CILAMCE PANACM RIO DE JANEIRO 2021

Improving HAWT Blade Design with multiphase BEM application and GA based airfoils for Low Reynolds conditions

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Abstract. Over the years, renewable energy sources are being implemented and improved. One such case is of wind turbines. Some of the many challenges in this area are wind turbine placement and design. In low Reynolds conditions coupled with highly turbulent air flow, the airfoil design is particularly complicated. By extension, this complicates the design of the whole blade. In this paper, a fast method to determine good geometry for the wind turbine blade is established. After flow conditions are set, by repeatedly applying the BEM method, more accurate descriptions of the flow on the blade are obtained. Afterwards, finding best NACA airfoils as a base and using Bezier curves as a geometry creator, a population of airfoils goes through a Genetic Algorithm. For each blade region, a GA generated airfoil is found. Finally, the BEM method is used to determine the new expected power coefficient with the new airfoil geometries. For the case used in this study, the final power coefficient obtained was 0.28% lower than the target.

Keywords: Blade Element Momentum Method, Panel method, Bezier curves, Wind Turbine Blade Optimization, Genetic Algorithm

1 Introduction

Over the past years, the world has experienced an increase in its quality of life and it is expected that this trend continues according to Heylighen and Bernheim [1]. However, according to Arto et al [2], one hindrance that accompanies such development is the increase in total primary energy requirement of countries. Moved by this necessity and with an increase in climate awareness, renewable energy technologies experienced an explosive growth in the last few years. One such technology is the use of wind turbines for power generation. Data from GWEC [3] shows that although global installations continue to grow, the challenge presented by fossil-fuel energy sources is still ongoing. Drew et al [4] argues that there are two approaches for this problem: improve placement and improve turbine design. This paper aims to create a fast method to determine good wind turbine blade geometry by using the Blade Element Momentum (BEM) Method in various steps to get more accurate flow descriptions, and get better airfoil profiles for each segment of the blade.

2 The BEM Method

The blade element momentum (BEM) method is a model used to acquire, by iteration, power and performance of a wind turbine based on its geometry and flow condition. This model is a combination of 2 different theories: the blade element theory (BET) and the Momentum Theory. The method used in this paper is the second method described in by Manwell et al [5].

First, the blade is divided in N elements. Next, with the flow conditions, the polar curves for the initial airfoil profile are obtained. Afterwards, the value of angle of attack (α), lift coefficient (C_l) and drag coefficient (C_d) with the best ratio C_l/C_d is obtained.

An estimation of the speed ratio, angle of relative wind, chord length and local solidity is obtained using optimum rotor theory. According to Manwell et al [5], for energy generation, 3 is a good number of blades accounting for structural dynamic problems. Furthermore, the tip speed ratio can be between 4 and 10.

The values calculated for the optimum rotor will be an initial guess to start the iteration to find the best geometry. With these values, the axial (a) and angular induction (a') factors can be calculated. This starts the iteration process, because with the values of a and a' , new values of chord length, angle of relative wind and local solidity can be calculated. Furthermore, a tip-loss factor can be calculated at each step with a and a', accounting for the fact that the blade is of limited length. With the new values of flow and geometry, the local thrust coefficient can be calculated. The new values of a and a' can be calculated paying attention to using Glauert empirical relation if the local thrust coefficient is greater than 0.96. With convergence, the power coefficient of the turbine can be calculated and the power obtained after.

3 Bezier Curves

Bezier curves are frequently used in aerodynamic optimization as shown by Peigin and Epstein [6]. They are parametric curves, related to the Bernstein polynomial, defined by the formula below:

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} t^i P_i \quad (1)$$

Where n+1 is the number of points, n is the degree of the curve, $\binom{n}{i}$ are the binomial coefficients and P_i are the points used.

