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Optimization of Aerodynamic and Structural Performances of a Wind Turbine Blade by the Ant Colony Algorithm (ACO)

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Abstract: The purpose of this study is to optimize the energy efficiency of a wind turbine blade and reduce its cost. In this paper, we define several optimization targets such as maximizing Cl / Cd ratio and minimizing the deformation and mass of the blade. To solve this multi-objectives optimization problem, we used the ant colony heuristic optimization method on a blade model computed by the BEM and the FEM methods. The optimization results are compared with the results obtained by the BEM method.

Key words: Wind turbine · Aerodynamic performance · Blade Optimization · Ant Colony · BEM · FEM

INTRODUCTION

Wind turbines have become among the most requested energy sources in the world. This evolution of demand can be assigned to several reasons which making it more competitive with fossil fuels and fissile energy. For instance, wind energy is a clean energy that does not emit any toxic gases or wastes; and it is renewable and sustainable. However, the cost of manufacturing and operating wind machines is still high and as a result, the cost of the energy produced is still high. Manufacturers of wind turbines and researchers working on the development of these machines are still trying to produce machines that are more reliable with high profitability and lower production cost. Moreover, the literatures show several research works aimed to optimizing the performance of wind turbines [1-3].

The optimization of wind machines can be done over several levels. Some researchers are working on the development of control algorithms to maximize the power produced [4, 5]. Other contributions are working on optimizing the geometry and structure of the machine components, especially the blades [3, 6].

First, the blades optimization requires the definition of optimization objectives. Some researchers define the general objective of minimizing the cost of energy and maximizing annual production [7]. Under this objective, several parameters can be defined as specific optimization goals. For an accurate optimization, we must take into account all the parameters acting on the blades behavior. In other words, we must define several optimization targets; we refer then to a multi-objective optimization [8]. Numerous optimization techniques are proposed by researchers. Among these, we found the classical techniques based on mathematical functions[9], which require a perfect knowledge of the studied system. Recently, smarter methods inspired from nature have being emerged. For instance, heuristic or evolutionary methods can yield perfect optimization results [1, 2, 10].

In this paper, we apply a heuristic optimization algorithm called the ant colony algorithm to optimize the aerodynamic and structural performance of the blade to reduce the cost of energy produced and improve the annual production cost. In the first phase, we proposed a model of a blade optimized by BEM method coupled with the structural model developed by finite element methods. In the second phase, we applied the ant colony method.Finally, we compare the optimization results obtained with a conventional method.

BladeModeling

Aerodynamic BEM Model of the Blade: The Blade Element Momentum theory (BEM) method developed by Glauert is used by most of the blade simulation software thanks to its simplicity and calculation speed and thus the accuracy of the obtained results. It is the combination of the axial flow method, which uses a dynamic equilibrium on a rotary annular flow tube and the

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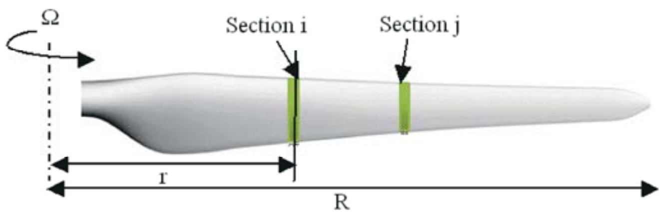


Fig. 1: Representation of the blade and sections.

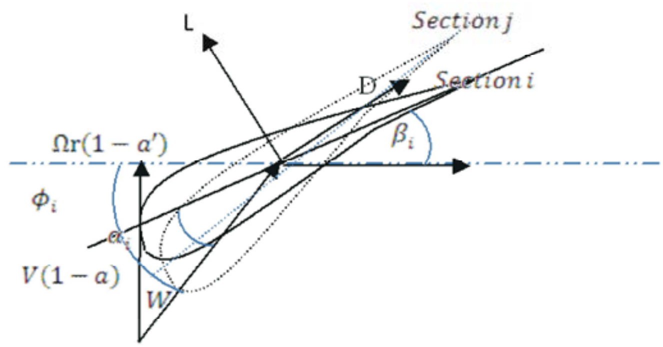


Fig. 2: Geometric representation of the blade sections.

