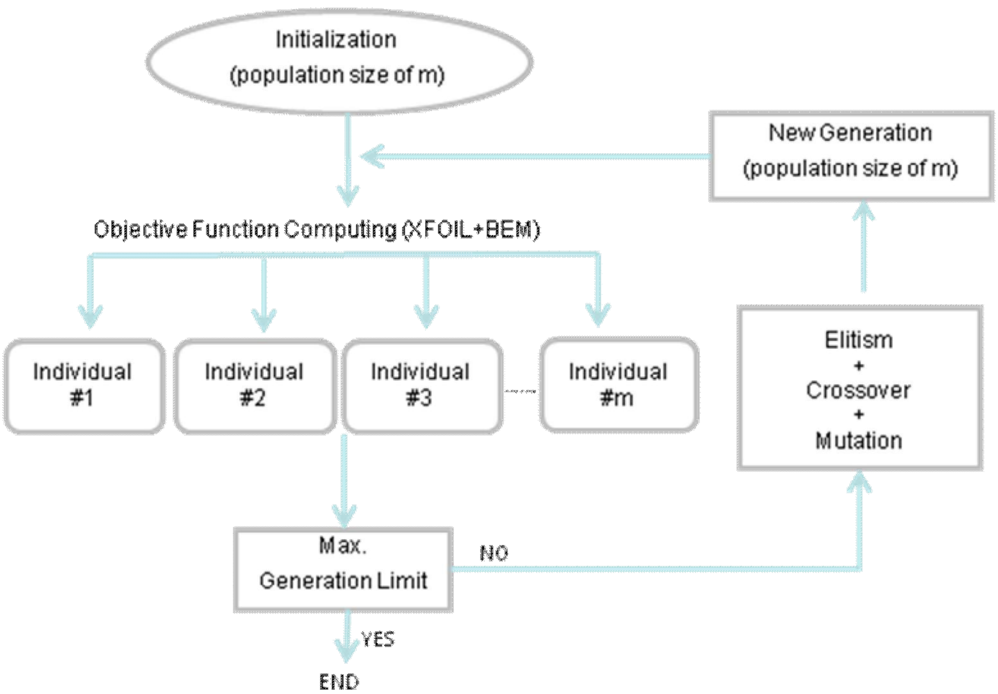

Figure 5: *Genetic Algorithm Optimization Process*

The Genetic Algorithm optimization process is summarized in Figure 5. The objective of the optimization process is maximizing the generated power which is computed with BEM and XFOIL calculations. After the generation of the population with the required size, the power calculations are conducted for each individual. These calculations are independent from each other. Thus, the process is inherently parallel and it is feasible to apply a parallel-programming in order to reduce the runtime for solving a problem and also increase the size of the problem that can be solved. In this study, Message Passing Interface (openMPI) technique is applied and data is passed between the processes in a distributed memory environment. The number of required cores is defined by the population size.

The chord length distribution, the twist distribution and the blade profiles at root, mid and tip sections are the design variables of the optimization process. There are two approaches used for defining the chord length and twist distributions. Firstly, studies on the NordTank wind turbine are done considering the chord length and twist at each blade element. Thus, continuity in the spanwise is not taken into account. As the second approach, Bezier spline is used and consequently, continuous distributions are obtained. Blade profiles are selected from NACA four digit airfoil series. The properties such as the maximum camber, the maximum camber position and the thickness are taken as the design variables. Totally 1024 different NACA four digit airfoils are used in the design process and the ranges for the airfoil properties considered are as follows:

- Maximum camber range from 1% to 8% (with increment of 1%)
- Maximum camber location range from 10% to 80% (with increment of 10%)
- Maximum thickness range from 10% to 40% (with increment of 2%)

OPTIMIZATION APPLICATIONS

Optimization studies for the NordTank Wind Turbine

Validating the aerodynamic analysis tools, an optimization study is then conducted on the baseline NordTank turbine. Firstly, only the blade profiles are assigned as the design variables. The variation of power coefficient during the optimization process and the selected NACA airfoils for the blade tip, mid and root sections are shown in Figure 6. The optimization study is performed at 10 m/s and the number of design variables is 9. Within the scope of this study, constraints regarding the thickness of the airfoils are not prescribed. Because of this reason some unusual airfoil profiles especially for the root region of the blade are selected.

