10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2019-063**
18-20 September 2019 - METU, Ankara TURKEY

AERODYNAMIC OPTIMIZATION OF HORIZONTAL AXIS WIND TURBINE ROTOR BY USING BEM, CST METHOD AND GENETIC ALGORITHM

Keriman Oğuz[1]
ASELSAN
Ankara, Turkey

Nilay Sezer-Uzol[2]
METU
Ankara, Turkey

ABSTRACT

In this study, it is aimed to perform aerodynamic design and optimization of horizontal axis wind turbine (HAWT) rotor airfoils and blades. The Class-Shape Transformation (CST) method and the Parametric Section (PARSEC) method are used for the airfoil geometry representations. The aerodynamic data is obtained by a panel solver, XFOIL. Genetic Algorithm (GA) is used for the optimization of new airfoil geometries. Performance comparisons of CST and PARSEC parameterization methods are presented by results of S809 airfoil optimization. For rotor power calculations, the Blade Element-Momentum (BEM) theory is used. Validation studies for BEM are performed for the selected test rotors of NREL Phase III and NREL Phase VI. Lastly, new wind turbine rotor blades are designed by using the optimized airfoil geometries with CST and PARSEC methods.

INTRODUCTION

Wind turbine design is an interdisciplinary optimization study covering mainly aerodynamic, mechanical and electrical design fields. In aerodynamic design of rotor, blade geometry is an essential optimization area since it is directly related the flow dynamics and thus turbine power production. When it comes to airfoil geometry optimization, the primary effort is put on representing airfoil geometries with minimum number of parameters when having ability to make the local modifications properly as well as efficiently.

There are numerous considerable researches conducted in METU about wind turbine blade design and optimization. Firstly, Ceyhan et al., 2008-2009, optimized a HAWT blade to harvest maximum power for different airfoil sections, chord and twist distributions by using developed BEM tool and GA [Ceyhan, 2008-2009]. Then, Sağol et al., 2009-2010, designed and optimized HAWT blades for a specific wind site aiming minimum cost of energy (CoE) again by utilizing BEM and GA [Sağol, 2009-2010]. After that, Polat et al., 2011-2013, studied aerodynamic geometry optimization methodology for HAWT blades in order to get maximum power with BEM and GA by defining new airfoil profiles with Bezier curves at three different sections of the blade [Polat, 2011-2013]. Moreover, Polat et al., 2014, investigated design of HAWT blades and airfoils as well as helicopters' comparatively [Polat, 2014]. Elfarra et al.,

[1] MS Graduate Student, Dept. of Aerospace Engineering in METU, Systems Design Engineer at ASELSAN,
E-mail: kkarakas@aselsan.com.tr
[2] Assoc. Prof. Dr., Dept. of Aerospace Engineering in METU, METUWIND in METU, E-mail: nuzol@metu.edu.tr

2010-2015, examined blade tip geometry, twist angle distribution and pitch angle optimization for a HAWT blade by using CFD, GA and artificial neural networks [Elfarra, 2010-2015].

There are many recent studies in the literature about airfoil and blade optimization approaches. Mukesh et al., 2013, formulated an airfoil optimization process with PARSEC and validated this method by optimizing NACA 2411 airfoil geometry and performing wind tunnel tests for optimized airfoil [Mukesh, 2013]. Vecchiaa et al., 2014, proposed an airfoil geometry design procedure based on the PARSEC parameterization for airfoil shape descriptions and special GA optimization method coupled with Nash Game Theory equilibrium solutions [Vecchiaa, 2014]. Engfer et al., 2015, presented a blade design method using CST and B-splines representations for airfoils having low CoE optimization objective with high annual energy production (AEP) [Engfer, 2015]. Okrent, 2017, studied on optimization of airfoil geometry for a UAV with GA using NACA 4 digit airfoils, CST parameterized airfoil families and PARSEC parameterized airfoil families [Okrent, 2017].

The objectives of this study are to optimize aerodynamically airfoil geometries with Class-Shape Transformation (CST) and Parametric Section (PARSEC) methods and to design of HAWT blades with these optimized airfoils. Implementation steps can be summarized as follows: Firstly, CST and PARSEC Methods are used to represent baseline sectional airfoil geometries. Then, Genetic Algorithm (GA) is used to optimize the airfoil profiles for specific blade sections for maximum C_l/C_d objective. Their aerodynamic data is simultaneously obtained by a panel solver software, XFOIL. Finally, Blade Element-Momentum (BEM) Theory is used to calculate power production of the newly designed rotor. The main design procedure is briefly given in Table 1 below:

Table 1. Main Design Procedure

Procedure	
Airfoil Geometry Design	Parametric Section Method (PARSEC)
	Class-Shape Transformation Method (CST)
Aerodynamic Data	Panel Solver Software - XFOIL
Power Calculations	Blade Element-Momentum (BEM) Theory
Optimization Technique	Genetic Algorithm (GA)

METHODOLOGY

Airfoil Geometry Representation Methods

There are many different approaches for airfoil geometry representations such as discrete set of airfoil coordinates, Bezier and B-Spline curves, free form representation, orthogonal basis functions, perturbations to a reference airfoil, PARSEC, CST, etc. [Kulfan, 2006]. It is desired to define airfoil geometry in an accurate, simple, smooth and robust way allowing local modifications. In this research, CST and PARSEC methods are selected as airfoil representation methods based on their aerodynamically meaningful parameterization capability and ability to control the airfoil shape with comparatively lower number of parameters.

CST Method

CST Method is a general mathematical transformation technique that is used to describe a variety of 2D and 3D geometries. In this method, the shape function and class function is introduced. The shape function depicts the geometry of the structure where the class function makes the method applicable for different kind of geometry families [Kulfan, 2007]. In this method, round nose airfoils are represented by a general mathematical description depending on nose radius, forebody shape and aftbody shape parameters. The generalized mathematical formulation of the airfoil geometry scaled to the chord length is given as;

$$y(x) = \underbrace{\sqrt{x}}_{\mathrm{I}} \cdot \underbrace{(1-x)}_{\mathrm{II}} \cdot \underbrace{\sum\nolimits_{i=0}^{N} A_i \cdot x^i}_{\mathrm{III}} + \underbrace{x \cdot y_{TE}}_{\mathrm{IV}} \tag{1}$$

I : Round nose radius providing term;
II : Sharp trailing edge providing term;
III : Specific geometry shape between round nose and sharp aft end providing term;
IV : Trailing edge thickness controlling term.