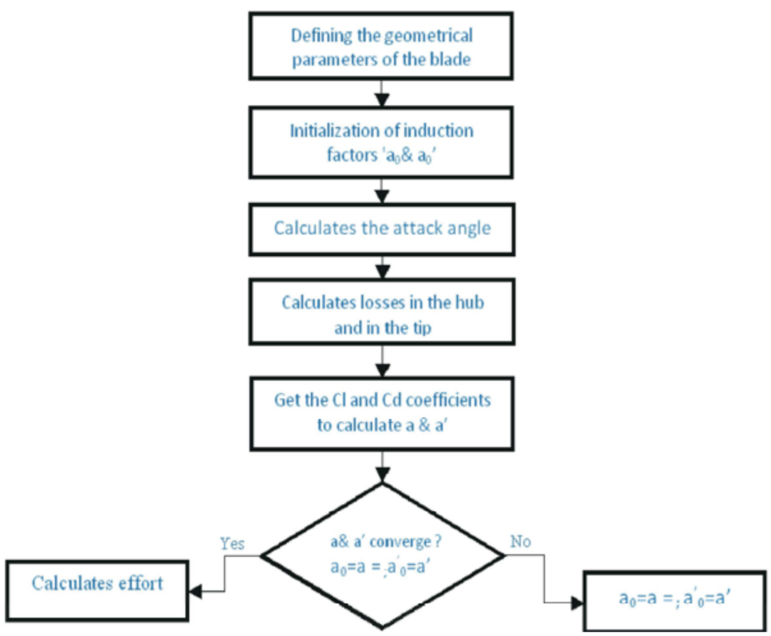
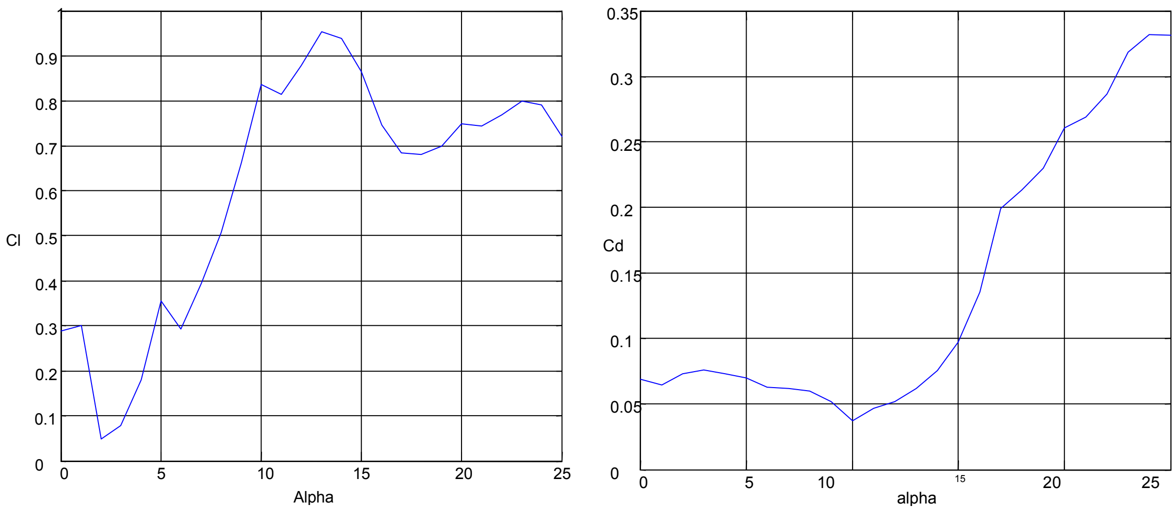


Fig. 3: Organization chart of the BEM method.

blade element method, which consists of discretizing the blades into dr elements in order to determine the forces applied on each element from the aerodynamic coefficients of blade profile. This method is based on the division of the flow into annular control volumes of thickness d, to which the balance of momentum and energy is applied. These rings extend from the upstream infinity to the downstream infinity with respect to the rotor. The lift and drag forces as well as the tangential moments can be calculated from the incident wind speed and the angle of attack. The aerodynamic characteristics of the air profile are predefined[11].

The BEM calculation procedure is started by initializing the axial and tangential induction factors (a) and (a') (a = 0 & a' = 0), then calculating the wind angle Φ and the attack angle α using the following formula:



(a) Coefficient of lift Cl (b) Coefficient of drag Cd

Fig. 4: Aerodynamic coefficients of the blade as a function of the attack angle.

