

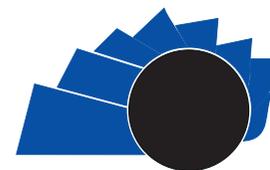


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Visión Electrónica

A CASE-STUDY VISION

## Blade design for horizontal axis wind turbine: 3D model.

*Diseño de hélices eólicas para aerogenerador de eje horizontal: modelo 3D.*

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#### ABSTRACT

Wind energy is one of the best important sources of renewable energy and an excellent alternative for the transition to sustainable energy that the planet earth needs. The wind energy is contained in the air particles in movement, forming kinetic energy. This energy could be transformed into another type of energy such as electricity, through the use of wind turbines. It is known that horizontal axis wind turbines are more efficient energetically, the power output of a horizontal axis wind turbine depends of it aerodynamic performance; therefore, the correct geometric design of the propeller is essential for an optimum wind turbine. This article analyzes the most relevant aspects in the design of a wind propeller, using MATLAB® software to illustrate its behavior, suggests an ideal airfoil for wind applications to use in the 3D modeling of the blades using the computer assisted design, this blades has been built with a 3D printer.

#### RESUMEN

La energía eólica es una de las más importantes fuentes de energía renovable y una excelente alternativa para la transición a energías sustentables que el mundo necesita. Está contenida en las partículas de aire en movimiento en forma de energía cinética, y puede ser transformada en otra forma de energía como la eléctrica con el uso de aerogeneradores. Se sabe que los aerogeneradores de eje horizontal tienen un mayor rendimiento energético, y la potencia generada por los de eje horizontal depende de su desempeño aerodinámico; por tanto, el correcto diseño geométrico de la hélice es imprescindible en un aerogenerador óptimo. En este artículo se analizan los aspectos más relevantes en el diseño de una hélice eólica, utilizando el software MATLAB® para ilustrar su comportamiento; se sugieren perfiles aerodinámicos ideales en aplicaciones eólicas a partir de los cuales se ha hecho el modelamiento 3D de las hélices en las herramientas de diseño asistido por computador, dichas hélices han sido construidas con el uso de una impresora 3D.

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## 1. Introduction

Since ancient times, human beings have used the energy stored in moving air particles. Wind energy was used on a daily basis since the invention of sailing ships; subsequently, it was used for different tasks such as grinding and pumping, which led, in the XVIII century, to develop machines with more elaborated models that took into account certain aerodynamic parameters and had mechanisms that improved their functioning. In 1892, in Denmark, professor Latour designed the first electric wind turbine, starting the development of the modern wind technology [1].

The energy present in moving air particles is so abundant that it could satisfy the world energetic demand. Wind energy is renewable and clean; it is produced by the differences in atmospheric pressure resulted from the uneven heat that the earth's surface receives from the sun. However, approximately only 2% of the solar energy that reaches the Earth becomes wind, and only a fraction of this can be transformed into electric energy; [2] despite of this, wind is an excellent energetic resource. A wind turbine uses the kinetic energy associated to the movement of the wind particles that impact the propeller, which by being coupled with an electric generator produces a usable potential difference (voltage). Currently, wind power needs greater prominence, aimed at changing the paradigm of obtaining energy to an environmentally sustainable one, highlighting that wind power production involves significantly lower environmental costs than those from using fossil fuels.

In this paper, we calculate and simulate, using Matlab® software, the optimum propeller for a low-power wind turbine that works at an average annual speed of 4-6 m/s, to show the aerodynamic behavior of

the blades and their main features also the 3D model are built. We suggest the reader to become familiar with the concepts of the momentum theory and fluid mechanics, among others, which are not explained here because it is out of the scope of this paper.

## 2. Useful concepts for the propeller design.

When extracting energy from the wind, it is important to take into account the relation between the shape of the airfoil and its aerodynamic features. The geometric shape used to design the propeller must minimize losses and maintain acceptable levels of rigidity and stability. To obtain the mathematical model that expresses the behavior and the main features of the propeller, we will consider an ideal turbine that is represented by a disc with no thickness and an infinite number of blades view Figure 1.