To eliminate non-analytical behavior of the formula, the shape function $S(x)$ is defined as;

$$S(x) = \frac{y(x) - x\, y_{TE}}{\sqrt{x} \cdot [1-x]} \tag{2}$$

$S(x)$ can be redefined as a weighted summation as follows;

$$S(x) = \sum_{i=0}^{N} \left[A_i \cdot x^i\right] \tag{3}$$

The class function $C(x)$ is introduced with the general form as;

$$C_{N2}^{N1}(x) = (x)^{N1}[1-x]^{N2} \tag{4}$$

For round nose airfoils, class function parameters are $N1 = 0.5$ and $N2 = 1$.
The generalized formula representation of an airfoil becomes:

$$y(x) = C_1^{0.5}(x) \cdot S(x) + x \cdot y_{TE} \tag{5}$$

The unit shape function $S(x) = 1$ can be decomposed into Bernstein polynomial of order n and can be defined as;

$$S_i(x) = K_i x^i (1-x)^{n-1} \tag{6}$$

where

$$K_i \equiv \binom{n}{i} = \frac{n!}{i!\,(n-i)!} \tag{7}$$

All smooth airfoils can be obtained from unit shape function by the use of Bernstein polynomial decomposition technique controlling the important design parameters such as leading edge radius, continuous curvature around a leading edge, boattail angle and closure to a specified thickness [Kulfan, 2007].

Equation 5 can be decomposed for upper and lower surfaces;

$$y(x)_{upper} = C_1^{0.5}(x) \cdot S_{upper}(x) + x \cdot \Delta y_{TE\_upper} \tag{8}$$

$$y(x)_{lower} = C_1^{0.5}(x) \cdot S_{lower}(x) + x \cdot \Delta y_{TE\_lower} \tag{9}$$

where

$$S_{upper}(x) = \sum_{i=0}^{n} \left[A_{upper\ i} \cdot S_i(x)\right] \tag{10}$$

$$S_{lower}(x) = \sum_{i=0}^{n} \left[A_{lower\ i} \cdot S_i(x)\right] \tag{11}$$

$A_{upper\ i}$ and $A_{lower\ i}$ are described as the CST weighting coefficients. These terms are directly related the airfoil's specific geometry and become optimization parameters in design and optimization of new airfoil geometries.

PARSEC Method

PARSEC method, [Sobieczky, 2000], defines a linear combination of explicit mathematical functions to define airfoil geometry. 6th order polynomials are used to represent upper and lower surfaces where parameters are directly obtained from airfoil geometry. General formulation of PARSEC method is turned to be such that:

$$y_{upper} = \sum_{n=1}^{6} A_{upper\,n}\, x^{n-\frac{1}{2}} \tag{12}$$

$$y_{lower} = \sum_{n=1}^{6} A_{lower\,n}\, x^{n-\frac{1}{2}} \tag{13}$$

Total 12 geometric parameters are introduced in Figure 1 as; the leading edge radius for upper curve ($r_{LE,upper}$), the leading edge radius for lower curve ($r_{LE,lower}$), maximum thickness location for upper curve (x_{upper}, y_{upper}), upper crest curvature ($y_{xx,upper}$), maximum thickness location for lower curve (x_{lower}, y_{lower}), lower crest curvature ($y_{xx,lower}$), trailing edge position (y_{TE}), trailing thickness (Δy_{TE}), trailing edge angle and trailing edge wedge angle (α_{TE} and β_{TE}).

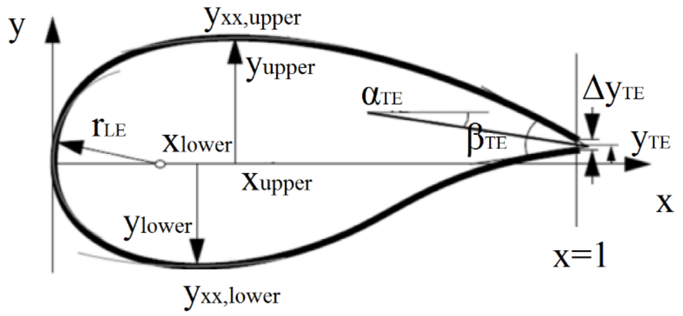

Figure 1. PARSEC Geometric Parameters [Sobieczky, 2000]

Rotor Aerodynamics – BEM Theory

BEM is a powerful and widely used theory to predict wind turbine performance fast and easily. BEM Theory equates separately obtained force relations in Momentum Theory and Blade Element Theory. It predicts the induced velocities by calculating related induction factors. Then, the power and the thrust of the wind turbine can be easily calculated.

$$T_{blade\ element} = T_{momentum} \tag{14}$$

$$Q_{blade\ element} = Q_{momentum} \tag{15}$$

$$a = \frac{1}{\frac{4\,\mathrm{F}\sin^2\varphi}{\sigma C_n} + 1}; \quad a' = \frac{1}{\frac{4\,\mathrm{F}\sin\varphi\cos\varphi}{\sigma C_t} - 1}; \quad \sigma = \frac{N_b c}{2\pi r} \tag{16,17,18}$$

In this study, considering hub and tip loss corrections, Buhl's highly loaded rotor correction, basic BEM equations are modified. In order to overcome convergence problems, Ning's guaranteed convergence method for solution of BEM equations is followed [Ning, 2013]. In this method, instead of solving two nonlinear induction equation system iteratively, the problem is reduced to one nonlinear root finding problem by introducing a proper residual function parameterized as a function of flow angle.

Genetic Algorithm

Genetic Algorithm (GA) is a multi-objective, semi-random search optimization technique having survival of the fittest strategy. Optimization scheme generates a population of possible solutions, evaluates the solutions according to a fitness function, selects a set of fit parent solutions, and reproduce those parents to generate a new population of possible solution. Crossover, reproduction and mutation operations are used in natural selection process in the population. In this study, GA is used in optimization of the airfoil geometries defined with CST and PARSEC parameterization methods.