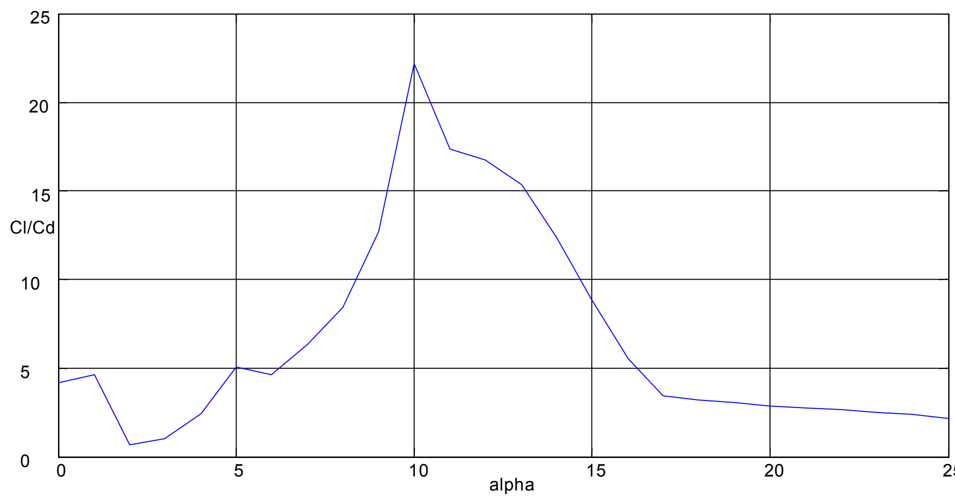


Fig. 5: Cl / Cd ratio depending on the attack angle.

$$\emptyset = arctg\frac{(1-a)V}{(1+a')r\Omega} \quad (1)$$

To calculate the losses in the hub and tip of the blade we use the following two equations:

$$F_p = \frac{2}{\pi}\arccos\left(\exp\frac{-B(R-r)}{2R\sin\phi}\right) \quad (2)$$

$$F_{hub} = \frac{2}{\pi}\arccos\left(\exp\frac{-B(r-r_{hub})}{2r_{hub}\sin\phi}\right) \quad (3)$$

Subsequently, we used C1 and Cd coefficients, which were determined from a CFD numerical computation of the S809 profile (Figures 4 and 5), to recalculate the axial and tangential induction factors a and a' by the following relations:

$$a = \frac{Bc(C_l\cos\phi + C_d\sin\phi)}{8\pi rF\sin^2\phi + Bc(C_l\cos\phi + C_d\sin\phi)} \quad (4)$$

$$a' = \frac{Bc(C_l\sin\phi + C_d\cos\phi)}{8\pi rF\sin\phi\cos\phi - Bc(C_l\sin\phi + C_d\cos\phi)} \quad (5)$$

With F is the coefficient of loss in the rotor. If (a)> 0.4, the method is invalid, then the factor must be corrected by the following equation.

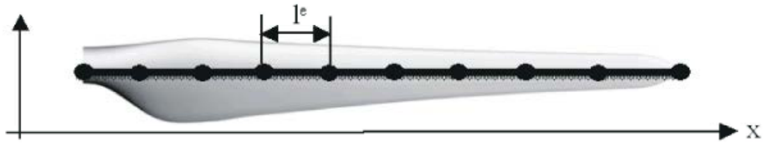


Fig. 6: Simplified structural model of the blade.

$$a = \frac{1}{2}\left[2 + K_a(1-2a_c) - \sqrt{(K_a(1-2a_c))^2 + 4(K_a\ a_c{}^2 - 1)} \right] \quad (6)$$

With

$$K_a = \frac{8\pi rF\sin^2\phi}{BC(C_l\cos\phi + C_d\sin\phi)} \quad (7)$$

We repeat these steps until we have a convergence of (a) and (a′) then we calculate the torques and aerodynamic forces given by formulas (8) (9).

$$dT = 4\pi F\rho V^2 \text{a}(1-a)rdr \quad (8)$$

And

$$dM = 4F\rho\Omega V\, \text{a}'(1-a)\pi r^3 dr \quad (9)$$

The coefficient of pressure or thrust Ct is by definition:

$$C_t = \frac{T}{\frac{1}{2}\rho V^2 2\pi rdr} \quad (10)$$

Aerodynamic Characteristics: The blade studied in this case study is based on the S809 air profile. The aerodynamic performances are found using a CFD numerical calculation. Fig. 4 (a) and (b) respectively illustrate the evolution of the lift coefficient Cl and Cd as a function of the attack angle.

The improvement of the aerodynamic performance of the blade involves the increase of the thrust force and the reduction of the drag force, this objective is translated by the maximization of the C1 / Cd ratio, FIG. report according to the attack angle.

