Aerodynamic Optimization for Wind Turbine Blade-Section

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ABSTRACT

Wind turbines are one of the promising renewable energy sources. Horizontal axis wind turbines HAWTs dominates the wind turbine industry. In this study, a multipoint multi objective airfoil drag minimization for horizontal axis wind turbine is performed. The process starts from NREL S809 low Reynold's number airfoil as base design shape at a Reynolds number of 5.5×10^5. A combination of potential flow solver and numerical genetic search algorithms (GA) is used. A code prepared and verified by the author is used as aerodynamic design tool. Class-Shape-Transformation (CST) method is used for airfoil shape parametrization through all the design process. The results show significant drag coefficient minimization over the entire range of angles of attack. The method converges to the optimum shape in about 10 generations which shows it is an efficient design approach.

Keywords: Wind turbine blade-section, Optimization, aerodynamic efficiency, airfoil parametrization, airfoil optimization.

1. Introduction

Efficient wind turbine blade section design can enhance power output through decreasing drag or increasing lift to drag ratio or enhancing operational wind turbine characteristics such as resistance to dust formation or reducing noise associated with blade operation. A wind turbine blade can be made of one section (airfoil) or can have different airfoils along the blade span. Aerodynamic and structure characteristics constitute the main criterion for wind turbine blade design. The aerodynamic characteristics of wind turbine section (airfoil) depend highly on their shapes.

The geometry of an airfoil can directly affect the lift, drag and pitching moment coefficients during operation and therefore affect the amount of energy a wind turbine can generate [1]. Therefore, improving the airfoil shape of the wind turbine can effectively improve wind turbine performance in energy production. Airfoil shape optimization is an important branch in design that basically involves determination of the shape of an object so as to minimize or maximize an objective function subjected to predefined design constraints.

Wind-turbine designers use shape optimization to improve blade performance in utilizing wind energy. In this context, airfoil shape optimization improves aerodynamic performance by minimizing drag, or/and increasing lift to drag ratio L/D. Wind turbine designers focus on these objectives because the rotor blade of a wind turbine acts like a wing with lift force turning the blade around the wind turbine axis and thereby driving an electric generator to generate electricity. The energy produced by a wind turbine is related to, among many other factors, the lift-to-drag ratio and the rotational speed of the rotor.

In this paper, airfoil shape optimization using Genetic Search Algorithms GAs is adopted. a penalty function is utilized that directs the optimization process toward the solution. The airfoil shape optimization process based on Genetic search algorithms GA systematically changes the coefficients of a CST airfoil parametric representation function. An aerodynamic code, based on inviscid-viscos interaction method, is then called to calculate the lift, drag and pitching moment coefficients for a given angle of attack and Reynolds number. The aerodynamic coefficients of each candidate airfoil are assessed by the objective function which is based on weighted sum method. A penalty function is implemented to enforce constraints if they are violated. This optimization methodology can be applied to direct and inverse design problems.

Aerodynamic shape design/optimization is a challenging problem because the governing fluid dynamics are nonlinear [2]. Genetic algorithm is a good shape optimization algorithm because it can deal with large number of continuous and integer design variables as it searches highly multimodal and discontinuous design spaces [3]. National Renewable Energy Laboratory (NREL) has developed a family of airfoils for HAWT applications [4] since 1984. The main objective of present paper is to minimize drag of NREL S809 laminar flow airfoil at three angles of attack in the middle of the operating range and at Reynolds number of 5.5x105. This airfoil is 21% thick whose design and experimental data are published in [5]. NREL Phase II, Phase III, and Phase VI HAWT blades are composed of S809 airfoil from root to tip. The flow is incompressible where laminar separation can occur on the airfoil suction side for angles of attack ranging from 0 to 5.13 degrees. Turbulent trailing edge separation can also occur at high angles of attack.

2. CST Airfoil parametrization function

This method is developed my Brenda Kulfan in Boeing Commercial Airplanes, as illustrated in [6, 7], and its characteristics has been thoroughly studied in many works as in [8]. In CST method an airfoil geometry is expressed by the mathematical expression of Eq.(1).

$$\xi(\psi) = \sqrt{\psi}(1-\psi)\sum_{i=1}^{N} A_i \psi^i + \psi \xi_T \tag{1}$$

Where $\psi = \frac{x}{c}, \xi = \frac{y}{c}$ and $\xi_T = \frac{\Delta\xi_{TE}}{c}$