VALIDATION AND RESULTS

CST Validation

The CST fitting MATLAB code, AirfoilCST, is validated for the S809 airfoil profile. S809 airfoil is used in common in NREL Phase III and NREL Phase VI rotor blades. In Figure 2, 6^{th} and 10^{th} order CST fitting results for S809 airfoil profile is presented. It is concluded that 6^{th} order CST parameterization is sufficient to define airfoil geometry.

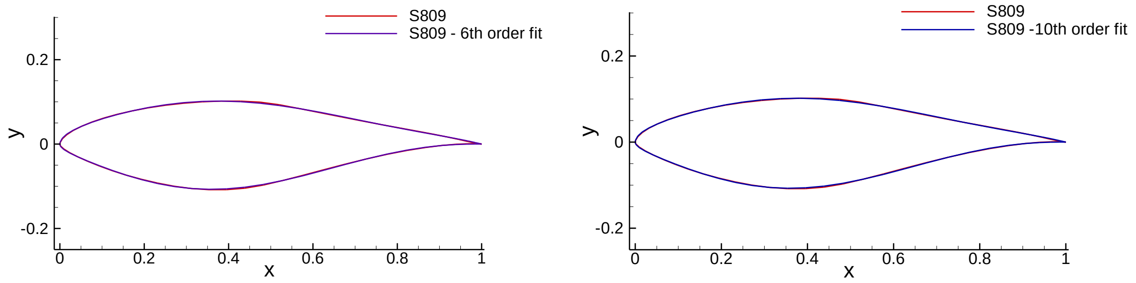

Figure 2. 6^{th} (left) and 10^{th} (right) order CST Fitting Results for S809 Airfoil Profile

PARSEC Validation

The PARSEC fitting MATLAB code, AirfoilPARSEC, is validated for the S809 airfoil profile. In Figure 3, PARSEC fitting results for S809 airfoil profile is presented. It can be observed that PARSEC fitting is successful to define baseline geometry smoothly.

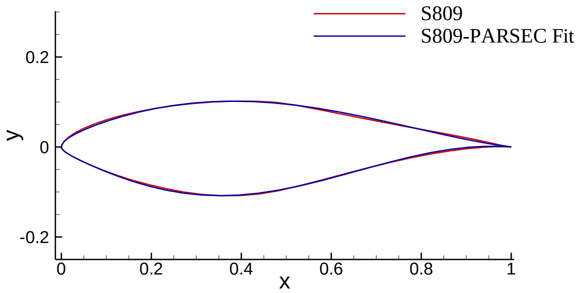

Figure 3. PARSEC Fitting Result for S809 Airfoil Profile

Aerodynamic Coefficients Calculation Validation

In order to obtain airfoil aerodynamic coefficients, C_l and C_d, at different Reynolds numbers (Re) and angle of attacks (AoA), the panel solver, XFOIL, is utilized. For stall region calculations, a MATLAB code is written which uses Viterna-Corrigan extrapolation to get 360^0 airfoil polar data. For validation case, S809 aerodynamic coefficients are calculated for Re=750.000 and compared to the results of “AirfoilPrep v2.02.03”, an open source code, and also wind tunnel test results. Results are shown for C_l in Figure 4, for C_d in Figure 5.

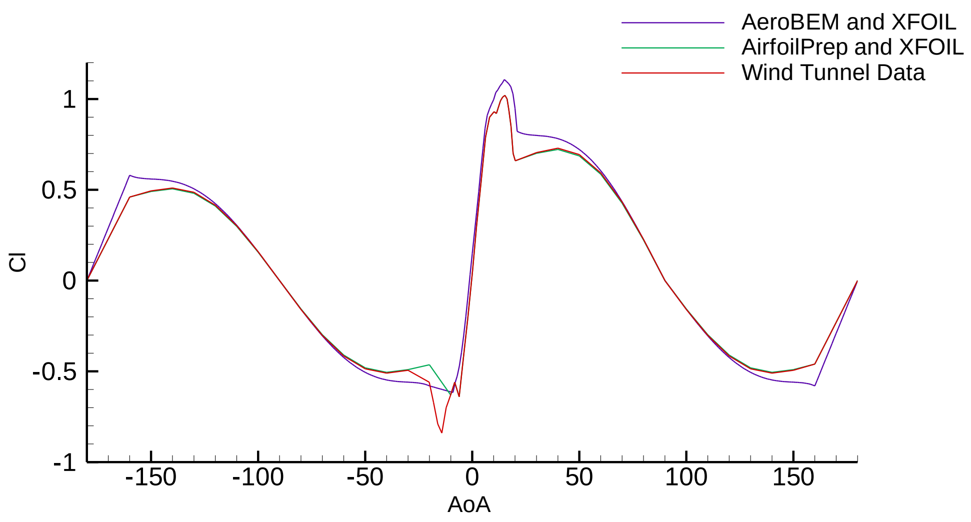

Figure 4. C_l vs *AoA* for S809 Airfoil Profile (Re=750.000)

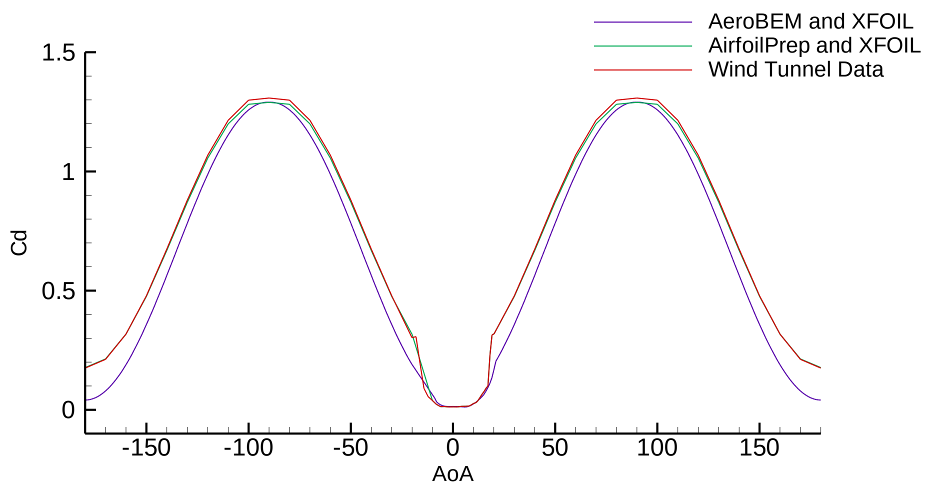

Figure 5. C_d vs *AoA* for S809 Airfoil Profile (Re=750.000)