Structural Model: The structural behavior has a very remarkable influence on the profitability of the blade. Thus, taking cogeneration of the vibratory effects in the optimization operation is very important. We have developed, in this part, a structural model of a blade by the element method. The blade is conceded as a one-dimensional beam as shown in Fig. 6.We seek to develop a motion equation of the following form:-

$$M\ddot{q} + C\dot{q} + Kq = F$$

where M is the matrix of global masses, C is the damping matrix, K is the stiffness matrix and $\ddot{q}$, $\dot{q}$, & q represent respectively the nodal vectors of acceleration, velocity and displacement.

The matrices of masses and stiffness are respectively obtained by the following equations:

$$M_e = \rho s(x)\int_e N_e^T(x)N_e(x)dx \quad (11)$$

$$K^e = \int_0^{l^e} EI\left(\frac{d^2N}{dx^2}\right)^T \left(\frac{d^2N}{dx^2}\right)dx \quad (12)$$

The interpolation function of Hermite is defined by:

$$N(x) = [N_1(x)N_2(x)N_3(x)N_4(x)] \quad (13)$$

With

$$\begin{cases} N_1(x) = 1 - 3\left(\frac{x}{l}\right)^2 + 2\left(\frac{x}{l}\right)^3 \\ N_2(x) = \left(\frac{x}{l}\right) - 2\left(\frac{x}{l}\right)^2 + \left(\frac{x}{l}\right)^3 \\ N_3(x) = 3\left(\frac{x}{l}\right)^2 - 2\left(\frac{x}{l}\right)^3 \\ N_4(x) = -\left[\left(\frac{x}{l}\right)^2 - \left(\frac{x}{l}\right)^3\right] \end{cases} \quad (14)$$

From the equations (11) and (12), we obtain the matrices of the masses and of elementary rigidity.

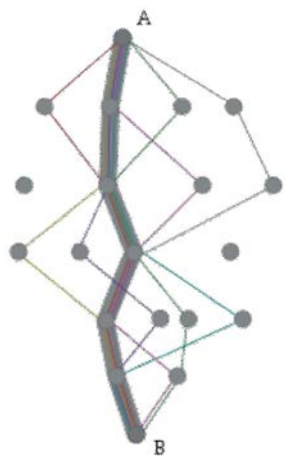


Fig. 7: Optimal path determined by the ant colony algorithm.

$$M^e = \frac{\rho s(x) l^e}{420}\begin{bmatrix} 156 & 22l^e & 54 & -13l^e \\ 22l^e & 4l^{e2} & 13l^e & -3l^{e2} \\ 54 & 13l^e & 156 & -22l^e \\ -13l^e & -3l^{e2} & -22l^e & 4l^{e2} \end{bmatrix} \quad (15)$$

where $s(x)$ is the section of each element.

$$K = \frac{EI^e}{l^{e3}}\begin{bmatrix} 12 & 6l^e & -12 & 6l^e \\ 6l^e & 4l^{e2} & -6l^e & 2l^{e2} \\ -12 & -6l^e & 12 & -6l^e \\ 6l^e & 2l^{e2} & -6l^e & 4l^{e2} \end{bmatrix} \quad (16)$$

Assuming that I (x) is constant for a given element and that it varies from one element to another in a quadratic way.

$$I(x) = I_1\left[l + \left(\sqrt[4]{\frac{I_2}{I_1}} - 1\right)\frac{x}{L}\right]^4$$

I_1: is the quadratic moment of the embedding section.

I_2 : is the quadratic moment of the free section of the blade.

By assembling these matrices, we finally obtain the matrices of the masses and rigidity of the blade.

Optimization of the Blade

Optimization by the Ant Colony Algorithm: The ant colony algorithms were proposed by Colorni, Dorigo and Maniezzo in 1992 and first applied to the commercial traveler problem. The principle of this method is based on the particular behavior of ants, which use to communicate a particular volatile chemical called pheromone[12], [13].

The displacement rule, called the "proportional transition random rule", is written mathematically in the following form (17):

$$p_{ij}^k(t) = \begin{cases} \dfrac{\tau_{ij}(t)^{\alpha}.\eta_{ij}^{\beta}}{\sum_{l \in J_i^k} \tau_{il}(t)^{\alpha}.\eta_{il}^{\beta}} & \text{si } j \in J_i^k \\ 0 & \text{si } j \notin J_i^k \end{cases} \quad (17)$$

where J_i^k is the list list of possible movements for an ant k when it is on a city i, η_{ij}. The visibility, which is equal to the inverse of the distance of two positions: I & j ($1/d_{ij}$) and $\tau_{ij}(t)$ and the intensity of the track at a given iteration t. The two main parameters controlling the algorithm are α & β, which control the relative importance of the intensity and visibility of an edge.