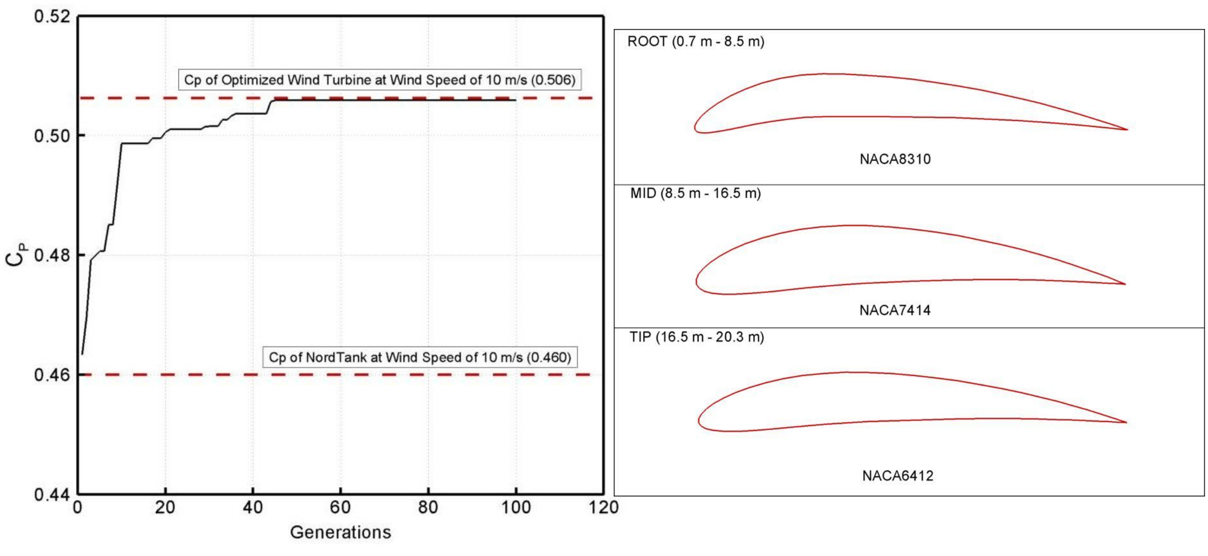

Figure 6: *Power Coefficient Variation and Selected Airfoils (Case 1)*

For the second case, the chord length and twist distributions and the blade profiles are employed as the design variables and the total number of design variables is reached to 43. Wind speed is taken as 10 m/s. NACA four digit airfoil profiles are chosen for different blade regions as shown in Figure 7. The chord length and twist distributions are selected for each blade element (totally 17 blade elements). Limits at each blade element assigned for the chord length and twist distributions as the %25 greater and the %25 lower than the original value as depicted in Figure 8. Thus, minor changes in the chord length and twist distributions are allowed in order not to diverge from the original problem. The chord length values found by optimization process are reached to the prescribed limits due to the fact that the aerodynamic forces are directly proportional to the area of the blade element. The optimization achieves about 10% increase in the power production.