4 The Genetic Algorithm

The method is based around Darwin's evolution theory where an initial population is generated, each member is evaluated following an evaluation criterion, the best members are then reproduced with a defined crossover rate and mutation chance for each new individual. With the new population generated, the process is repeated until convergence of evaluation is achieved or number of iterations is satisfied.

In this paper, for each iteration a population of 10 individuals are evaluated, the 4 best individuals reproduce with a crossover rate of 50% and, in generating the new population, the new individuals will be subjected to a mutation chance of 30%. The algorithm will run until 200 iterations.

Although the genetic algorithm is a very robust method, it is also very time consuming. Furthermore, great care must be applied in generating a new population, otherwise unrealistic profiles will waste computational time.

The restrictions applied in the generating process of each individual are shown below:

- Extrados curve y coordinates bigger than the intrados y coordinates for similar x coordinate;
- Minimum thickness in any part of the airfoil of at least 0.04;
- Minimum thickness of 0.025 at 0.9c;
- Maximum thickness not greater than 0.3;
- Check curvature along extrados and intrados to avoid wave profiles;

5 Methodology

The process starts by defining the situation the wind turbine will be used. In this paper, the location analyzed will be the southeast region in Brazil expecting the use of wind turbine on top of buildings. This specific case is chosen because low-Reynold's wind turbines are still underperforming according to data from ENCRAFT [7] and this flow bodes well with the aerodynamic solver used.

Next, the initial flow conditions are defined based on the mean windspeed of the region, the altitude of the expected flow, and an initial guess for mean blade chord length. The blade length of the wind turbine can be estimated by using the power formula from Manwell et al [5].

$$P = \frac{1}{2}\rho\pi R^2 U^3 \eta C_p \quad (2)$$

Where P is the rotor power, ρ is the air density, R is the blade length, U is the windspeed, η is the mechanical/electrical efficiency and C_p is the power coefficient.

Having defined the flow conditions, an initial guess of NACA profile is used to help create the first blade geometry. With a starting profile defined, BEM method will be used to acquire the first blade geometry parameters. With this geometry, the flow conditions throughout the blade are defined. The blade is separated in 3 regions: hub, middle and tip. The hub region will be the initial 20% length of the blade. The middle region will be between 20% and 90% of the length of the blade and the tip region will be the last 10% of the blade.

For each region, an average flow condition is obtained. Afterwards, it is used an association of the software XFoil and MATLAB to determine the best NACA 4-digit series for each given flow conditions. These NACA profiles will be used as a starting point for the coming optimization algorithm.

Applying BEM again but now with the new NACA profiles, a secondary blade geometry is created and the flow conditions for each region are updated. Having defined a good starting point geometry and the flow condition expected to operate, the NACA profile will be reverse engineered into Bezier curves using the method introduced by Fazil and Jayakumar [8] and 6 control points will be obtained each for the upper and lower surface. Of those points the starting and ending points are invariant but the 4 middle points for each surface can be varied in an interval to generate new geometries.

Next, the 8 variable Bezier control points and an also variable angle of attack for the airfoil are inserted in a Single-Objective Genetic Algorithm (SOGA) evaluating the L/D ratio for each airfoil. This evaluation criterion is defined because the L/D ratio is the most important parameter for a wind turbine design according to Burton et al [9]. Now for each segment of the wind turbine blade, a GA generated airfoil will be obtained.

Finally, updating the airfoil geometry of each segment and using BEM, the expected power output of the final blade geometry is derived.