Once the tour of positions is completed, an ant k deposits a quantity of $\Delta\tau_{ij}(t)$ pheromone on each edge of its course:

$$\Delta\tau_{ij}^k(t) = \begin{cases} \dfrac{Q}{L^k(t)} & \text{si } (i,j) \in T^k(t) \\ 0 & \text{si } (i,j) \notin T^k(t) \end{cases} \quad (18)$$

where $T^k(t)$ is the trajectorycarried out by the ant k at iteration t, $L^k(t)$ is the length of the trajectoryand Q is the setting parameter. At the end of each iteration of the algorithm, the pheromones deposited at the previous iterations by the ants evaporate from a $\rho\tau_{ij}(t)$. And at the end of the iteration, we have the sum of the pheromones which have not evaporated and those which have just been deposited:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^k(t) \quad (19)$$

With $\Delta\tau_{ij}(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^k(t)$ and m is the number of ant used for iteration t & ρ is a setting parameter.

Implementationon the Blade: When talking about blade optimization, we are searching for a perfect geometrical and structural configuration that gives a maximum energy productivity and efficiency. In an optimization procedure, we can define an optimization objective. In this case, we called a mono-objective optimization, but we can also define several optimization objectives and we called a multi-objective optimization.

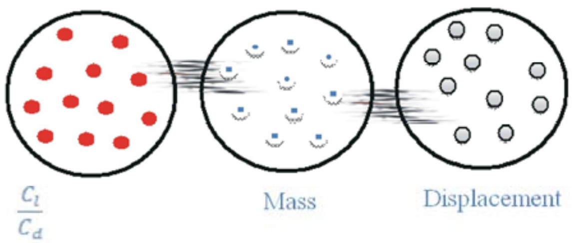


Fig. 8: Formulation of blade optimization parameters.

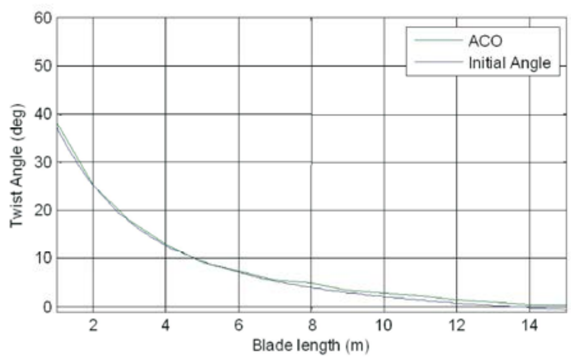


Fig. 9: Distribution of the twist angle on the blade for the initial and the optimized blades.

In the case of wind turbine blades, the main objective is generally the improvement of annual energy production. This can be described by several sub-objectives. The first objective is the maximization of the lift force and the minimization of the drag force by maximizing the power factor of the rotor Cl / Cd. The second objective is the minimization of the deformations of the blade by adjusting the blade thickness, but without exceeds the maximum mass of the blade, which must be considered.

The optimization variable is the rope, the twisting angle and the thickness of each blade element.

From these objectives, we seek an optimal configuration of the blade. The ant colony algorithm is applied as shown in Figure 8. The three circles cluster together the possible values of the optimization variables, while the algorithm must selects the optimal values.

Formulation of the Objective Function: The choice of optimization objectives is a critical task in an optimization procedure. In our case, we have chosen as objective, the maximization of the Cl / Cd ratio: in other words, the increase of the lift forces of the blade and minimized the drag forces, which generates undesirable deformations. We also define as objective the minimization of the displacement of the blade. The objective functions of this optimization are:

$$f_1 = \max\left(\frac{C_l}{C_d}\right) \tag{20}$$

$$f_3 = \min(m) \tag{21}$$

$$f_2 = \min\left(\int_{R_{hub}}^{R} d_i.dr\right) \tag{22}$$

The optimization of the blade is controlled by geometric and structural constraints. The strings, twisting angles and thicknesses of each element of the blade are subject to the following constraints.

$$c_{\min} \le c_1 \le \ldots \le c_i \le c_{\max} \tag{23}$$

$$\beta_{\min} \ge \beta_1 \ge \ldots \ge \beta_i \ge \beta_{\max} \tag{24}$$

$$m_{\min} \ge m_1 \ge \ldots \ge m_i \ge m_{\max} \tag{25}$$

Simulation Results: The ACO optimization process is performed on an initial blade model calculated by the BEM method.

