A design of the wind turbine blade geometry adapted to a specific site Using Algerian wind data

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Résumé - La modélisation aérodynamique de l'hélice d'un aérogénérateur est une étape essentielle dans la conception de cette machine. Son objectif est de calculer les efforts aérodynamiques qui s'exercent sur les pales, de déterminer les paramètres optimaux de ces pales et d'estimer la puissance maximale extraite par cette machine.
La conception de la géométrie de des pales a pour objectif de déterminer la forme optimale capable d'extraire le maximum d'énergie.
Cette conception est réalisée pour un type de profil aérodynamique donné et adapté à un site spécifique, car cette modélisation doit être basée sur une analyse statistique des données métrologiques du site en question.
Dans ce travail les efforts aérodynamiques ainsi que la puissance maximale extraite sont calculés pour une éolienne de petite taille.
Cette conception a un grand impact sur le rendement de cette machine et par conséquent sur sa faisabilité économique.
Mots clés : Energie Eolienne, Aérodynamique, Analyse Numérique, mécanique des fluides.

Abstract
The aerodynamic modeling of the wind turbine blades constitutes one of the most important processes in the design of the turbine.
The aim of this modeling is to calculate the aerodynamic loads, to determine the optimal parameters of the blades and estimate the wind extracted power.
The design of the blade geometry must provide the optimal shape of the rotor blade capable to produces the maximum extracted power.
This design must be done for a specific aerodynamic profile and a specific site, since this modeling must be based on statistical analysis of meteorological data of this given site.
In this work aerodynamic loads for small wind turbine blades is calculated as well as the total power extracted by the turbine.
This design has a great impact on the turbine efficiency and consequently on its economical feasibility.
Key words: Wind Energy, Aerodynamics, Numerical Methods, fluid mechanics.

1. Introduction

Small wind turbine technology can be a meaningful contributor to long-term economic growth by assuring independence in energy supplies and providing benefits to local economy. Moreover wind is a clean non-polluting energy source and the electricity generated by this mean is becoming economically efficient compared to other sources.
The aerodynamic modeling of the wind turbine blades constitutes one of the most important processes in the design of the turbine.

The rotor blades are the most important part of this turbine because of their aerodynamic shape and profiles that play the main role in extracting wind energy.
The aerodynamic modeling is used in order to estimate the aerodynamic loads and the wind extracted power. This modeling must be done for a given wind speed and a given rotor blades.
The design of the blade geometry must provide the optimal shape of the rotor blade capable to produces the maximum extracted power.
In order to determine the optimal shape of the blades, one must compute the optimal parameters of the blade geometry such as the chord length distribution, the thickness and the twist angle distribution along the blade span.
In the aerodynamic modeling two aerodynamic theories are used, the first one is the axial momentum theory and the second is the blade element theory [1].
In the first theory, the flow is considered to be completely axial, while in the second theory the effect of wake rotation is included, assuming that the flow downstream rotates.

The momentum theory that employs simply the mass and momentum conservation principles cannot provide alone the necessary information for the rotor design. However, the blade element theory that uses the angular momentum conservation principal, gives complementary information about the blade geometry such as airfoil shape and twist distribution. When both theories are combined the aerodynamic loads and the produced power can be obtained.
In order to compute the optimal parameters of the blade geometry that give the maximum power, an iterative algorithm is used until the maximum value of extracted power is reached.

This design must be done for a specific aerodynamic profile and a specific site, since we must use the characteristic wind speed that gives the maximum available power in a given site.
This characteristic wind speed is determined by statistical modeling of meteorological data.
The design can be repeated for different sites and profiles.
The estimation of aerodynamic loads can be useful as well in strength calculation of the blades in order to predict the structural problems such as fatigue failure, which is the major cause of wind turbine breakdown. This design has a great impact on the turbine efficiency and consequently on its economical feasibility.

2. Aerodynamic modelling

In the aerodynamic modeling two aerodynamic theories are used.

2.1 The axial momentum theory

In this simple one-dimensional model, airflow is assumed to be incompressible, completely axial and rotationally symmetric [2].
This model applies the principles of mass and momentum conservation on the annular control volumes surrounding the flow as shown in figure 1.