A schematic with a summary of the design process is shown below:

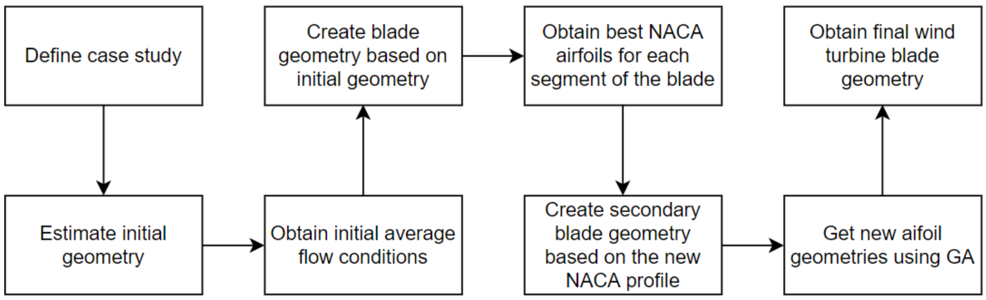

Figure 1. Design process schematic

6 Results

At a height of approximately 30 meters the windspeed can be estimated from data of CEPEL [10] at 4.5 m/s. The air flow conditions used in this study are presented at the table below:

Table 1. Air flow parameters on this study

Parameter	Nomenclature	Value	Unit
Altitude	h	30	[m]
Average windspeed	U	4.5	[ms^{-1}]
Air density	ρ	1.22	[$kg \cdot m^{-3}$]
Air dynamic viscosity	μ	1.82e-5	[$kg \cdot s^{-1} \cdot m^{-1}$]

Applying a target power of 1kW, target power coefficient of 0.5 and an expected efficiency of 70% and with values from Table 1, the blade length is estimated.

Furthermore, an average chord length must be estimated. In this paper, for the initial guess, the average chord length of the wind turbine is 5% of the blade length. Finally, for an initial guess of airfoil, the NACA 0012 is used.

This profile is well documented for wind turbine applications as shown by Silisteanu and Botez [11].

With the values in Table 1, and the average chord length the Reynold's and Mach's numbers can be calculated.

Table 2. Initial guess for blade geometry and derived flow conditions

Parameter	Value	Unit
Target power	1000	[W]
Target power coefficient	0.5	[---]
Expected efficiency	0.7	[---]
Blade length	4.05	[m]
Average chord length	0.2025	[m]
Initial Reynolds number	6.11e4	[---]
Initial Mach number	0.0132	[---]

After obtaining the first geometry, and with the information of the flow conditions at the 3 regions of the blade, the best NACAs are found for each region. The results are presented below:

Table 3. Best NACAs for each region of the blade based on the previous geometry

Region	NACA	best Cl/Cd
Hub	3512	76.49
Middle	4512	94.07
Tip	3512	82.98

With the NACAs from Table 3, the geometry of each NACA is transformed into Bezier curves and the control points are obtained. An example of Bezier curve generated by the NACA 3512 and the intervals at which the control points will vary is presented below:

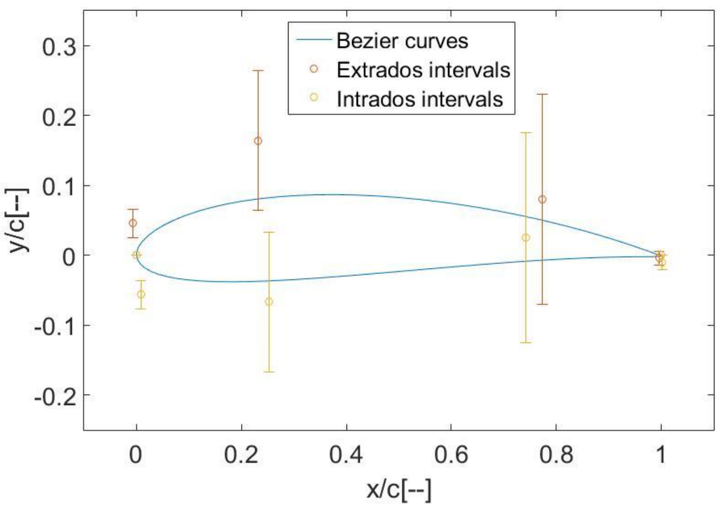

Figure 2. Intervals for the NACA 3512 Bezier control points

With the flow conditions obtained from the second geometry, the inputs are inserted in the Genetic Algorithm and a population of 10 geometries are created.