In this expression airfoil nose shape is governed by the term $\sqrt{\psi}$, while the term $(1-\psi)$ controls the trailing edge angle and the last term $\psi\xi_T$ represents the trailing edge thickness. The term $\sum_{i=1}^{N} A_i\psi^i$shapes the rest of the airfoil surface. The equation can be rearranged to give the so-called class function and denoted by $S(\psi)$ given by Eq.(2).

$$S(\psi) = \frac{\xi(\psi)-\psi\xi_T}{\sqrt{\psi}(1-\psi)} \quad \text{with } S(0) = \sqrt{2\frac{r}{c}} \quad \text{and } S(1) = tan\beta + \frac{\Delta Z_{TE}}{c} \tag{2}$$

The shape function can be formulated by using Bernstein polynomial in which first term represent leading edge radius and last term represent trailing edge angle and thickness. The rest of the terms cannot affect neither leading edge radius nor trailing edge properties, and thus called shaping terms.

If Bernstein polynomial of order$n$ is used then the shape function takes the form

$$S_i(\psi) = K_i\psi^i(1-\psi)^{n-i} \quad \text{with} \quad K_i = \binom{n}{i} = \frac{n!}{i!(n-i)!} \tag{3}$$

Using this shape function the airfoil upper and lower surfaces can be expressed as

$$\begin{aligned} \xi_{up} &= \sqrt{\psi}(1-\psi)\sum_{i=1}^{N} A_{up}S_i(\psi) + \psi\Delta\xi_{up} \\ \xi_{LO} &= \sqrt{\psi}(1-\psi)\sum_{i=1}^{N} A_{LO}S_i(\psi) + \psi\Delta\xi_{LO} \end{aligned} \tag{4}$$

Where $\Delta\xi_{up} = \frac{Yu_{TE}}{C}$ and$\Delta\xi_{LO} = \frac{YL_{TE}}{C}$ are upper and lower trailing edge thicknesses respectively. The coefficients A_{up} and A_{LO} can be found for different airfoil shapes. This formulation methodology is suitable for systematic design optimization approach. The terms of the shape function always sum up to 1. The sum of airfoil terms results in airfoil surface coordinates. When the coefficients are assigned to some value they will scale up or down the corresponding term, and thus different airfoil shape is formed with any perturbed coefficient.

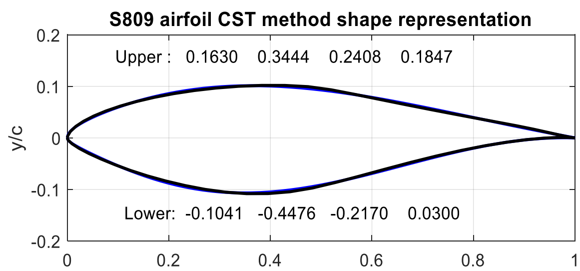


Figure 1 Representation of S809 airfoil with 4 parameter CST method

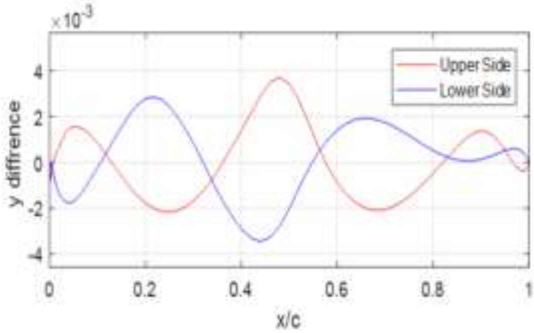


Figure 2 Difference in airfoil y coordinates between original and CST representation

Figure (1) shows S809 airfoil constructed with 4 degree-polynomial using CST function in the code. The values of the CST coefficients are also shown on the figure. The corresponding difference in shape representation is shown in the lower part of the figure. It can be said that these polynomial combination fits very well the airfoil shape.

3. Aerodynamic code

The aerodynamic code used in this paper was validated in [9]. It uses inviscid-viscous interaction approach to solve air flow over the airfoil. For inviscid solution Karman-Trefftz conformal mapping is implemented. Karman-Trefftz calculation procedure starts with mapping a given airfoil shape into a true circle in three subsequent transformations, the resulting derivatives of these transformations are multiplied with the velocity distribution around a circular cylinder. The value of the circulation is fixed by applying Kutta condition at trailing edge image of the true circle. The resulting inviscid velocity distribution at a specified angle of attack is used to derive the boundary layer solution.

The boundary layer solution starts at leading edge stagnation point. The boundary layer integral equations were solved numerically. The boundary layer integral solution enables the evaluation of lift viscous corrections, total drag, and laminar separation bubble location.