The kinetic energy present in the wind is given by (1).

$$E_c = \frac{1}{2} m V_1^2 \quad (1)$$

Where:

$m$ : Mass

$V_1$ : wind speed

When a wind flow impacts the airfoil in the Figure 2, moving from the leading edge to the trailing edge, winds with different speeds are generated on the upper surface; higher speeds decrease the pressure, lifting the airfoil. Concurrently, the pressure increases on the lower surface, which also contributes to lift the airfoil; this phenomenon is called lift. Figure 3 shows and approximation of the differences in pressure.

**Figure 1.** Ideal disc and wind current [3].

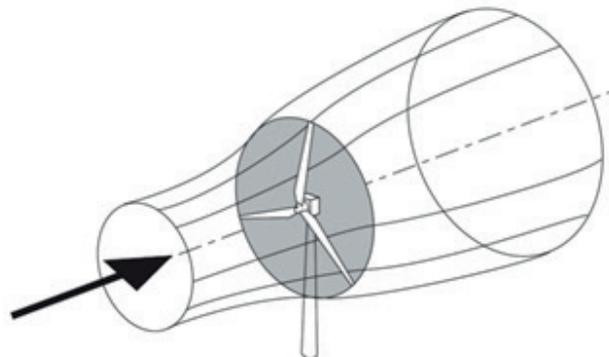


Figure 2. Parts of an airfoil [4].

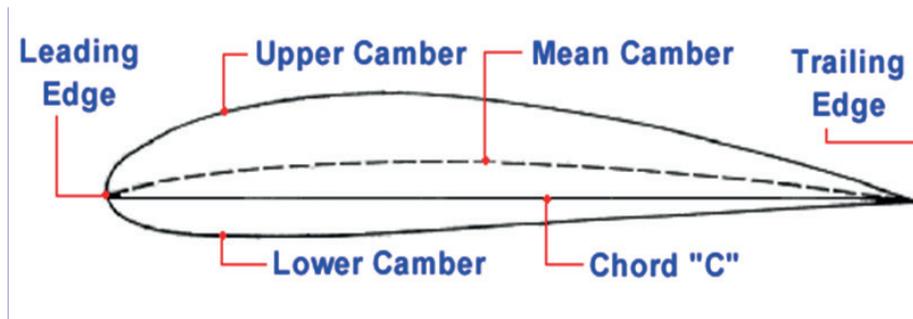
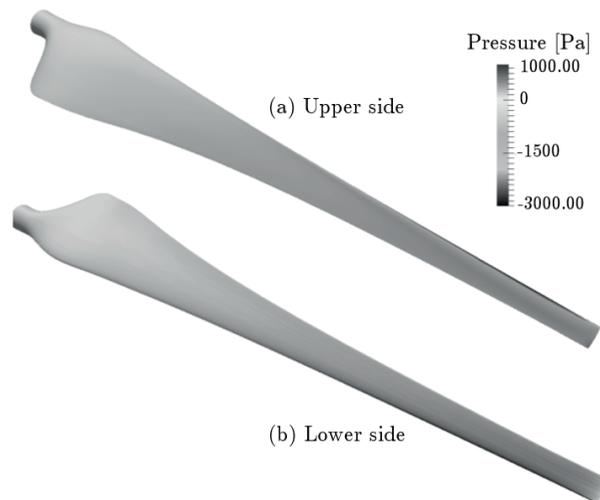


Figure 3. Ideal shape and configuration of the blade [5].



### 2.1. Reynolds number

The Reynolds number, calculated by (2), relates the viscous and inertia forces in a propeller. In aeronautics, high Reynolds numbers are common since this coefficient proportionally depends on the speed. Conversely, Reynolds number are smaller for wind propellers.

$$Re = \frac{F_i}{F_v} = \frac{\rho L V_1}{\mu} \quad (2)$$

Where:

$\rho$ : Fluid density

$\mu$ : Dynamic viscosity of the fluid

$L$ : Propeller length

### 2.2. Power

**Available Power:** It refers to the power required to move the air particles at a certain speed or the energy available in the wind that flows through a specific area at a determined time. The power associated to the wind flow is available as a consequence of the kinetic energy present in the wind, and is calculated by (3).

$$P_d = \frac{E_c}{t} = \frac{1}{2t} m V_1^2 = \frac{1}{2} \rho A V_1^3 \quad (3)$$

Where:

$P_d$ : Available power

$E_c$ : Kinetic energy of the air particles

$A$ : Area through which the wind flows

In equation (3), the most important variable is the wind speed since both the area and the air density are kept constant. Consequently, power mainly depends on wind speed, showing a fluctuating exponential growth, which compels to use control systems that stop the turbines when the wind speed is so high that can burn the electronic devices or break the mechanic elements.