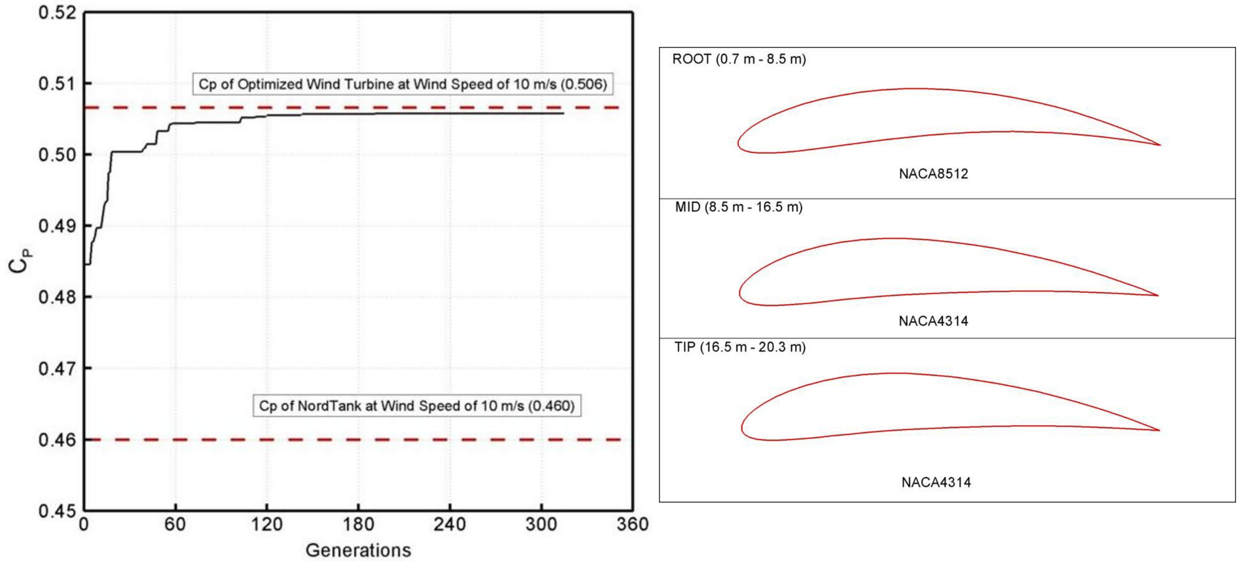

Figure 7: *Power Coefficient Variation and Selected Airfoils (Case 2)*

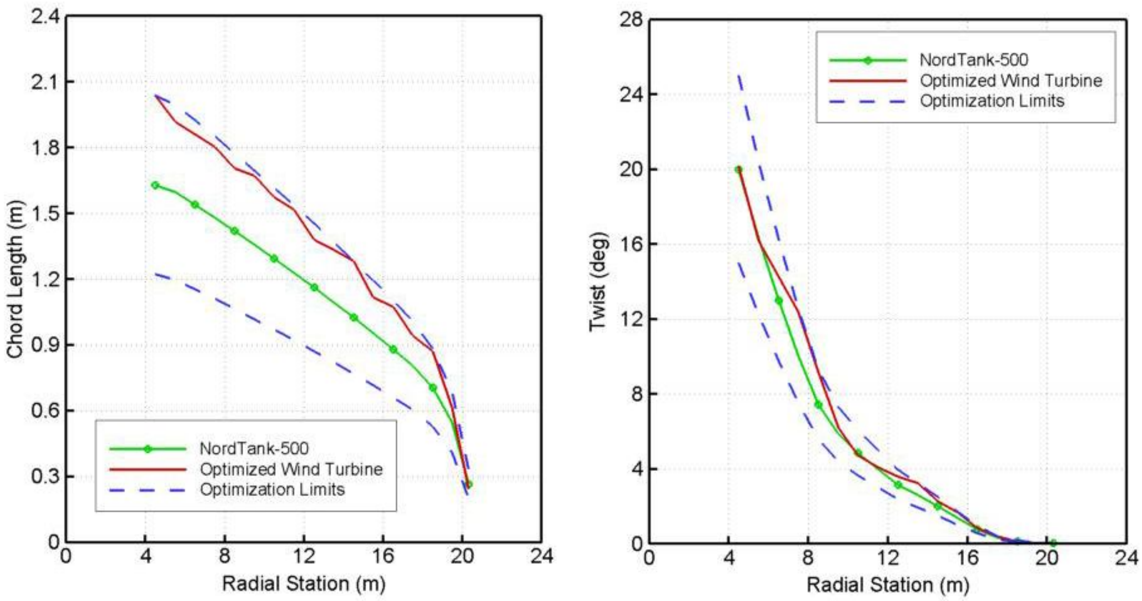

Figure 8: *The Chord Length and Twist Distributions (Case 2)*

Employing chord and twist values at each blade element as design variables results in distributions that are not continuous. Thus, the distributions are not realistic. To get rid of this problem, chord and twist distributions are defined by Bezier spline for the third optimization case. Optimization is done for wind speed of 10 m/s and totally, 15 design variables are taken into account. The selected airfoils, the variation of power coefficient and the chord and twist distributions are given in Figure 9 and Figure 10.