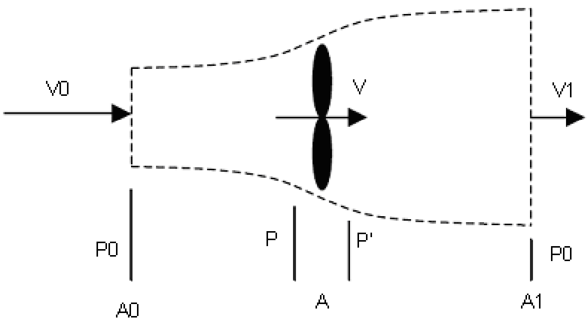

Figure 1: Annular control volume

The thrust force *T* at the rotor disc can be found, by applying the conservation of linear momentum to the control volume in the axial direction:

$$T = \dot{m}(V_0 - V_1) = \rho AV(V_0 - V_1) \qquad (1)$$

Where ρ is the density of the air.
Bernoulli's equation can be applied to obtain the thrust as:

$$T = \frac{1}{2}\mathrm{A}\rho(V_0^2 - V_1^2) \qquad (2)$$

The power extracted from the wind by the rotor is:

$$P = \frac{1}{2}\dot{m}(V_0^2 - V_1^2) = \frac{1}{2}\rho VA(V_0^2 - V_1^2) \qquad (3)$$

Introducing the axial interference factor, *a*, which is defined as the fractional decrease in wind velocity between the free stream and the rotor plane:

$$V = (1-a)V_0 \qquad (4)$$

The trust expression of equation (2) becomes:

$$T = \frac{1}{2}\rho AV_0^2 4a(1-a) \qquad (5)$$

The power extracted by the rotor is:

$$P = \frac{1}{2}\rho AV_0^3 4a(1-a)^2 \qquad (6)$$

2.2 The blade element theory

This analysis uses the angular momentum conservation principle, taking into account the blade geometry characteristics, in order to determine the forces and the torque exerted on a wind turbine. This method is known as *blade element theory* [3].

The control volume used in the previous one-dimensional model can be divided into several annular stream tube control volumes, which split the blade into a number of distinct elements, each of length *dr* (figure 2).

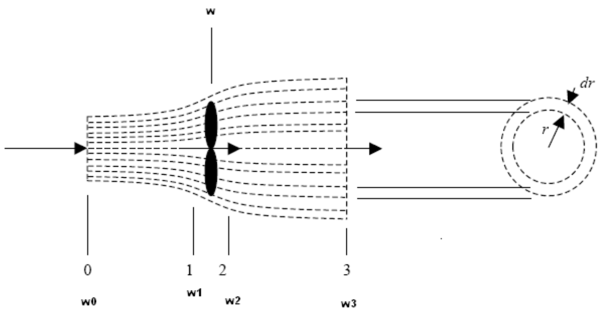

Figure 2: Annular stream tube control volumes

In this theory it is assumed that there is no interference between these blade elements and these blade elements behave as airfoils.

The differential rotor thrust, *dT*, at a given span location on the rotor (at a specified radius *r*) can be derived from the previous theory using equation (5):

$$dT = 4a(1-a)\rho V_0^2 \pi r dr \qquad (7)$$

In the previous model, it was assumed that airflow doesn't rotate. However, the conservation of angular momentum implies the rotation of the wake, if the rotor is to extract useful torque. Moreover, the flow behind the rotor will rotate in the opposite direction [3].

The effect of wake rotation will be now included. In describing this effect, the assumption is made that upstream of the rotor, the flow is entirely axial and that the flow downstream rotates with an angular velocity ω. The conservation of angular momentum can be applied to obtain the differential torque at the rotor disc, *dQ*, resulting in:

$$dQ = 2\pi\rho V \omega r^3 dr \qquad (8)$$

The total torque is:

$$Q = 2\pi\rho \int_0^R V \omega r^3 dr \qquad (9)$$

The differential extracted power is given by the expression:

$$dP = 2\pi\rho\Omega V \omega r^3 dr \qquad (10)$$

The total extracted power is:

$$P = 2\pi\rho\Omega \int_0^R V \omega r^3 dr \qquad (11)$$

In order to calculate *P* and Q, the wake angular velocity ω has to be known. Introducing, for this purpose, the tangential interference factor a' defined as:

$$\omega = a'\Omega \qquad (12)$$

The differential lift and drag forces are:

$$dL = C_L . dq \qquad (13)$$

$$dD = C_D . dq \qquad (14)$$

With:

$$dq = \frac{1}{2}\rho W^2 dA = \frac{1}{2}\rho W^2 c dr \qquad (15)$$

Where C_L and C_D are lift and drag coefficient.