**Extractable power:** It is the mechanic energy transmissible to the propeller; for its analysis, the air passing through an ideal wind tunnel is studied, applying both the momentum theory and the Bernoulli's equation. Because the speed of the wind impacting the propeller is different from the one crossing the plate formed by the rotating propeller, it is necessary to introduce an interference coefficient (a) that describes this difference in speeds, obtaining (4).

$$Pe = \frac{1}{2} \rho A V_1^3 a (a - 1)^2 \quad (4)$$

Where:

$P_e$ : Power extracted by the propeller.

$a$ : Interference coefficient.

Interference coefficient (a) describes this difference in speeds  $V_1$  and  $V_2$ :

$$a = \frac{1}{2} \left( 1 - \frac{V_2}{V_1} \right) \quad (5)$$

**Power coefficient:** The mathematical descriptions of the available power ( $P_d$ ) and the extractable power ( $P_e$ ) permit introducing the power coefficient ( $C_p$ ), which will let us describe the propeller's behavior regarding its capacity to capture the energy available in the wind, according to (6).

$$C_p = \frac{P_e}{P_d} = 4a(a - 1)^2 \quad (6)$$

Replacing the expressions for  $P_e$  and  $P_d$  in (6):

$$\begin{aligned} C_p &= \frac{P_e}{P_d} = \frac{1}{2} * \frac{(v_1^2 - v_2^2) * (v_1 + v_2)}{v_1^3} \\ &= \frac{1}{2} * \left( 1 - \frac{V_2^2}{V_1^2} \right) * \left( 1 + \frac{V_2}{V_1} \right) \\ &= \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left( 1 + \frac{V_2}{V_1} \right) * \left( 1 + \frac{V_2}{V_1} \right) = \end{aligned}$$

Obtaining:

$$\left[ \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left( 1 + \frac{V_2}{V_1} \right)^2 \right]$$

Replacing in (6) the expression for the interference coefficient 'a' in (5):

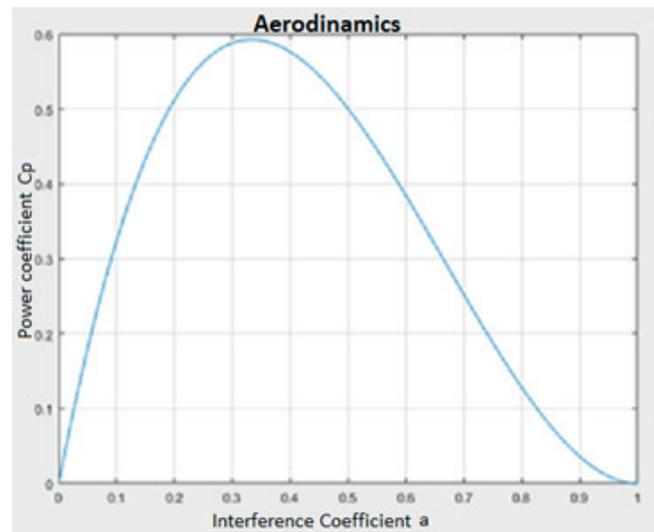
$$\begin{aligned} 4a(a - 1)^2 &= 4 * \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left[ 1 - \frac{1}{2} \left( 1 - \frac{V_2}{V_1} \right) \right]^2 = \\ \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left[ 4 - 4 * \left( 1 - \frac{V_2}{V_1} \right) + \left( 1 + \frac{V_2}{V_1} \right)^2 \right] &= \\ \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left[ 1 + 2 * \frac{V_2}{V_1} + \frac{V_2^2}{V_1^2} \right] & \end{aligned}$$

Obtaining again:

$$\left[ \frac{1}{2} * \left( 1 - \frac{V_2}{V_1} \right) * \left( 1 + \frac{V_2}{V_1} \right)^2 \right]$$

This is a simple way to prove the validity of the expression (5).