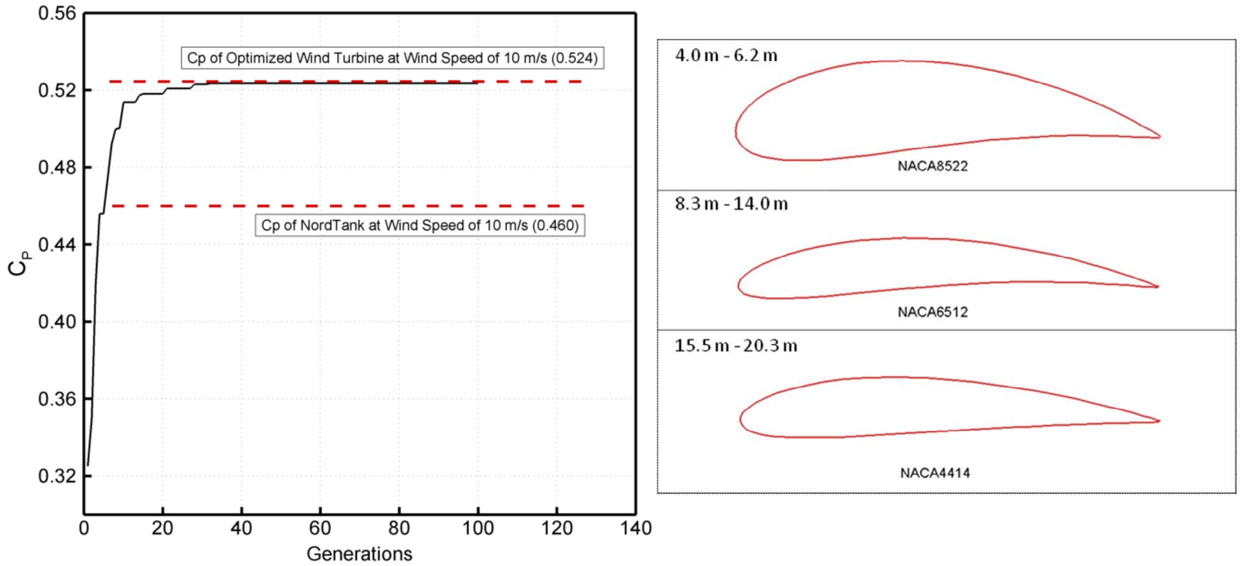

Figure 9: *Power Coefficient Variation and Selected Airfoils (Case 3)*

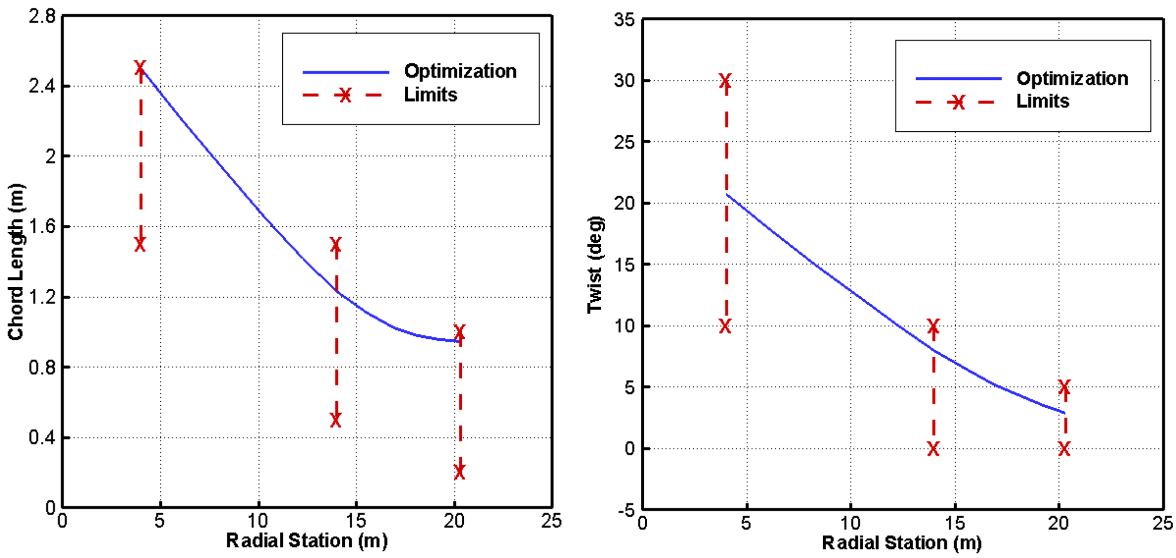

Figure 10: *The Chord Length and Twist Distributions (Case 3)*

Parallelization of the utilized optimization tool makes the process more feasible to perform. Different population sizes are tried out in order to assess the effects of parallelization. As shown in Figure 11, optimization studies are carried out for population sizes of 5, 10, 20 and 40. For each case totally 4000 individuals are created. For example, for the case with 5 population size 800 generations are created whereas for the one with 40 population size 100 generations are formed. There is randomness in the

GA optimization process sometimes causing unpredictable results such as the case with smaller population size can reach to a better solution in fewer generations. For this case, the one having population size of 5 is reached to a better solution in fewer generations compared to one with 10 population size. On the other hand, the ones having population sizes of 20 and 40 are converged to a better solution with fewer generations as expected. There is small amount of data transferring between the processors making the computation time for each generation nearly the same independently from the population size. Considering the computation time for solving a generation for each case is nearly equal, using greater population size is advantageous in terms of reaching the best solution in a smaller time period. Thus, it is the benefit of the parallelization.