The components of the resulting force are (see figure 3.):

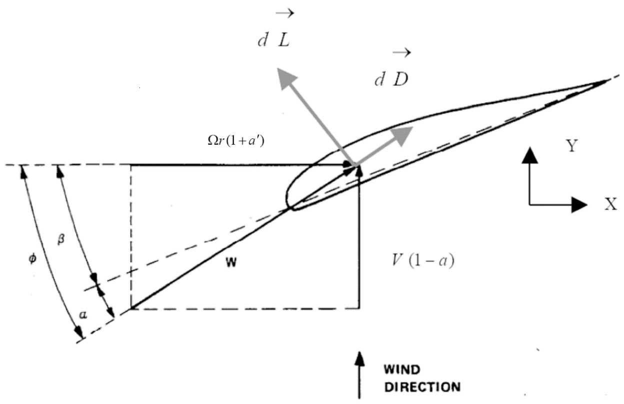

Figure 3: Blade element section at radius r

$$dF_x = C_x .dq \qquad (16)$$

$$dF_y = C_y .dq \qquad (17)$$

Where:

$$C_y = C_L \cos\phi + C_D \sin\phi \qquad (18)$$

$$C_x = C_L \sin\phi - C_D \cos\phi \qquad (19)$$

The following relation can be derived from figure 3:

$$\tan\phi = \frac{(1-a)V_0}{(1+a')\Omega r} \qquad (20)$$

Where:

$$\alpha = \phi - \beta \qquad (21)$$

The differential thrust and torque can now be derived as follows:

$$dT = BC_y dq = BC_y \frac{1}{2}\rho W^2 cdr \qquad (22)$$

$$dQ = BC_x dqr = BC_x \frac{1}{2}\rho W^2 crdr \qquad (23)$$

Equating the thrust in equations (7) and (22) as well as the torque in equations (8) and (23), will yield to the expressions of the both interference factors:

$$a = \frac{1}{\frac{4\sin^2\phi}{\sigma C_y} + 1} \qquad (24)$$

$$a' = \frac{1}{\frac{4\sin\phi\cos\phi}{\sigma C_x} - 1} \qquad (25)$$

Where σ is the local solidity, which is defined by the following formula:

$$\sigma = \frac{cB}{2\pi r} \qquad (26)$$

In order to carry out this calculation:

- The wind speed must be determined from the graph of the power probability density (figure 5).
- This calculation procedure is repeated iteratively till the values of the interference factors are corrected.
- In order the get the optimal blade geometry that can extract the maximum power, one must use the optimal incidence angle α_{opt} that gives $(C_L/C_D)_{max}$

The distributions of aerodynamic loads (at different blade stations) due to a wind speed of 15 m/s for a blade having a *NACA* 63-421 profile, are given by table 1.

Table 1: Distribution of aerodynamic loads wind speed 15 m/s
Profile NACA 63-421

Station (r/R)	Axial force (N)	Tangential force (N)	Torque (N.m)
0.16	86.02	221.24	206.30
0.25	81.92	351.16	305.56
0.34	73.37	466.19	372.82
0.43	57.87	586.57	467.49
0.51	35.67	764.83	724.62
0.60	39.33	908.37	1120.22
0.69	83.60	998.27	1686.21
0.78	221.50	1012.80	2591.9
0.87	211.31	1109.45	2746.15
0.96	169.79	1181.84	2434.31
1.00	140.04	1206.90	2100.65

The local (differential) loads obtained are integrated numerically, over the length of the blade, to determine the overall aerodynamic loads as well as the total output power.

3. Statistical Analysis of Wind Data

In this part a statistical analysis is carried out in order to estimate wind characteristics in different regions of Algeria and accordingly determine the most efficient sites.

The statistical distribution of wind speed (the frequency of occurrence of each speed) is also valuable in making an optimal design of wind turbine such as in fatigue failure prediction as well as in the adaptation of a machine to a site [4].