**Figure 4.** Power coefficient vs Interference coefficient.



Source: own.

$C_p$  reaches its maximum value when  $\frac{dC_p}{da} = 0$

$$\frac{dC_p}{da} = 4(a - 1)(3a - 1) = 0 \tag{7}$$

Then:  $a = \frac{1}{3}$ , therefore, by substituting in (6), we obtain the power coefficient maximum value:

$$C_{pmax} = \frac{16}{27} \cong 0,593 \tag{8}$$

This value, known as the Betz's coefficient, it means that 59% efficiency is the BEST that conventional wind turbine can achieve in extracting power from the wind. Although this model is inexact because it involves fewer variables than other models, in the practice, it achieves the highest efficiencies.

### 3. Propeller Design

Given this  $C_{pmax}$  it is possible to calculate a practical mathematical approximation of  $C_p$  that depends on the number of blades in the rotor ( $C_{pn}$ ).

#### 3.1. Speeds ratio

Besides the power coefficient ( $C_p$ ), the parameter ( $\lambda$ ) that relates the angular speed of the propeller ( $\omega$ ) and the speed of the wind ( $V$ ) allows characterizing

completely the aerodynamic behavior of the propeller, according to (9).

$$\lambda = \frac{\omega_r L_b}{V_1} \tag{9}$$

$$C_{pn} = C_{pmax} * \lambda \left[ \lambda + \frac{1,32 + \left(\frac{\lambda - 8}{20}\right)^2}{N^{\frac{2}{3}}} \right]^{-1} - \frac{0,57\lambda}{\left(\frac{CL}{CD}\right)\left(1 + \frac{2}{N}\right)} \tag{10}$$

Where:

$N$ : Number of blades

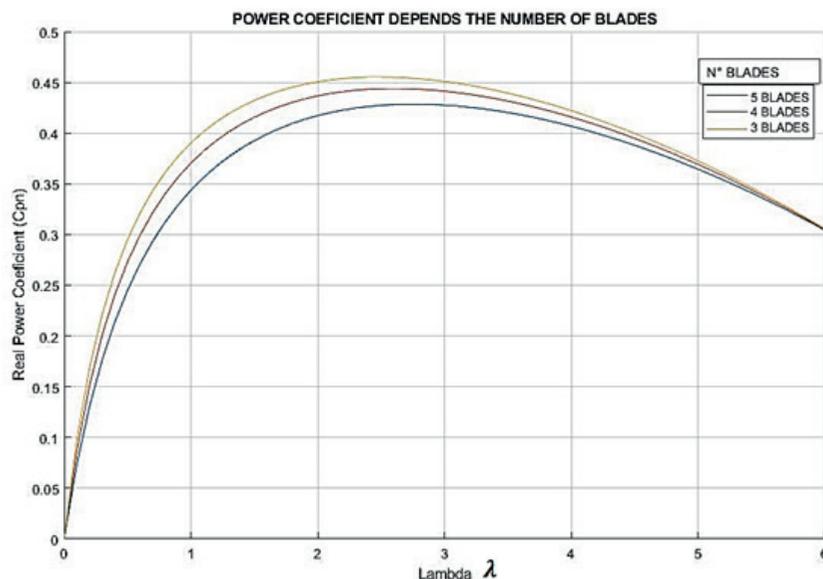
$CL$ : Lift Coefficient

$CD$ : Drag Coefficient

The representation of equation (10) for different number of blades is given in Figure 5.

The propeller efficiency increases when the number of blades increases view Figure 5 above; however, it is important to consider the cost-benefit ratio in regard to the number of blades. Nowadays, most of the wind turbines are built with three blades, because the cost of each blade does not justify coupling an extra one. Surely, this cost-benefit ratio varies with the model and place of implementation, therefore, every design should include this analysis.

**Figure 5.** Power coefficient as a function of the speeds ratio ( $\lambda$ ). Upper curve: five blades, Middle curve: four blades; lower curve: three blades.



Source: own.