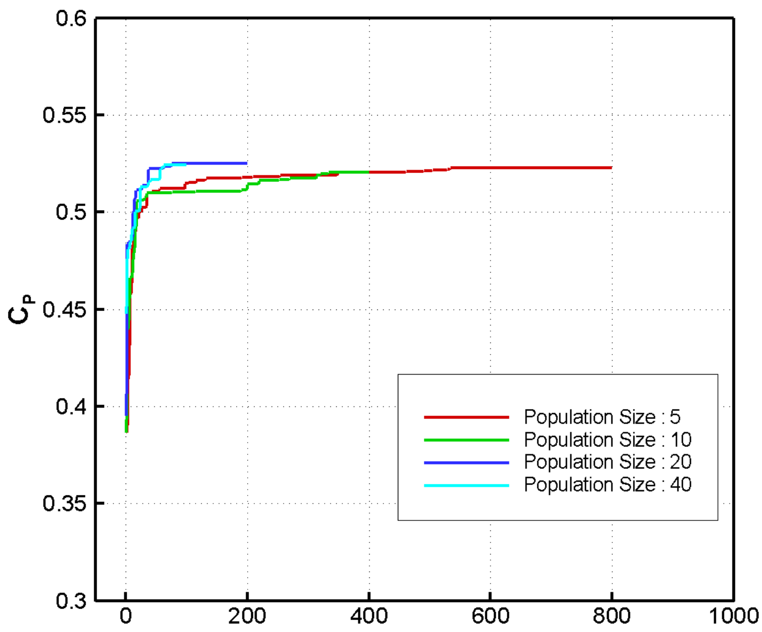

Figure 11: *Comparison for Different Population Sizes*

Design Optimization of a 1MW Wind Turbine

In this section, the design optimization for a 1 MW wind turbine is explained. Firstly, competitor study is conducted in order to decide on the number of blades, the rotor diameter, the rotor speed and the nominal wind speed. The design optimization process is carried out for a wind turbine having these settled properties. The chord length and twist distributions are defined by a Bezier spline composed of two piecewise cubic Bezier curves. In this method, chord length and twist values at root, mid and tip of the blade are design variables and these values are calculated for the rest of the blade elements. Hence, the distributions are continuous curves and the designs are more realistic.

The rotor diameter is the main feature of a wind turbine that dominates power generation. An increase in the swept area of the rotor leads to higher capture of the wind energy. However, there are some drawbacks on diameters such that weight increases with longer blades. In addition, there is a restriction in the tip speed considering aerodynamic noise considerations. For the design optimization study, the rotor diameter is decided based on the competitor study. In Figure 12, rotor sizes and corresponding power capacities of 1300 commercial wind turbines are shown [The Wind Power website, 2011]. A trend line is depicted that relates the rotor diameter and the power. According to this line, a wind turbine having a rotor diameter of 58 m is expected to achieve 1 MW power.