The calculation procedure is repeated by adding boundary layer momentum thickness to the airfoil sides, until the change in airfoil shape is negligibly small. This requires only few iterations, making this approach very efficient for airfoil design by systematic airfoil shape perturbation. The procedure is explained elsewhere [10, 11]

4. Objective function formulation

In this paper a MultiPoint Multi Objective (MPMO) function is implemented as an objective function. A range of angles of attack of 0 ,2, and 4 at Reynold's number of 5.5×10^6 is selected as design points. The objective is to minimize drag keeping the same lift to drag ratio. The objective function is formulated as in the following equation.

$$f = \sum_{i=1}^{n_\alpha} \left[w_{cd}(i)\, c_d(i) - K_{cl}(i)\, w_{cl}(i)\, (c_{ld}(i) - c_l(i)) \right] \tag{5}$$

In this equation lift constrained drag minimization problem is formulated. The aerodynamic objective function is given by the first term where w_{cd} and c_d is the weighting coefficients and drag coefficients for each angle of attack.

The aerodynamic constraints are enforced by the second term. The penalty coefficient K_{cl} is specified to each design point as per it's importance to the design process. The factor w_{cl} is weighting factor for lift coefficient, while c_{ld} and c_l are design and lift coefficient for the candidate airfoil. If the constraints are violated a factor $K_{cl} > 1$ is multiplied by constrained term.

When multipoint optimization is studied this function is applied to each design point separately and the sum is minimized. The geometric constraints are given by upper and lower bounds of each airfoil surface. Figure (3) show these geometric bounds together with initial airfoil. The airfoil surfaces are allowed to change within prespecified range. These bounds will grantee a realistic airfoil shapes to the aerodynamic calculation. These bounds are sent to GA optimization function, so that any candidate of the airfoil-population should lie within these limits.

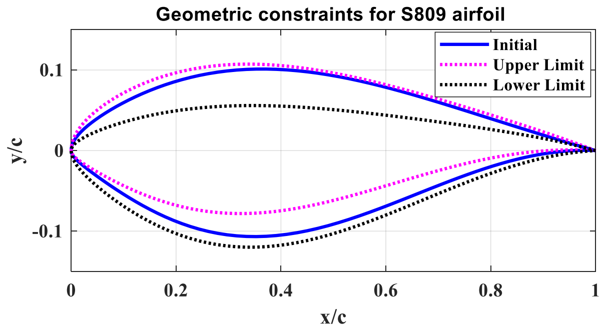
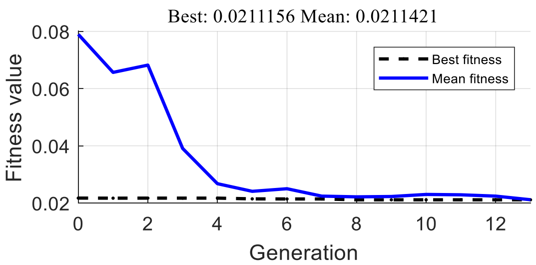


Figure 3 Geometric constraints

5. Results and discussion

Appling the above described methodology with GA method population size of 30 airfoils per generation. The optimization process drives the solution to the optimum design in about 10 generations, as illustrated in Fig(4) .



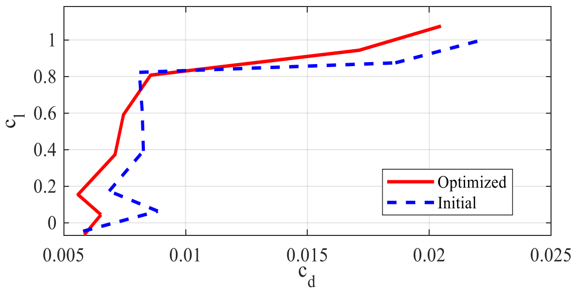


Figure (4) Convergence history of GA method

Figure (5) Comparision of drag polar

A total of 1030 function evaluations were needed to arrive at the best airfoil shape. The drag polar curve, Fig. (5) shows clearly a significant improvement in drag coefficient in the entire range of angle of attack of about 8% of the original value. The aerodynamic constrains function was working successfully in which the lift was slightly lower than the original airfoil. The aerodynamic efficiency in terms of lift to drag ratio was kept fixed at the same values with angle of attack. Figure (6) and (7) show comparison between initial and optimal airfoil shapes. Values of lift coefficient and Lift to drag ration are kept close to the target values for whole design range. A comparison between initial and optimum airfoil shapes is shown in Fig. (8). It can be seen that the optimized maximum airfoil thickness is slightly less than that of the initial airfoil. For the root section of a wind turbine blade a thicker airfoil is desirable to carry structure and aerodynamic loads.