### 3.2. Airfoil

The airfoil is the shape of the blade as seen in cross-section; its geometric characteristics are designed to produce the pressure differences that generate lift, which largely determines the aerodynamic performance of the propeller. The desired airfoil for a wind propeller must have a low Reynolds number (since it depends on the wind speed), and ideally, a very thin but rigid blade.

The 4-digit NACA (National Advisory Committee for Aeronautics) airfoil is useful for wind power applications because it has a flat lower surface (it has no chamber) that makes construction straightforward. Other options are available, such as CLARK Y and FX 63-137; the latter although is more efficient, its construction is more difficult.

Figure 6 shows the 4-digit NACA airfoil developed with the NACA 4-digit airfoil generator (Divahar Jayaraman, 2009). This airfoil is useful

for wind power applications, since they are not only about the air particles impacting the blade, but about taking advantage of the lift phenomenon to make the propeller move, as we explained above. This type of airfoil has acceptable efficiency and rigidity features, and is easy to construct, which makes it an excellent choice to implement in horizontal axis wind turbines.

When designing the blades, the airfoils are coupled as if they were length differentials ( $\Delta L$ ); these, in turn, decrease in size as they move away from the rotational core. This occurs because each  $\Delta L$  has a different speed when the propeller is turning; if the cord length was equal along the blade, points of structural stress would arise, which could break the blade or generate problematic vibrations. Additionally, the building material must have an acceptable rigidity, but at the same time must be light. Currently, Teflon-covered (polytetrafluoroethylene) polymers are commonly used, since their friction coefficient is low (0.08), which increases performance.

Figure 6. 4-digit NACA airfoil constructed in MATLAB® [6].

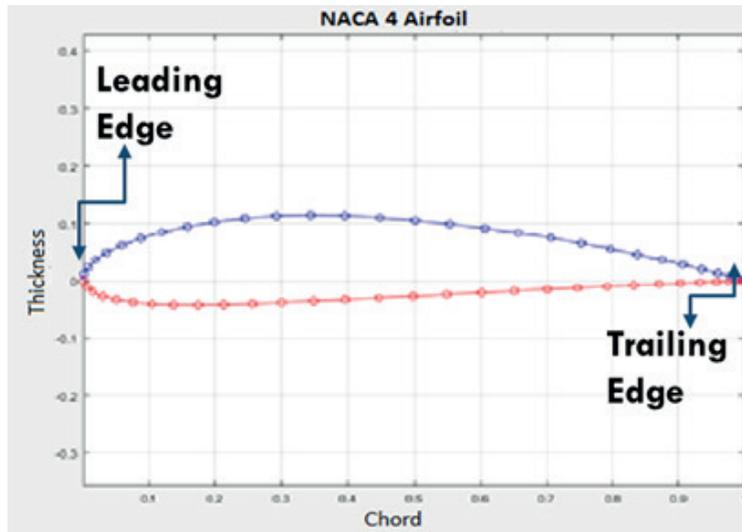
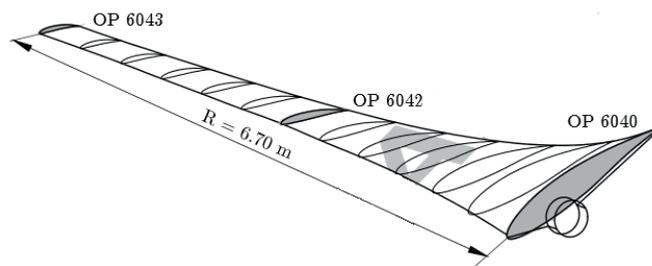


Figure 7. Desired shape and configuration of the blade [7].



The propeller ratio is defined according to the functioning power in equation 11.

$$R = \sqrt{\left(\frac{2P}{\rho\pi V_i^3\gamma}\right)} \tag{11}$$

Where:

$R$ : Propeller ratio (blade length)

$P$ : Nominal power

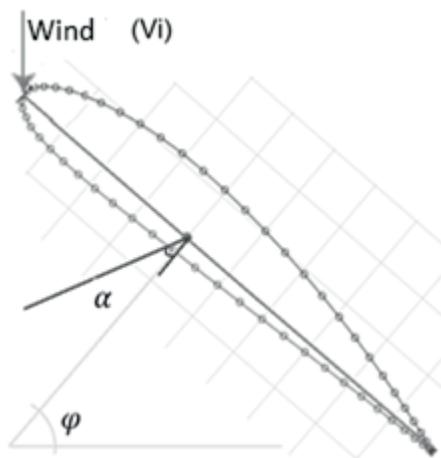
$\gamma$ : Wind turbine general performance

The wind turbine general performance ( $\gamma$ ) includes the efficiency of both the generator and the electric system, and usually reaches a value of 30% or even 40% in the best cases.