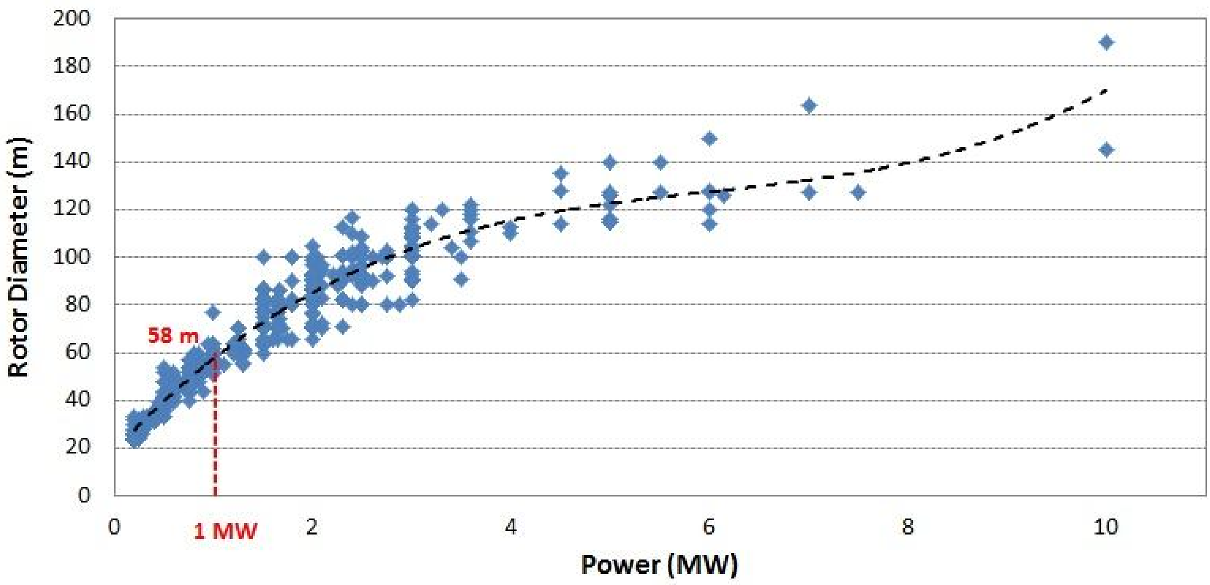

Figure 12: *Rotor Diameter and Rated Power Relation*

The technical specifications of some commercial wind turbines having power capacities between 0.6 MW and 1.25 MW are tabulated in Table 1. Three-blade configuration is decided in accordance with its general acceptance in the wind turbine industry. Among competitors, minimum nominal wind speed is 12 m/s and this value is selected in order to force the optimization process. The rotor diameter of 50 m is selected as smaller than the value found from the trend line and the commercial wind turbines. Tip speed is a decisive factor in aerodynamic noise generation and it is advised to restrict the tip speed within the limit of 65 m/s [Mathew, 2006]. The rotor speed is determined based on the tip speed considerations and the rotor diameter. Hence, the rotor speed comes out to be 25 rpm.

Table 1: *Competitor Study*

	Suzlon-52	Enercon-E53	Vestas-V52	Enercon-E44	Dewind-D6	Suzlon-S66
Rated Power (MW)	0.6	0.8	0.85	0.9	1.0	1.25
Rotor Diameter (m)	52	53	52	44	62	66
Rotor Speed (rpm)	24	12-28	26	12-34	20	13-20
Tip Speed (m/s)	65	78 (max.)	71	78 (max.)	65	69 (max.)
Number of Blades	3	3	3	3	3	3
Nom. Wind Speed (m/s)	13	13	16	16	12	14

A 1 MW wind turbine blade composed of NACA four digit airfoil profiles is designed. The selected airfoils for different regions of the blade and the blade geometry are given in Figure 13.

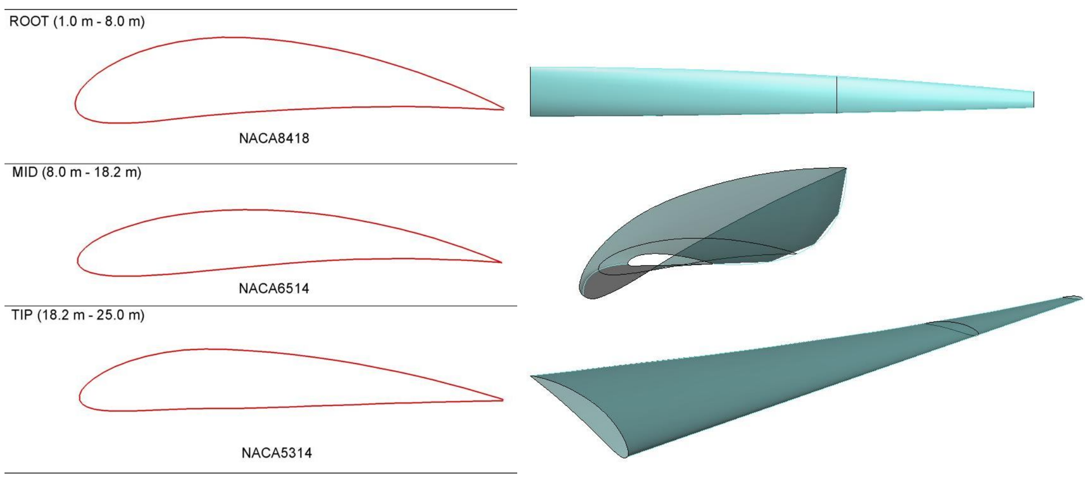

Figure 13: *Selected Airfoils and Blade Geometry*

The chord and twist distributions defined by Bezier splines are depicted in Figure 14. As it can be observed, especially the root parts of the blades are highly twisted. The reason for this that, at root region the tangential velocity is lower. The wind is coming from the lower side of the airfoils and the airfoil profiles are turned into the wind direction which decreases the angle of attack and thus, prevents stall.