BEM Analysis Validation

The rotor aerodynamic analyses are performed by using an in-house MATLAB BEM code, AeroBEM. AeroBEM is validated for NREL Phase III and NREL Phase VI reference wind turbines. The geometric parameters of these rotors are given in Table 2, chord length distributions are shown in Figure 6, and twist angle distributions are given in Figure 7.

Table 2. The Geometric Parameters of NREL Phase III and NREL Phase VI Rotors

Rotor Parameters	NREL Phase III	NREL Phase VI
Blade Number	3	2
Rotor Radius	5.03 m	5.03 m
Rotational Speed	71.63 rpm	71.63 rpm
Cut-in Wind Speed	6 m/s	6 m/s
Rated Power	19.8 kW	19.8 kW
Hub Radius	0.723 m	1.275 m
Blade Pitch Angle	3°	0°
Twist Angle	Nonlinear: 44° (hub) — 0° (tip)	Nonlinear: 20° (hub) — -1.775° (tip)
Blade Chord Distribution	Constant	Linear

Hub Chord Length	0.4572 m	0.737 m
Tip Chord Length	0.4572 m	0.358 m
Airfoil Profile	S809	S809

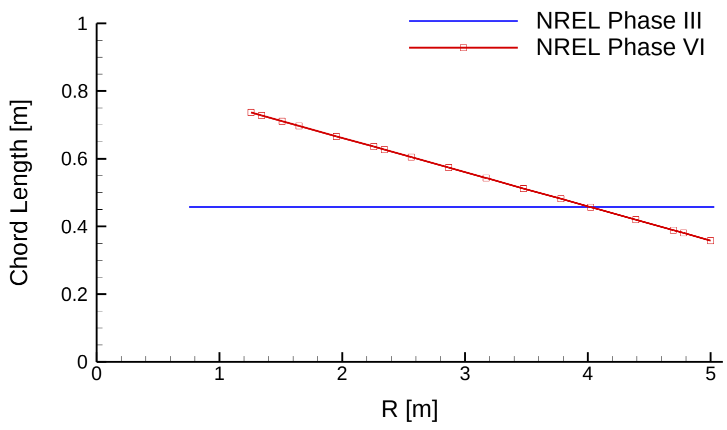

Figure 6. Chord Distributions for NREL Phase III and NREL Phase VI rotors

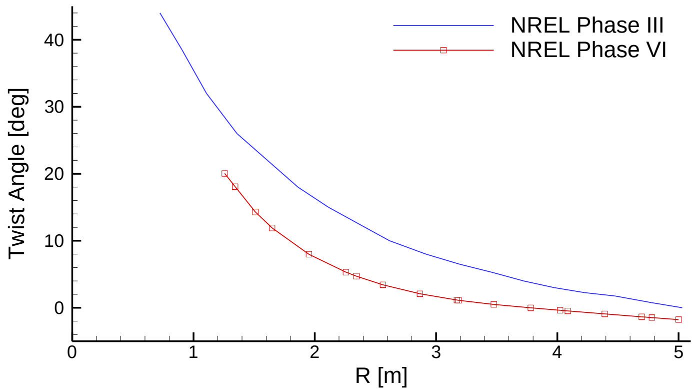

Figure 7. Twist Angle Distributions for NREL Phase III and NREL Phase VI rotors

For validation studies, AeroBEM analyses results are compared to WT_Perf code, which is an open source code based on BEM theory developed by NREL and experimental data. NREL Phase III power comparison is given in Figure 7 and thrust comparison is given in Figure 9. NREL Phase VI power comparison is given in Figure 10 and thrust comparison is given in Figure 11. In order to prevent C_l and C_d data interpolation and extrapolation errors in power calculations, only the experimental C_l and C_d data are used for Re=750.000. This creates a discrepancy between experimental results and BEM calculations for both rotors. Despite the inconsistency between experimental results, it is observed that AeroBEM and WT_Perf results are in very good agreement. The slight variations are due to the interpolation technique differences of these methods.