### 3.3. Angle of attack

The angle of attack is formed by the airfoil in relation to the direction of the oncoming wind, that is, the angle at which the blade cuts the wind. By definition, if the blade cuts the wind with a large angle of attack, it generates a loss in lift that, in turn, decreases the propeller efficiency.

**Figure 8.** Angle of attack  $\alpha$  and rotation  $\varphi$ .



Source: own.

Therefore, we must optimize the angle of attack along the blade. The blade undergoes different speeds along its extension, which produces a variation in the angle of attack; this occurs because the tip of the blade, which has a higher relative speed, cuts the wind at a different angle than the base of the blade, which has a lower relative speed; consequently, the change in the angle of attack is more abrupt at the base of the blade than at the tip Figure 9. Because the angle of attack varies, the blade must be skewed, according to (12).

$$\alpha = \tan^{-1} \frac{\sin \varphi}{\lambda + \cos \varphi} \tag{12}$$

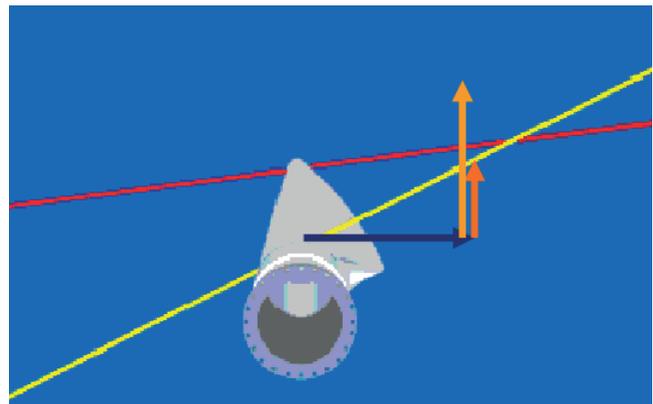
Where:

$\alpha$  = Angle of attack

$\varphi$  = Angle of rotation

The angle of rotation ( $\varphi$ ) denotes an arbitrary position at which the airfoil is located in relation to the wind

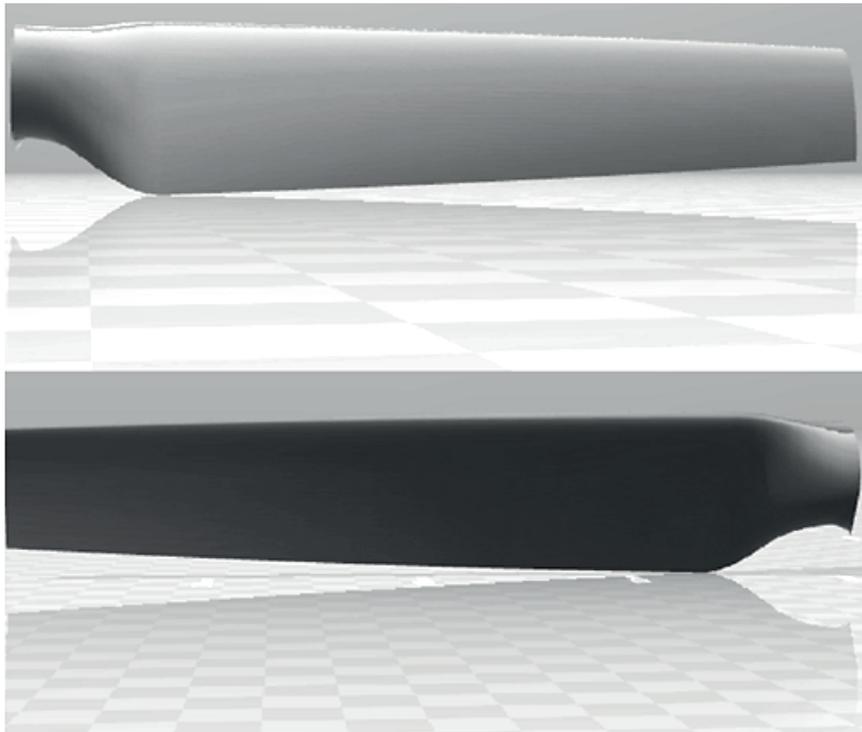
**Figure 9.** Variation of the attack angle [2].