The ant colony algorithm has selected a path of the calibration angle values and the lengths of the strings from the capacitor matrix. This path gives an optimal geometric configuration.

By comparing the simulation results obtained by the BEM method and by BEM optimization, it is noted that the optimized angle of adjustment of the various positions on the blade is displaced a little, but the curve has always kept its shape, Fig. 9.

Similarly, we note that the rope length of the optimized blade is decreased in zone 1 and increased in zone 2, Fig. 10.

By exploitation of these results, we reconstruct the 3D models of the initial and the optimized blades. Fig. 11 clearly illustrates the evolution of the rope and the twist angle of the two models in different areas of the blade.

To validate the efficiency of this optimization method, we calculated the evolution of the power coefficient for each model. Fig. 12 illustrates the improvement of the power factor by a percentage of 10.34% in a TSR = 5 compared to the other curve.

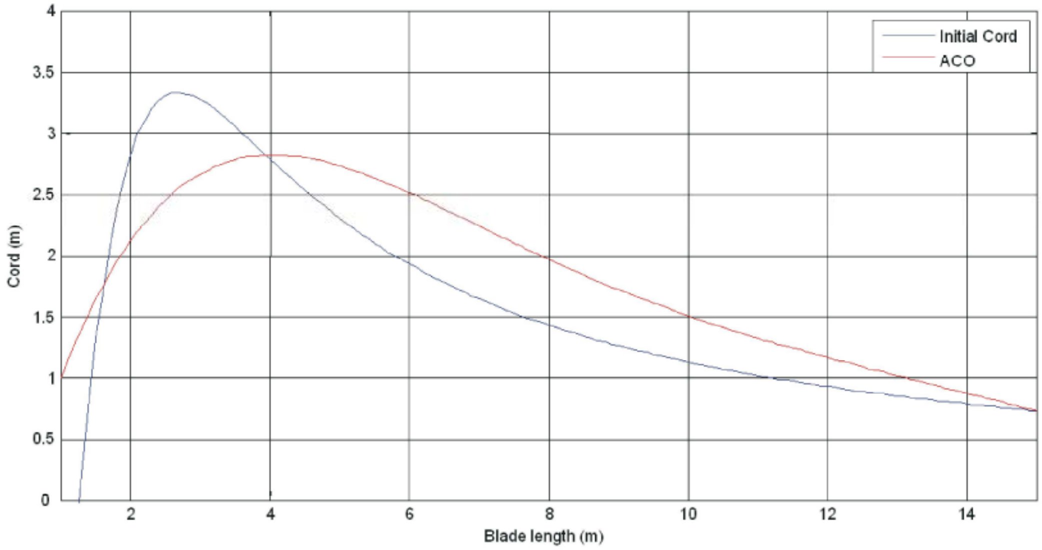
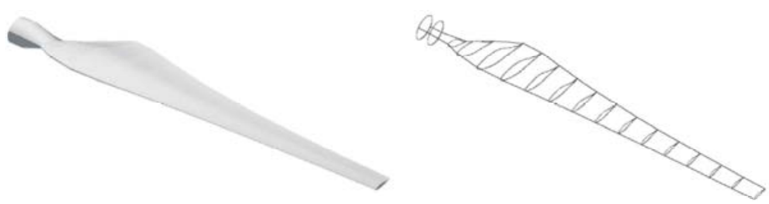


Fig. 10: Distribution of the rope on the blade for the initial and the optimized blades.



(a) 3D model of initial blade

(b) 3D Model of optimized blade

Fig. 11: 3D geometric representation of initial and optimized blades.