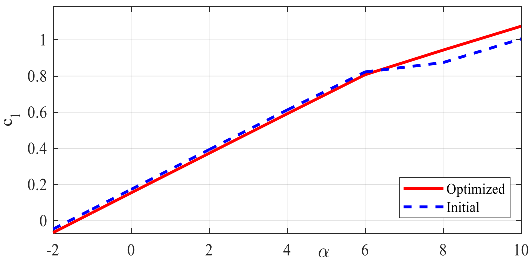


Figure (6) Variation of lift coeffiecrnt with angle of attack

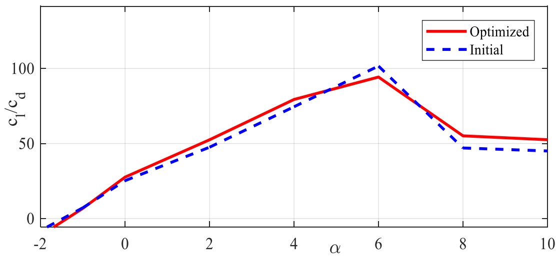


Figure (7) Comparision of L/D ratio

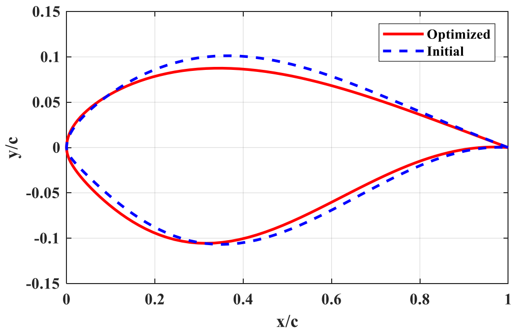


Figure (8) Comparison between initial and optimum airfoil shapes

6. Conclusion

In this paper, a multipoint multi objective genetic algorithm optimization has been employed to optimize the shape of a widely used research airfoil NREL S809. The main goal was to minimize drag at three angles of attack laying at the middle of operating range of the airfoil. An inviscid-viscos interaction-based code is used. This methodology is fast during preparation and efficient while calculation compared to CFD based methodology which requires more time and effort. The optimized airfoil shape shows improved drag coefficient compared with original airfoil at the specified flow conditions. This work can be extended by comparing the drag coefficients for the optimized airfoil to that calculated by other blade analysis codes, such as, Qbalde code.

References

[1] Perez-Blanco, H., McCaffrey, M. Aerodynamic Performance of Preferred Wind Turbine Airfoils. in Proceeding of ASME Turbo Expo 2012: Power for Land, Sea and Air, GT 2012. Copenhagen, Denmark.

[2] DeFalcot, I., DelBalio, R., Cioppa, A.D., Tarantino, E. A parallel genetic algorithm for transonic airfoil optimization. in In Proceeding of International Conference on Evolutionary Computation. 1995.

[3] Brian, J.R., William, C.A., Anastasios, L.S., Aerodynamic and Aeroacoustic Optimization of Airfoils via a Parallel Genetic Algorithm, in AIAA Paper, 98-4811.

[4] J. L. Tangler and D. M. Somers, "NREL airfoil families for HAWTs," in Wind Power, pp. 117–123, Washington, DC, USA, 1995. View at Google Scholar

[5] D. M. Somers, "Design and Experimental Results for the S809 Airfoil," NREL/SR-440-6918, January 1997.

[6] Kulfan B, Bussoletti J. " Fundamental" Parametric Geometry Representations for Aircraft Component Shapes. In11th AIAA/ISSMO multidisciplinary analysis and optimization conference 2006 Sep 6 (p. 6948).

[7] Kulfan BM. Universal parametric geometry representation method. Journal of Aircraft. 2008 Jan;45(1):142-58.

[8] Ceze M, Hayashi M, Volpe E. A study of the CST parameterization characteristics. In27th AIAA Applied Aerodynamics Conference 2009 Jun 22 (p. 3767).

[9] Abobaker, Mostafa, et al. ,Aerodynamic characteristics of low Reynolds number airfoils, Technical Gazette , 24.1 (2017): 111-118.

[10] Abobaker, Mostafa.,Low Reynolds number airfoils. PhD thesis, Belgrade, 2017.

[11] Mostafa Abobaker, Airfoil Optimization by Systematic Shape Modification at Low Reynolds Number, cist conference 2019 ,Tripoli, 2019