OPTIMIZATION OF AERODYNAMIC AND STRUCTURAL PERFORMANCES OF A WIND TURBINE BLADE BY THE ANT COLONY ALGORITHM

M. Tahiri*
Laboratory of Energetic, Faculty of Science,
Abdelmalek ESSAADI University, Tetouan, Morocco

A. Djebli
Laboratory of Energetic, Faculty of Science,
Abdelmalek ESSAADI University, Tetouan, Morocco

A. Mimet
Laboratory of Energetic, Faculty of Science,
Abdelmalek ESSAADI University, Tetouan, Morocco

*Corresponding Author: Mohamed Tahiri*, Laboratory of energetic, Faculty of Science, Abdelmalek ESSAIDI University, Tetouan, Morocco.

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 $C_l / C_d$ 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.


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1. 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 blade's 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 been 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.

2. BLADE MODELING
2.1. 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 blade element method, which consists of discretizing the blades into \( \bar{d} \) 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].

![Figure 1 Representation of the blade and sections](image-url)
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 \(\Phi\) and the attack angle \(\alpha\) using the following formula

\[
\Phi = \arctg \frac{(1-a)V}{(1+a')r\Omega}
\]  

(1)

To calculate the losses in the hub and tip of the blade we use the following two equations:
where
\[ F_p = \frac{2}{\pi} \arccos \left( \exp \left( \frac{-B(R-r)}{2R \sin \phi} \right) \right) \]  
\[ F_{hub} = \frac{2}{\pi} \arccos \left( \exp \left( \frac{-B(r-r_{hub})}{2r_{hub} \sin \phi} \right) \right) \]

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:
\[ a = \frac{Bc(C_1 \cos \phi + C_2 \sin \phi)}{8\pi F \sin^2 \phi + Bc(C_1 \cos \phi + C_2 \sin \phi)} \]  
\[ a' = \frac{Bc(C_1 \sin \phi + C_2 \cos \phi)}{8\pi F \sin \phi \cos \phi - Bc(C_1 \sin \phi + C_2 \cos \phi)} \]

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

With
\[ K_a = \frac{8\pi F \sin^2 \phi}{BC(C_1 \cos \phi + C_2 \sin \phi)} \]

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).
\[ dT = 4F\rho U^2 a(1-a)^2 r dr \]  
\[ dM = 4F\rho\Omega U a'(1-a)^2 \pi r^3 dr \]

The coefficient of pressure or thrust \( C_t \) is by definition:
\[ C_t = \frac{\tau}{\rho \pi V^2} \]

### 2.2. Aerodynamic Characteristic
The blade studied in this case study is based on the S809 air profile. The aerodynamic performances are found using a CFD numerical calculation. Figure 4 (a) and (b) respectively illustrate the evolution of the lift coefficient Cl and Cd as a function of the attack angle.
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Figure 4 Aerodynamic coefficients of the blade 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 $C_l / C_d$ ratio, FIG. report according to the attack angle.

Figure 5 $C_l / C_d$ ratio depending on the attack angle.

3. 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 Figure 6.

Figure 6 Simplified structural model of the blade.
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:

\[
M^e = A\int_0^l \varphi(N^e)^T N^e \frac{1}{2} l' d\zeta
\]

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

The interpolation function of Hermite is defined by:

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

With

\[
\begin{align*}
N_1(x) &= \frac{2}{l^3} x^3 - \frac{3}{l^2} x^2 + 1 \\
N_2(x) &= \frac{1}{l^2} x^3 - \frac{2}{l} x^2 + x \\
N_3(x) &= -\frac{2}{l^3} x^3 + \frac{3}{l^2} x^2 \\
N_4(x) &= \frac{1}{l^2} x^3 - \frac{1}{l} x^2
\end{align*}
\]

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

\[
M^e = \begin{bmatrix}
156 & 22l^e & 54 & -13l^e \\
22l^e & 4l^e & 13l^e & -3l^e \\
54 & 13l^e & 156 & -22l^e \\
-13l^e & -3l^e & 22l^e & 4l^e
\end{bmatrix}
\]

(15)

Where \( s(x) \) is the section of each element.

\[
K = EI^e \begin{bmatrix}
12 & 6l^e & -12 & 6l^e \\
6l^e & 2l^e & -6l^e & 2l^e \\
-12 & -6l^e & 12 & -6l^e \\
6l^e & 2l^e & -6l^e & 4l^e
\end{bmatrix}
\]

(16)

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

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

\( I_1 \) is the quadratic moment of the embedding section.
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$I_2$ : 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.

4. OPTIMIZATION OF THE BLADE

4.1. 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):

$$p^k_j(t) = \begin{cases} \frac{\tau^k_0(t)^\alpha \eta^k_0}{\sum_{i \in J^k_i} \tau^k_0(t)^\alpha \eta^k_0} & \text{si } j \in J^k_i \\ 0 & \text{si } j \notin J^k_i \end{cases}$$

Where $J^k_i$ is the list list of possible movements for an ant $k$ when it is on a city $i$, $\eta_{ij}$. The visibility, which is equal to the inverse of the distance of two positions: I & j $(1/d_{ij})$ and $\tau_0(t)$, and the intensity of the track at a given iteration $t$. The two main parameters controlling the algorithm are $\alpha$ & $\beta$, 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:

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

Where $T^k(t)$ is the trajectory carried out by the ant $k$ at iteration $t$, $L^k(t)$ is the length of the trajectory and $Q$ 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:

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

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

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 $\frac{C_l}{C_d}$. 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.

![Figure 8 formulation of blade optimization parameters](image)

### 4.3. 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 $\frac{C_l}{C_d}$ 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:

\[
f_1 = \max \left( \frac{C_l}{C_d} \right)
\]

(20)

\[
f_3 = \min(m)
\]

(21)

\[
f_2 = \min \left( \int_{R_{hub}}^{R_{tip}} d_i \, dr \right)
\]

(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.

\[
c_{\text{min}} \leq c_i \leq ... \leq c_i \leq c_{\text{max}}
\]

(23)

\[
\beta_{\text{min}} \leq \beta_i \leq ... \leq \beta_i \leq \beta_{\text{max}}
\]

(24)

\[
m_{\text{min}} \leq m_i \leq ... \leq m_i \leq m_{\text{max}}
\]

(25)

5. 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, Figure 9.

![Figure 9 Distribution of the twist angle on the blade for the initial and the optimized blades.](image)

Similarly, we note that the rope length of the optimized blade is decreased in zone 1 and increased in zone 2, Figure 10.
Figure 10 Distribution of the rope on the blade for the initial and the optimized blades.

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

![3D model of initial blade](image1)

(a) 3D model of initial blade

![3D Model of optimized blade](image2)

(b) 3D Model of optimized blade

Figure 11 3D Geometric representation of initial and optimized blades

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

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. Figure 13 shows the evolution of this coefficient for the two blades.

Figure 13 Coefficient of thrust of the initial blade and the optimized blade

Figure 14 Annual energy production of initial and the optimized blades
The optimization by the ant colony method allows us to improve the annual energy production of the machine. Figure 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.

### 6. 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.

![Initial blade](image1.png) ![Optimized blade](image2.png)

**Figure 15** Constraints concentration on the initial and the optimized blade.

### 7. 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 a 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 \( C_l/C_d \) coefficients, which positively influences the annual energy production of the machine which improved by 10%.

### REFERENCES


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