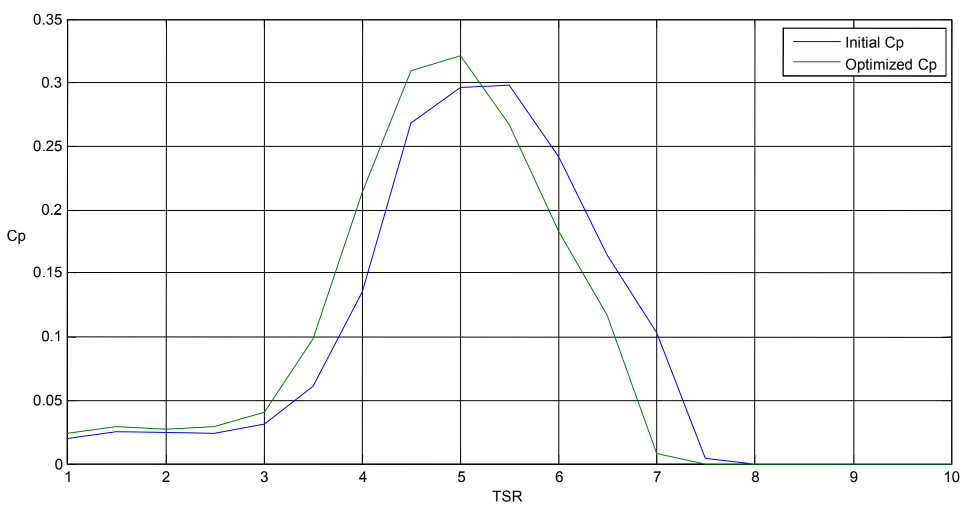


Fig. 12: Coefficient of power versus ratio of specific speed.

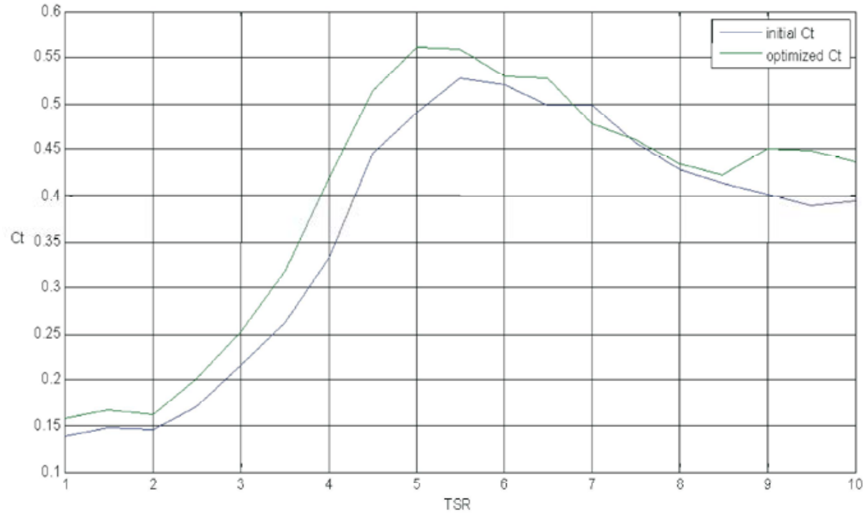


Fig.13: Coefficient of thrust of the initial blade and the optimized blade.

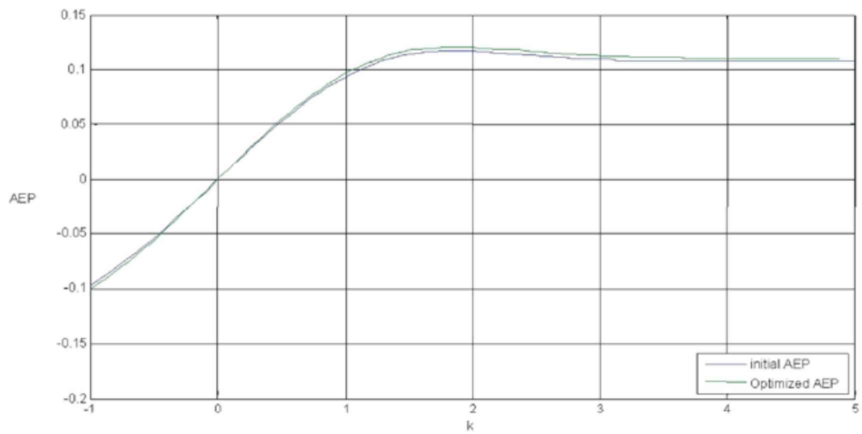
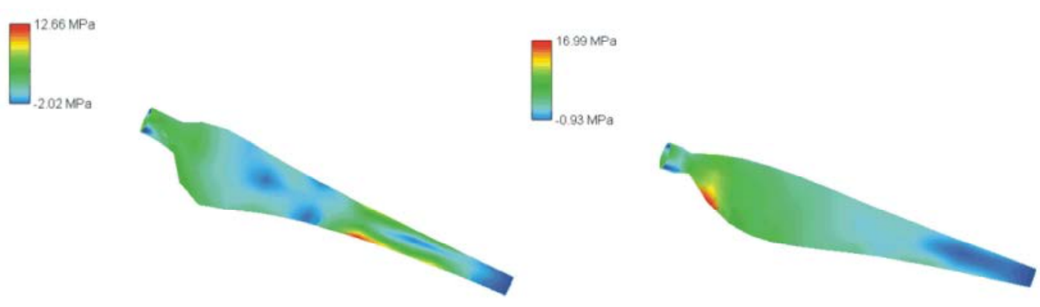


Fig. 14: Annual energy production of initial and the optimized blades.