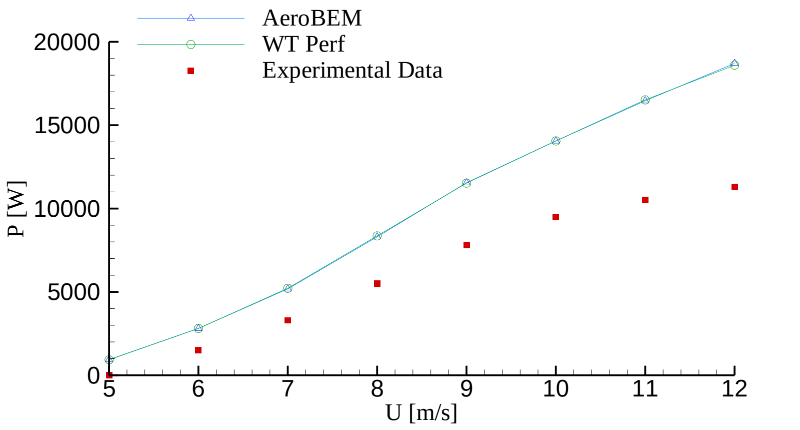

Figure 8. NREL Phase III Power Curve Comparison

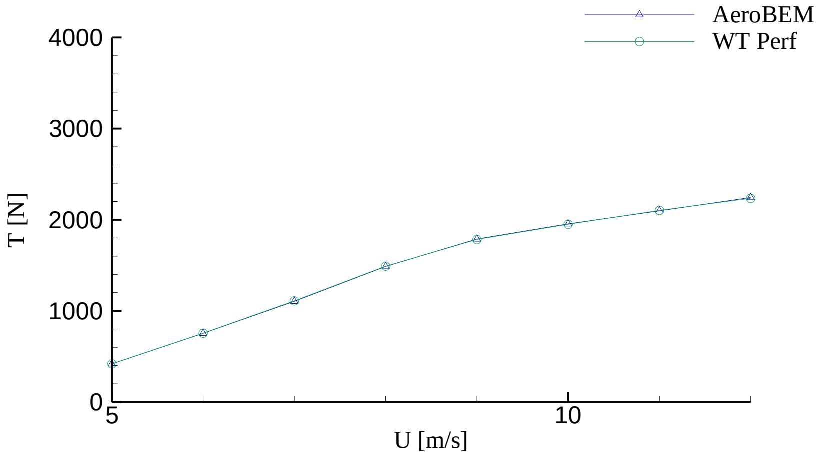

Figure 9. NREL Phase III Thrust Curve Comparison

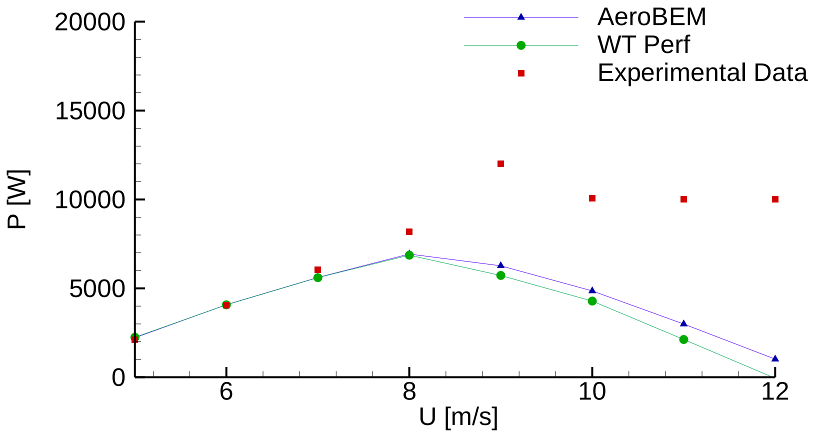

Figure 10. NREL Phase VI Power Curve Comparison

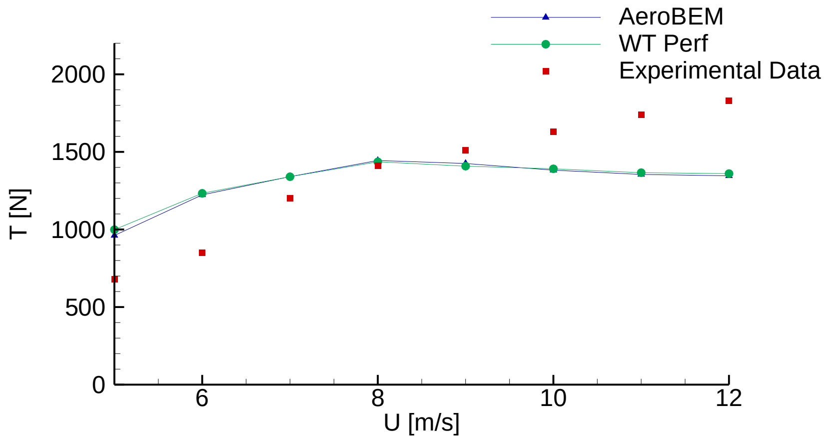

Figure 11. NREL Phase VI Thrust Curve Comparison

Airfoil Optimization with CST Method

In this section, it is aimed to optimize airfoil geometries for different regions of the blade with CST method. First of all, the blade is divided into three regions namely, blade root section, blade middle section and blade tip section. S809 airfoil is selected as baseline airfoil for CST optimization studies. For blade root section, due to the structural benefits, a thicker baseline airfoil is parameterized by modifying CST weighting coefficients of S809 profile. Then, the optimization is done by manipulating the CST weighting coefficients of this thicker baseline airfoil. At the blade middle section, S809 profile is used without any change. At the blade tip section, a thinner baseline airfoil is designed by CST using S809. The optimization is done by manipulating the CST weighting coefficients of this thinner baseline airfoil. The thicker and thinner baseline profiles generated by CST Method and S809 airfoil profile is given in Figure 12. When creating new baseline airfoils, airfoil thickness related CST weighing coefficients of S809 airfoil are increased and decreased %20. Corresponding CST weighing coefficients are given in Table 3.

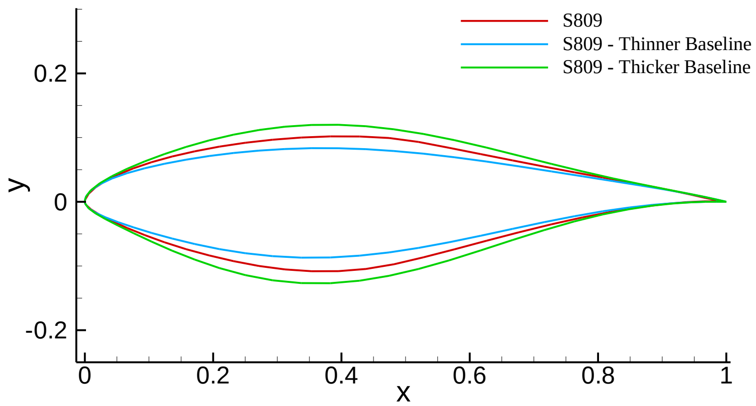

Figure 12. S809, Thinner Baseline and Thicker Baseline Airfoil Geometries Generated by CST Method

Table 3. CST Weighing Coefficients for S809 Airfoil Baselines

Airfoil	**5th Order Lower Surface CST Coefficients**					
S809 - Thinner Baseline %20	-0,127	-0,200	-0,322	-0,203	-0,087	0,017
S809 - Baseline	-0,127	-0,250	-0,403	-0,254	-0,087	0,017
S809 - Thicker Baseline %20	-0,127	-0,300	-0,484	-0,304	-0,087	0,017

Airfoil	**5th Order Upper Surface CST Coefficients**					
S809 - Thinner Baseline %20	0,182	0,186	0,253	0,244	0,139	0,242
S809 - Baseline	0,182	0,233	0,317	0,305	0,139	0,242
S809 - Thicker Baseline %20	0,182	0,280	0,380	0,367	0,139	0,242

For root section, optimization is performed for 5^0 AoA and $1x10^6$ Re where the problem is subjected to the objective function aiming to maximize C_l/C_d ratio. CST optimization results for root section is given in Figure 13.