## 4. Results

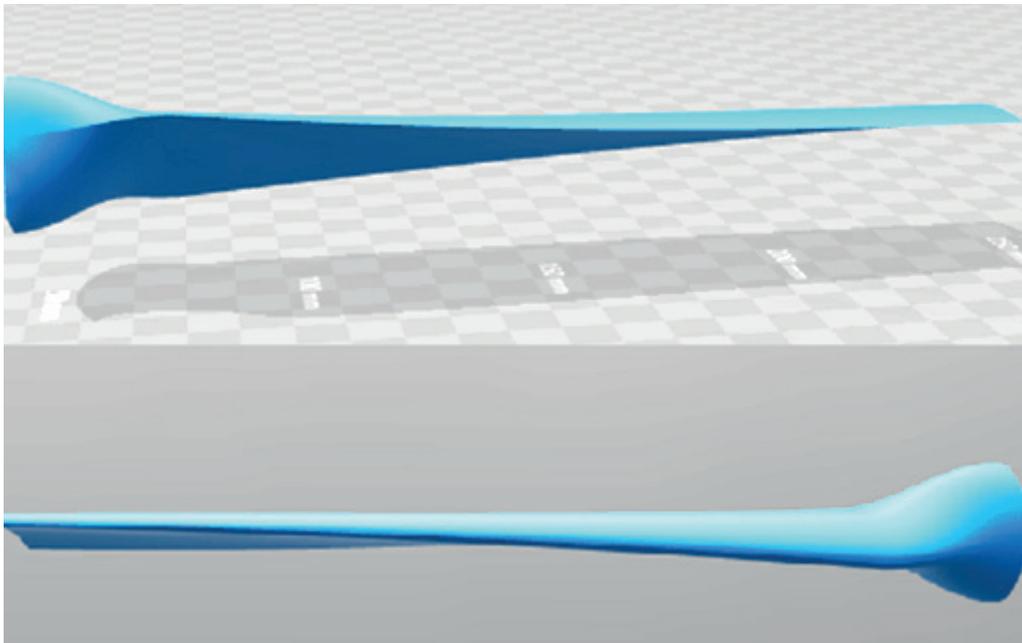
The model designed by the characteristics exposed before are present in Figure 10-12.

**Figure 10.** Blade-Frontal view.



Source: own.

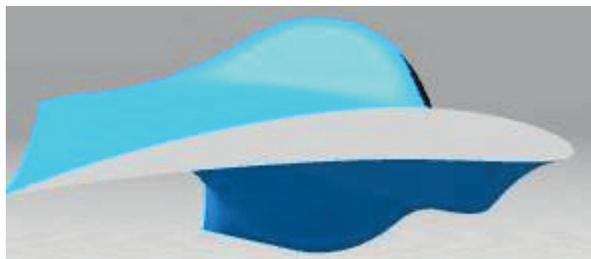
**Figure 11.** Blade-Trailing and leading edge view.



Source: own.

In the Figure 12 is shown the airfoil which the blade was designed, this airfoil was selected by the NACA 6212 parameters. [8].

**Figure 12.** Blade-Airfoil view.



Source: own.

## 5. Conclusions

In this paper, it is analyzed the most relevant aspects involved in the design of a wind turbine, focusing on the importance of choosing the correct airfoil, the variation in the cord length, the change ratio of the angle of attack, the number of blades, and the relation between the ratio and the nominal power.

The simulations performed, describe the behavior of the design variables and highlight the more appropriate configurations, providing the wind turbine designers with theoretical tools that allow them to know the general functioning of a wind propeller and the aspects that must be involved to achieve an optimum design.

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