(a) Initial blade (b) Optimized blade

Fig. 15: Constraints concentration on the initial and the optimized blade.

The lift coefficient Ct of the optimized blade is also evolved by a percentage of 14.28% with respect to the thrust/push coefficient of the initial blade. Fig. 13 shows the evolution of this coefficient for the two blades.

The optimization by the ant colony method allows us to improve the annual energy production of the machine. Fig. 14 shows the energy gain that reaches 10% compared to the wind turbine based on the initial blade. k is the factor of Weibull shape which defines the shape of the distribution and accepts a value from 1 to 3. A lower value would imply a very variable wind, whereas a constant wind would imply a higher k value.

Structural Analysis: By comparing the constraints concentration of the initial and the optimized blade, it is noted that the pressure on the end of the blade is reduced, which means that the deformation is minimized.

CONCLUSIONS

This work presents the application of a heuristic method called ant colony algorithm for the design and optimization of a wind turbine blade in order to provide a high performance blade.In the first phase of this work, we applied the BEM method and the finite element method to size a preliminary/initial blade that is used as a simulation reference.In the second phase and after defining q set of optimization objectives, we applied the ant colony method, this last determine an optimal path from optimization parameters points.

We approved the efficiency of this method by simulating the new parameters. We obtained a significant gain in the power and ratio Cl/Cd coefficients, which positively influences the annual energy production of the machine which improved by 10%.

REFERENCES

1. Anjali, M., C.T. Sasanka, C.D. Raj and K. Ravindra, 2014. Meta Heuristic Method for the Design Optimization of a Wind Turbine Blade, Int. J. Curr. Eng. Technol., 3(5).
2. Chan, C.M., H.L. Bai and D.Q. He, 2018. Blade shape optimization of the Savonius wind turbine using a genetic algorithm, Appl. Energy, 213: 148-157.
3. Sjølund, J.H. and E. Lund, 2018. Structural gradient based sizing optimization of wind turbine blades with fixed outer geometry, Compos. Struct., 203: 725-739, Nov. 2018.
4. Novaes Menezes, E.J., A.M. Araújo and N.S. Bouchonneau da Silva, 2018. A review on wind turbine control and its associated methods', *J. Clean. Prod.*, vol. 174, pp. 945-953, Feb. 2018.
5. Song, D., X. Fan, J. Yang, A. Liu, S. Chen and Y.H. Joo, 2018. Power extraction efficiency optimization of horizontal-axis wind turbines through optimizing control parameters of yaw control systems using an intelligent method, Appl. Energy, 224: 267-279.
6. Benini, E. and A. Toffolo, 2002. Optimal Design of Horizontal-Axis Wind Turbines Using Blade-Element Theory and Evolutionary Computation, J. Sol. Energy Eng., 124(4): 357-363.
7. Ning, S.A., XXXX. Objectives and Constraints for Wind Turbine Optimization, pp: 55.
8. Chehouri, A., R. Younes, A. Ilinca and J. Perron, 2016. Wind Turbine Design: Multi-Objective Optimization, in Wind Turbines - Design, Control and Applications, A. G. Aissaoui and A. Tahour, Eds. InTech, 2016.
9. De, M.F.M., 2013. Mathematical Optimization of Constructive Parameters in the Behavior of Vertical Axis Wind Turbines with Straight Blades', pp: 9.
10. '(2) Optimized chord and twist angle distributions of wind turbine blade considering Reynolds number effects', *ResearchGate*. [Online]. Available: https://www.researchgate.net/publication/258994126_Optimized_chord_and_twist_angle_distributions_of_wind_turbine_blade_considering_Reynolds_number_effects. [Accessed: 31-Jul-2018].
11. Mahmuddin, F., 2017. Rotor Blade Performance Analysis with Blade Element Momentum Theory, Energy Procedia, 105: 1123-1129.
12. Ünal, M., A. Ak, V. Topuz and H. Erdal, 2013. Ant Colony Optimization (ACO)', in Optimization of PID Controllers Using Ant Colony and Genetic Algorithms, Springer, Berlin, Heidelberg, pp: 31-35.
13. Ant Colony Optimization - Techniques and Applications | IntechOpen..