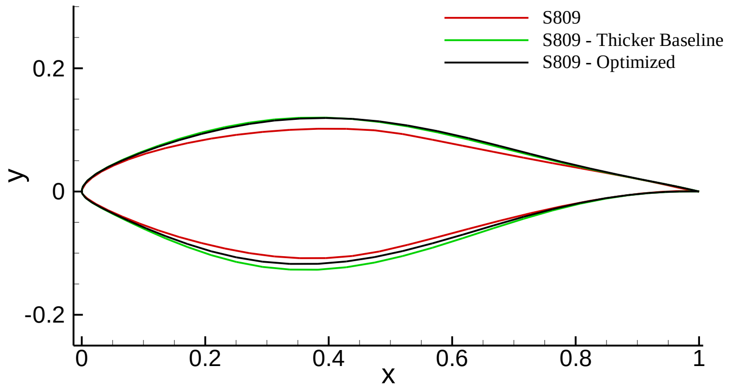

Figure 13. CST Optimization Results for Blade Root Section

For tip section, optimization is performed for 5^0 AoA and $5x10^6$ Re where the problem is subjected to the objective function aiming to maximize C_l/C_d ratio. CST optimization results for tip section is given in Figure 14.

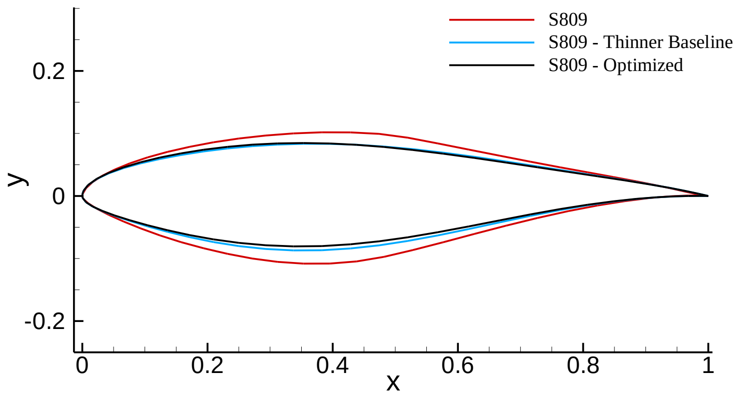

Figure 14. CST Optimization Results for Blade Root Section

Airfoil Optimization with PARSEC Method

In this section, it is aimed to optimize airfoil geometries this time with PARSEC method for the same blade regions defined in previous section. Maximum thickness and 2nd derivative of maximum thickness for upper and lower curves are selected as 4 PARSEC optimization parameters. Again for blade root section, a thicker baseline airfoil is parameterized by modifying PARSEC parameters of S809 profile. Then, the optimization is done by manipulating these PARSEC parameters of this thicker baseline airfoil. At the blade middle section, S809 profile is used without any change. At the blade tip section, a thinner baseline airfoil is designed by modifying PARSEC parameters of S809 profile. The optimization is done by manipulating the PARSEC parameters of this thinner baseline airfoil. The thicker and thinner baseline profiles generated by PARSEC method and S809 airfoil profile is given in Figure 15. When creating new baseline airfoils, airfoil thickness related PARSEC parameters of S809 airfoil are increased and decreased %20. Corresponding PARSEC parameters are given in Table 4.

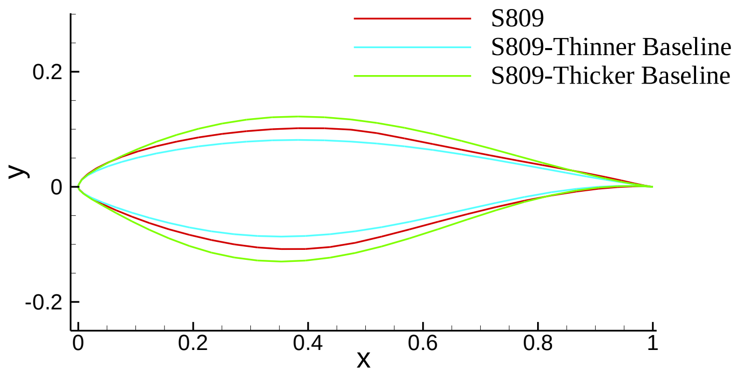

Figure 15. S809, Thinner Baseline and Thicker Baseline Airfoil Geometries Generated by PARSEC Method

Table 4. PARSEC Parameters for S809 Airfoil Baselines

Airfoil	y_{upper}	$y_{xx,upper}$	y_{lower}	$y_{xx,lower}$
S809 - Thinner Baseline %20	0,081	-0,739	-0,087	1,369
S809 - Baseline	0,102	-0,923	-0,108	1,711
S809 - Thicker Baseline %20	0,122	-1,108	-0,130	2,053

For root section, optimization is performed for 5^0 AoA and 1×10^6 Re where the problem is subjected to the objective function aiming to maximize C_l/C_d ratio. PARSEC optimization results for root section is given in Figure 16.