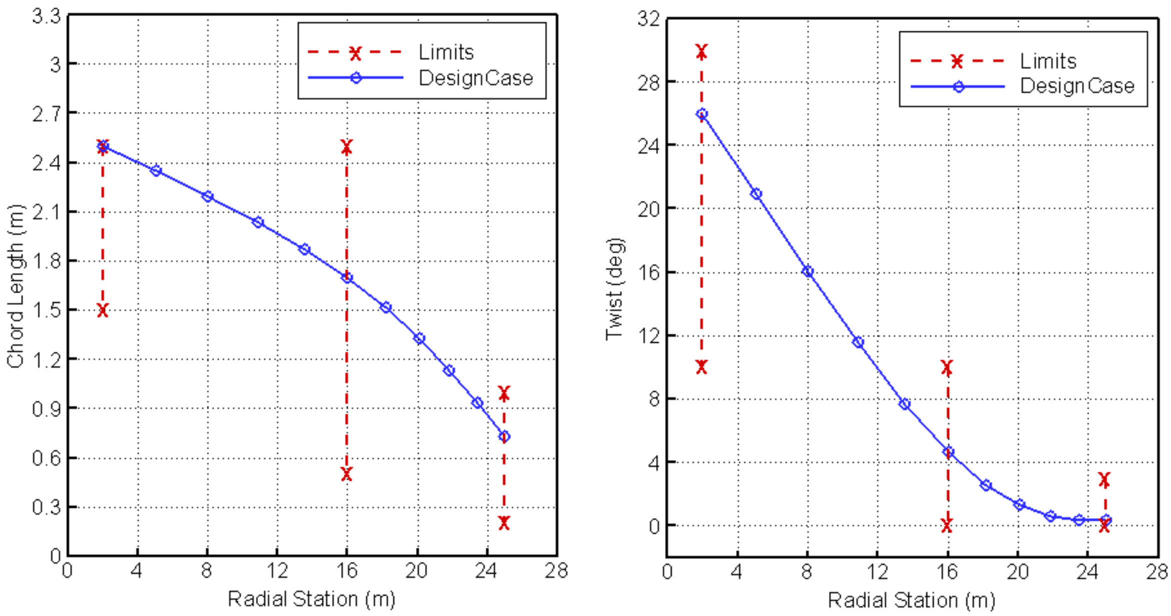

Figure 14: *The Chord Length and Twist Distributions (1 MW)*

CONCLUSION

In this study, an aerodynamic design optimization tool for horizontal axis wind turbine rotor blades based on Genetic Algorithm is developed. The aerodynamic shape optimization of the blades is done at the prescribed wind speed, rotor speed, rotor diameter and number of blades. The design variables are the chord length, twist and airfoil profiles. NACA four digit airfoil series are selected for the tip, mid and root regions of the blade. The objective function calculations are performed with the developed BEM tool and the open source potential flow solver, XFOIL. The BEM tool is employed to find the power generation. XFOIL provides necessary airfoil aerodynamic data at the required angle of attack and Reynolds number. With its integrated boundary layer solver, XFOIL has the capability of modeling viscous effects. Firstly, validation studies on the BEM tool and XFOIL are conducted against the experimental data of the wind turbines and airfoils. Satisfactory results lead to the next step which is the optimization applications on the existing wind turbines, Nordtank. Finally, a design optimization study is carried out. The chord length and twist distributions are obtained by the Bezier splines composed of two cubic Bezier curves in order to achieve a smooth variation along the span. The obtained results are satisfactory and are evidence of the success of the tool. The optimization tool developed in this study may further be improved. Rotor diameter may be included among the design variables. Minimum blade thickness at the root section may be imposed as a constraint. Computational Fluid Dynamics (CFD) methods can be used to analyze the designed wind turbines.

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