The Cl/Cd history throughout the implementation and some geometry examples are presented below for the hub, middle and tip region:

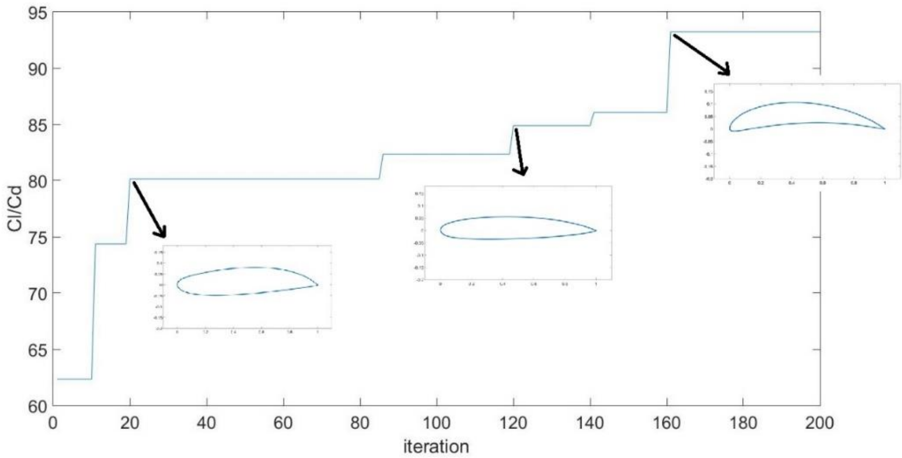

Figure 3. Optimization history for the hub region

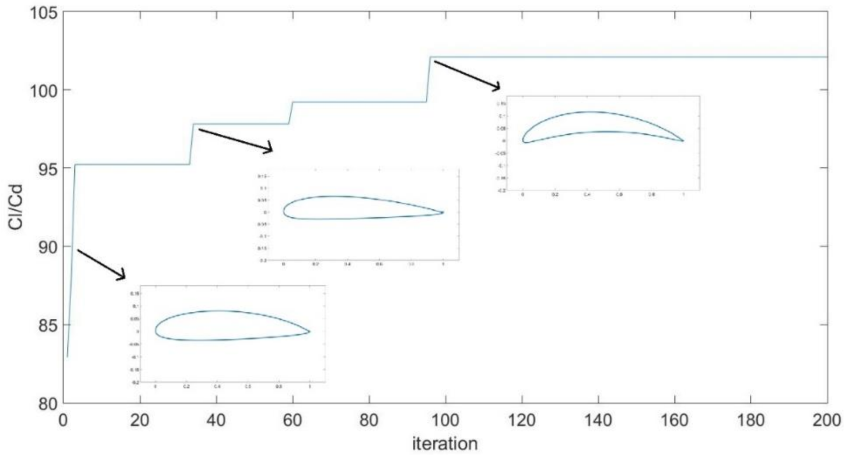

Figure 4. Optimization history for the middle region

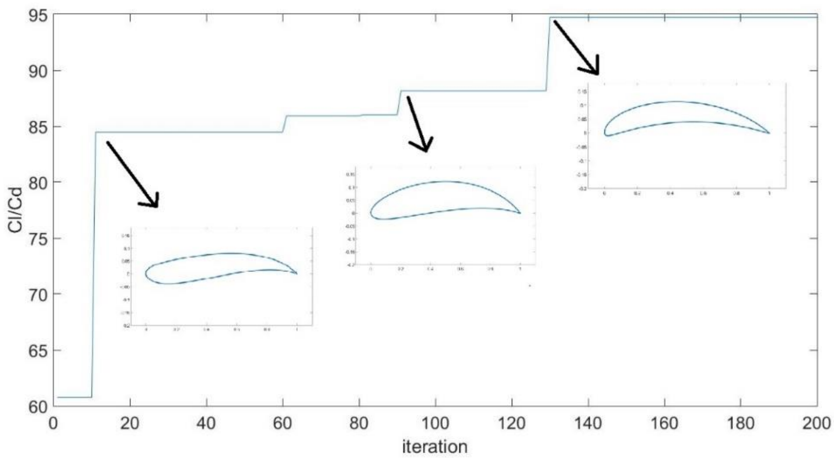

Figure 5. Optimization history for the tip region

With the new airfoils for all the 3 regions, the BEM method is used for the last time to obtain the final blade geometry. The configuration of chord length and pitch angle for the final geometry is:

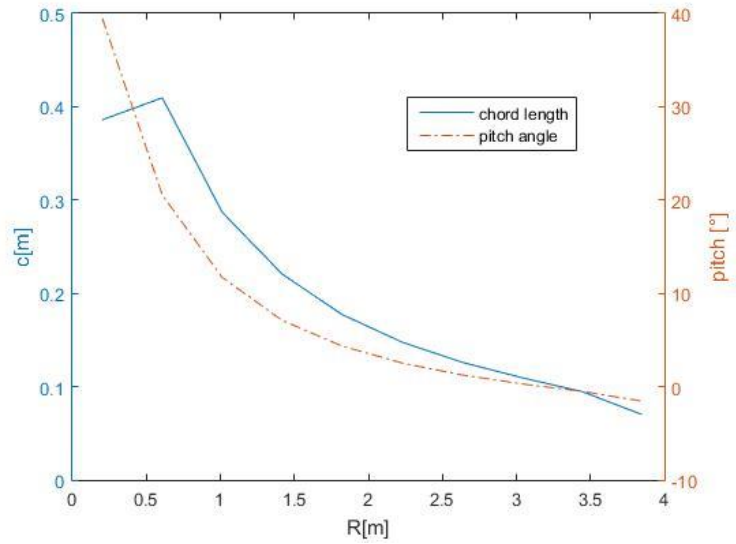

Figure 6. Chord length and pitch angle vs. distance from hub for the final geometry

The final performance parameters are shown on Table 4. The history of flow condition at each region of the blade for each geometry is shown on table 5.

Table 4. Performance parameters for the final geometry

Parameter	Nomenclature	Value	Unit
Tip-speed ratio	λ	8	[---]
Power coefficient	C_p	0.4986	[---]
Power	P	1000.9	[W]

Table 5. Final flow conditions at each blade region for the final geometry

	Region	Re [---]	Mach [---]
First geometry	Hub	1.96e5	0.0166
	Middle	2.68e5	0.0496
	Tip	2.56e5	0.0905
Second geometry	Hub	1.96e5	0.0166
	Middle	2.46e5	0.0548
	Tip	2.31e5	0.0961
Third geometry	Hub	1.52e5	0.0166
	Middle	1.97e5	0.0548
	Tip	1.79e5	0.0961

It is noticed that the final wind turbine power overshoots a little the target power defined in the beginning. This is due to the fact that the value used for blade length is rounded up. The table below presents a comparison between the 3 stages of geometries and the overall improvement:

Table 6. Comparison between geometries at different steps

Geometry	Cp [---]	Overall improvement
First	0.4649	- - -
Second	0.4753	2.24%
Final	0.4986	7.25%

7 Conclusions

The division of the blade in 3 regions helped improve power generation in 2% and the use of Genetic Algorithm to define the final airfoil profile for each region improved power generation overall by additional 5%. Both these percentages are coupled with the fact that the flow condition was being updated with each new geometry, making the selection of better profiles more accurate.

The method has its shortcomings. Since the evaluation method is dependent of XFOIL, transonic and supersonic flows can't be evaluated. So, there is a limit on the design windspeed that can be used. Nonetheless, for subsonic flows, XFOIL presents a good conformity of results with other method but it is much faster. The use of another evaluation method for the airfoil generation in the Genetic Algorithm may bring better results but with an increase in computational cost.

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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