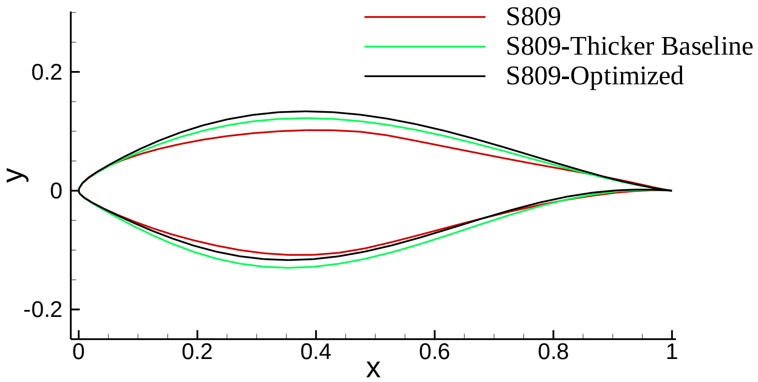

Figure 16. PARSEC Optimization Results for Blade Root Section

For tip section, optimization is performed for 5^0 AoA and $5x10^6$ Re where the problem is subjected to the objective function aiming to maximize C_l/C_d ratio. PARSEC optimization results for tip section is given in Figure 17.

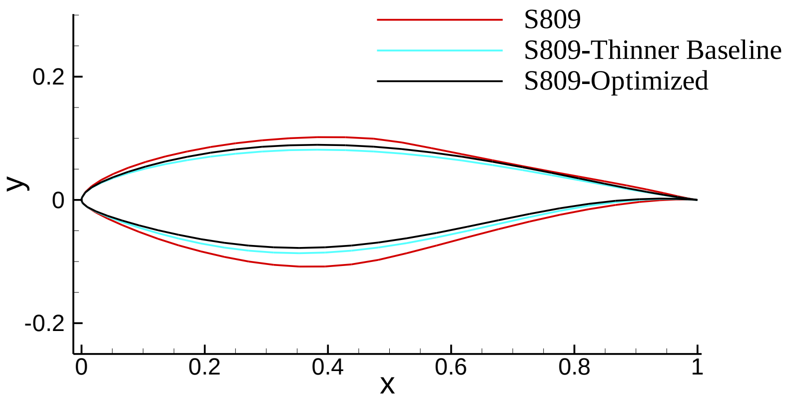

Figure 17. PARSEC Optimization Results for Blade Tip Section

Blade Design with Optimized Airfoils

In this section, two new blades are designed based on NREL Phase VI rotor, by using optimized airfoils with CST and PARSEC methods. The airfoil geometry distributions of newly designed blades are tabulated in Table 5. Other rotor geometry parameters are hold same as the reference rotor's.

Table 5. The Airfoil Geometry Distributions for Blade Design Studies

	0-25%R	**25-50%R**	**50-75%R**	**75-100%R**
NREL Phase VI Blade	Root Extension	S809	S809	S809
CST Parameterized Blade	Root Extension	Thicker Opt. Airfoil with CST	S809	Thinner Opt. Airfoil with CST
PARSEC Parameterized Blade	Root Extension	Thicker Opt. Airfoil with PARSEC	S809	Thinner Opt. Airfoil with PARSEC

In Figure 18, power curve for NREL Phase VI and newly designed turbines are shown. It is observed that the power curve is shifted for newly design turbine and the power production is increased up to 4.5% for 12 m/s freestream velocity. Although the airfoil geometries defined by CST and PARSEC methods slightly different than each other, their aerodynamic performance is nearly same. However, since the PARSEC method has limited design variables by definition, it cannot provide high fidelity for different airfoil geometries. On the other hand, CST method offers rich and flexible design space.

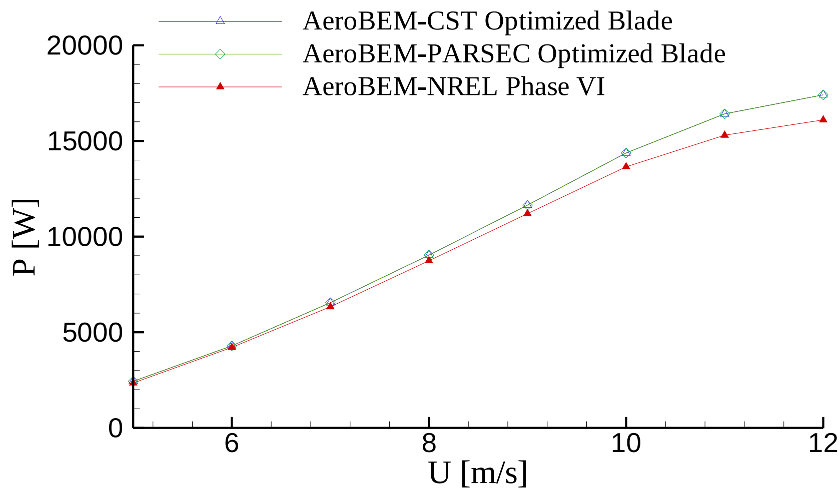

Figure 18. Power Curve Comparison for NREL Phase VI Reference Turbine and Newly Designed Rotors

CONCLUSIONS AND FUTURE WORK

In this paper, the aerodynamic optimization of the horizontal axis wind turbine rotor blades and their airfoil geometries with CST and PARSEC methods, BEM theory and GA are presented. CST and PARSEC parameterization approaches are shown for S809 baseline airfoil geometry. Different airfoil geometries are optimized for blade root and blade tip sections with GA by using these two methods. For power calculations of wind turbine rotor, BEM theory is used. Its validation is done by running NREL Phase III and NREL Phase VI rotor cases. At the end, two blades are designed with optimized airfoil geometries with CST and with PARSEC. The comparison of their power performances to reference wind turbine rotor, NREL Phase VI, and each other is discussed.

For future studies, blade planform parameters can be added to optimization algorithm in design of new blades. Three dimensional blade geometry can be parameterized by using CST method. Hybrid airfoil representation methods can be developed and their performance can be investigated. Wind tunnel tests can be done to validate aerodynamic performance of newly designed airfoils.

References

Ceyhan, O., (2008) *“Aerodynamic Design and Optimization of Horizontal Axis Wind Turbines by Using BEM Theory and Genetic Algorithm,”* MS Thesis, METU Dept. of Aerospace Engineering, September 2008.

Ceyhan, O., Ortakaya, Y., Korkem, B., Sezer-Uzol, N. and Tuncer, I.H., (2009) *“Optimization of Horizontal Axis Wind Turbines by using BEM Theory and Genetic Algorithm,”* 5th Ankara International Aerospace Conference, METU Ankara, Turkey, 17-19 August 2009.