3.1 Experimental Wind Data Statistical Distribution

The estimation of the wind resources presents a particular difficulty because of the variability of wind speed characteristics which varies with the season and the hour of the day [6].

The statistical distribution of wind speed characteristics varies also from one place to another, since it depends on the local climatic conditions and the landscape of the site.

Wind characteristics such as: average speed, speed frequency and directions facilitate the estimation of the total energy extracted by wind turbine. These parameters have a direct influence on the operation of turbine (starting, stopping, orientation etc.)

This information is also required to optimize the design of the wind turbine in order to maximize the extracted energy and minimize the electricity production cost [5].

In order to determine the wind properties of a site, wind data must be available over a long period of time (one to ten years).

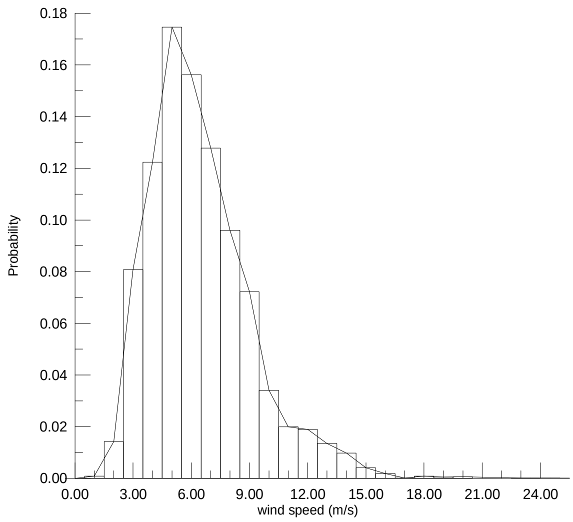

Figure 4: Probability Density of wind speed (Town of Adrar)

3.2 Estimation of the average available power (Power distribution)

The wind available power per unit area varies proportionally with the cube of the wind speed, as follows:

$$P = \frac{1}{2}\rho V^3 \qquad (27)$$

Where ρ is the density of the air, P is the available power of the wind per unit of area.

By multiplying the available power, at each wind speed, by the probability of the occurrence this speed, one obtains the distribution of the wind power at various speeds of wind; this last distribution is also called the power density [7].

It is important to note that at speeds higher than the mean velocity, in a given site, where the major part of power is produced.

The optimal design of the wind rotor, for a given site, must be based on the speed of wind that gives the maximum available energy. For the town of Tindouf (Figure5) this speed is 9 m/s.

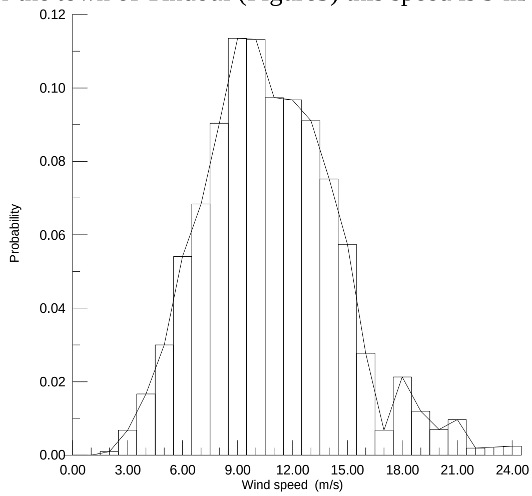

Figure 5: Probability Density of the average power (Town of Tindouf)

Conclusion

In this work the blade element theory was used to calculate aerodynamic loads for small wind turbine blades. This method can also estimate the power extracted by the turbine.

This design must be done for a specific aerodynamic profile and a specific site, since we must use the characteristic wind speed that gives the maximum available power in a given site. The value of this characteristic wind speed is determined from the wind data statistical analysis of this site.

The design can be repeated for different sites and profiles until we determine the right blade profile the suits each site.

According to results of the wind statistical analysis Tindouf has the highest average power. This average power is the most determinant parameter used in the selection of the wind site.

Actually the criterion of maximum annual energy production used to optimize blade geometry is not sufficient. Whereas the optimization of wind turbine must be based on minimum cost of energy which requires a multidisciplinary method that includes aerodynamic and structural models for blades along with a cost model for the whole turbine [8].

This work can be a part of a global optimization study aiming to minimize cost and structural problems of wind turbine while maximizing its energetic performance.

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