Elfarra, M., (2011) *“Horizontal Axis Wind Turbine Rotor Blade: Winglet and Twist Aerodynamic Design and Optimization Using CFD,”* PhD Thesis, METU Dept. of Aerospace Engineering, January 2011.

Elfarra, M.A., Akmandor, I.S., and Sezer-Uzol, N., (2011) *“Investigation and Optimization of Winglets for HAWT Rotor Blades,”* ETC 2011, 9th European Conference on TURBOMACHINERY Fluid Dynamics and Thermodynamics, Istanbul, Turkey, 21-25 March 2011.

Elfarra, M.A., Akmandor, I.S., and Sezer-Uzol, N., (2011) *"Pitch Angle Design of NREL VI Wind Turbine Blade,"* ECCOMAS CFD & OPTIMIZATION 2011-1080, An ECCOMAS Thematic Conference, Antalya, Turkey, 23-25 May 2011.

Elfarra, M.A., Sezer-Uzol, N., and Akmandor, I.S., (2010) *"Investigations on Tangential Tip Tilting for HAWT Rotor Blades,"* 10th International Conference on Clean Energy, ICCE-2010, Famagusta, North Cyprus, 15-17 September 2010.

Elfarra, M.A., Sezer-Uzol, N., and Akmandor, I.S., (2014) *"NREL VI Rotor Blade: Numerical Investigation and Winglet Design and Optimization Using CFD,"* Wind Energy, (Online Early View, 6 February 2013) Vol 17. Issue 4. pp 605-626, April 2014.

Elfarra, M.A., Sezer-Uzol, N., and Akmandor, I.S., (2015) *"Investigations on Blade Tip Tilting for HAWT Rotor Blades Using CFD,"* International Journal of Green Energy, (Published Online: 08 Oct 2014) Vol. 12, Issue 2, pp. 125-138, 2015.

Engfer, C., Canal, M., and Nualart, P., (2015) "Optimization Methods Applied to Wind Turbine Blade Design". Brazil Windpower 2015 Conference and Exhibition, Brazil. September 2015.

Kulfan, B.M., (2007) *"A Universal Parametric Geometry Representation Method – CST",* 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2007-0062, January 2007.

Ning, S.A., (2013) "A Simple Solution Method For The Blade Element Momentum Equations With Guaranteed Convergence," Wind Energy 17(9), July 2013. DOI:10.1002/we.1636.

Mukesh, R., Lingadurai, K., Selvakumar, U. (2013) "Airfoil Shape Optimization Using Non-Traditional Optimization Technique and Its Validation", Journal of King Saud University – Engineering Sciences (2014) 26, 191–197, published online 7 May 2013.

Oğuz, K., (2019) "Aerodynamic Design and Optimization of Horizontal Axis Wind Turbine Rotor Airfoil And Blade Geometries by Using CST Method, BEM Theory and Genetic Algorithm", MS Thesis, METU Dept. of Aerospace Engineering, September 2019.

Oğuz, K., Sezer-Uzol, N., (2019) "Yatay Eksenli Rüzgar Türbini Kanadı ve Kanat Profillerinin BEM ve CST Metotları ve Genetik Algoritma Kullanarak Aerodinamik Optimizasyonu", 5. İzmir Wind Symposium, will be presented October 2019.

Okrent, J., (2017) "An Integrated Method for Airfoil Optimization", MS Thesis, Lehigh University Dept. of Mechanical Engineering, May 2017.

Polat, O., (2011) *"Genetic Algorithm Based Aerodynamic Shape Optimization of Wind Turbine Rotor Blades Using A 2-D Panel Method with a Boundary Layer Solver,"* MS Thesis, METU Dept. of Aerospace Engineering, December 2011.

Polat, O., Sezer-Uzol, N., and Tuncer, I.H., (2011) *"Aerodynamic Optimization Of Horizontal Axis Wind Turbines Based On Panel Flow Solutions With BEM Theory And Genetic Algorithm,"* ECCOMAS CFD & OPTIMIZATION 2011 - 064, An ECCOMAS Thematic Conference, Antalya, Turkey, 23-25 May 2011.

Polat, O., Sezer-Uzol, N., and Tuncer, I.H., (2012) *"Aerodynamic Shape Optimization of Wind Turbine Blades Using A 2-D Panel Method With A Boundary Layer Solver And A Genetic Algorithm,"* European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2012), Vienna, Austria, September 10-14, 2012.

Polat, O., Sezer-Uzol, N., and Tuncer, I.H., (2013) *"Aerodynamic Shape Optimization of Wind Turbine Blades Using a Parallel Genetic Algorithm,"* AIAC-2013-154, 7. Ankara International Aerospace Conference, METU, Ankara, Turkey, 11-13 September 2013.

Polat, O., Sezer-Uzol, N., and Tuncer, I.H., (2014) *"Genetic Algorithm Based Aerodynamic Shape Optimization Tool for Wind Turbine Blades and its Implementation to Helicopters,"* AHS 70th Forum and Technology Display, Montreal, Canada, May 19-22, 2014.

Sağol, E., (2010) *“Site Specific Design Optimization of A Horizontal Axis Wind Turbine Based On Minimum Cost of Energy,”* MS Thesis, METU Dept. of Aerospace Engineering, January 2010.

Sağol, E., Sezer-Uzol, N., and Uzol, O., *(2009) “Site Specific Cost-Effective Design Optimization of A Horizontal Axis Wind Turbine,”* NUYEK 2009, Nuclear & Renewable Energy Sources with International Participation, Ankara, 28-29 September 2009.

Sobieczky, H., (2000) *“Aerodynamic Design and Optimization Tools Accelerated by Parametric Geometry Preprocessing,”* European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2000, Barcelona, 11-14 September 2000.

Vecchiaa, P.D., Daniele, E., D’Amato, E., (2014) “An Airfoil Shape Optimization Technique Coupling PARSEC Parameterization and Evolutionary Algorithm”, Elsevier Aerospace Science and Technology, Volume 32, Issue 1, January 2014, Pages 103-110.