



Evaluación Aerodinámica mediante CFD de Dispositivos en Punta de Aspa para Turbina Eólica

Aerodynamic evaluation with CFD of tip devices in blade for wind turbine

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Resumen

La región de la punta en las aspa de un rotor eólico se presenta el fenómeno de arrastre inducido, el cual disminuye la eficiencia aerodinámica de la turbina e incrementa los esfuerzos sobre la estructura. En este trabajo, se analizan computacionalmente (CFD) diferentes dispositivos de punta de aspa, con base en aplicaciones similares como Winglets, Split-Tips, Tip-Tanks, como alternativa de mejora de la aerodinámica. El Reynolds utilizado fue de $Re = 140000$ y modelo RANS de turbulencia K- ϵ , el ángulo de ataque (alfa) fue variado desde -25° hasta 25° . El análisis de los resultados mostró, respecto al aspa con punta base (sin modificación), incremento porcentual del coeficiente de sustentación (CL) así: Split-Tips = 3% Winglet = 4.6%, la punta tipo Tip-Tank no presentó mejora apreciable, La intensidad del vórtice de punta de aspa también mostró relación directa (incremento/disminución) cuando fue comparado con la variación del CD.

Palabras clave: CFD, Punta de aspa, Vórtices, Winglets, HAWT.

Abstract

The region of the tip in the blades of a wind rotor presents the phenomenon of induced drag, which decreases the aerodynamic efficiency of the turbine and increases the stresses on the structure. In this work, different tip devices are computationally analyzed (CFD), based on similar applications as Winglets, Split-Tips, Tip-Tanks, as an alternative to improving aerodynamics. The Reynolds used was of $Re = 140000$ and model RANS of turbulence K- ϵ , the angle of attack (α) was varied from -25° to 25° . The analysis of the results showed, with respect to the blade with base tip (without modification), percentage increase of the lift coefficient (CL) as follows: Split-Tips = 3.5% Winglet = 4.6%, tip Tip-Tank type did not present appreciable improvement The intensity of the tip tip vortex also showed a direct relationship (increase/decrease) when compared to the variation of the CD.

Keywords: CFD, Tip blade, Vortex, Winglets, HAWT.

1. Introducción

Wind generators are systems composed of 4 elements as they are; A wind rotor, an electric generator, the power control or regulation system and power transmission system. In

this work, we will focus on the first, the wind rotor; this element is composed of several blades. At the tips of these blades, a phenomenon known as tip vortex is generated, many works currently seek to increase the energy efficiency of these systems through geometrical improvements,

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in our case, a research and verification process will be carried out by simulation in blades variable chord for a wind rotor, with modifications in its tips known in some cases as Winglets. The Winglets, are aerodynamic elements in a vertical angle to the extradorso of the wing of an aircraft, are installed at the ends in order to decrease the resistance and vortices that are produced by the pressure difference [1]. The addition of a Winglet, at the tip of the blades of the horizontal axis wind turbine rotor, can increase its power output. [2]. Some work describes that the Winglets, can improve the capacity of power production, observable with the increase of the tip speed ratio, causing a maximum power increase of approximately 3.96% [2]. In the blades of a wind rotor, the aerodynamic efficiency decreases as the viscous drag force increases, to evaluate the performance of aerodynamic systems, measurements of aerodynamic coefficients with wind tunnels are generally made, allowing to observe that the aerodynamic performance of the wind turbines it is significantly influenced by the unstable flow around the rotor blades. [3]

The vortices are phenomena generated by pressure changes, these are helical, and often occur in rotating mechanical systems that are immersed in a fluid, because it is a phenomenon to study it can generate new ideas on developments that help control At present, computational methods such as CFD, based on MEF (finite element methodology) are used to analyze unstable aerodynamic characteristics that affect performance in HAWT (Horizontal-axis Wind turbine). [3].

Colombia has a privileged coastal geographical position, which is why there are great sources of wind resources. The power to implement this type of renewable energy contributes and motivates the research and development of wind power plants with efficiency improvements, which would allow obtaining energy from non-polluting way, and with the aim of guaranteeing supply in ZNI (non-interconnected areas of the nation)

2. Methodology

In order to achieve a CFD Analysis of the effect of use of the alar tip devices, in wind rotor blades, it is decided to carry out several design and development phases, in order to give an order to the work to be done.

2.1. *Exploration Phase*

In this phase, we look for the most useful information or documentation, which allows us to carry out a CAD design development, of several types of tip for the blade and its respective simulation in CFD, which also allows us to learn about this type of measurements, in order to obtain results that allow to evaluate the aerodynamic performance, and thus generate coherent conclusions about the use of tip devices in wind rotor blade.

2.2. *Mathematical Development and Design Phase:*

In this phase, the mathematical design will be carried out to allow the construction of a CAD, with a variable chord blade, using the design equations in an orderly manner. And so, generate the curves associated with the airfoil, according to typical design parameters, which facilitate the creation of a 3D design and subsequent CAD design of tips or Winglets to be evaluated.

2.3. *Simulation phase:*

With the 3D design of the blades and their tips, it is analyzed by specialized tools of CFD such as ANSYS16®, the behavior of the vortices of a blade, with several tips, in this phase, it is important to highlight the analysis and appropriate selection of the type and size of the finite element, as well as the type of mesh on the surface of the blade, this is known as Pre-processing, obtaining a simulation consistent with the curves of aerodynamic coefficients.

3. Results

Wind Rotors today, have several types of blades, which differ mainly by their geometry.

These always seek the best possible aerodynamic performance, depending on their geographical location and atmospheric conditions, there are two types of basic blade construction structures such as; Fixed chord blade and Variable chord blade, these last are characterized by their low drag coefficient. This design has been studied extensively and is described in several design methodologies and books, for our case we use the equations of design of variable chord blades, described in the book *INTRO TO WIND ENERGY* of E.H. Lysen (Chapter 4) [4].

Aerodynamic Coefficients:

One way to evaluate the performance of wing airfoil, are the aerodynamic coefficients that can be predicted, measured or simulated generally as a function of the angle of attack Alpha (α), which are:

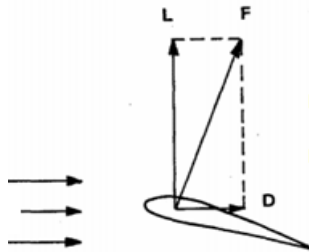


Figure 1. Force diagram for NACA airfoil, lift and drag forces. [4]

The aerodynamic coefficients are associated with the lift forces L, drag force D, and moment with respect to the quarter of chord M, as shown in equations (1), (2), (3).

$$c_L = \frac{L}{\frac{1}{2}\rho*V^2*A} \tag{1}$$

$$c_D = \frac{D}{\frac{1}{2}\rho*V^2*A} \tag{2}$$

$$C_{MAC} = \frac{M}{\frac{1}{2}\rho*V^2*A*cm} \tag{3}$$

3.1. CAD Design of Blade

In order to provide better mechanical conditions, it is intended that this blade has 3 types of airfoil direction, that are mechanically compatible and that allow a functional and resistant blade, airfoil robust or thick appearance for the root of the blade, suitable to resist efforts and a good mechanical coupling to the rotor. Also another airfoil for the blade body, which guarantees a typical lift coefficient, and finally, an airfoil shape for the tip, which allows the location of a mechanical coupling system for interchangeable tips, with intra- and extra-dorsal symmetrical, to search for it in the databases of NREL (National Renewable Energy Laboratory) [5], the coordinates of the airfoil and selecting them such that their geometric differences are subtle.

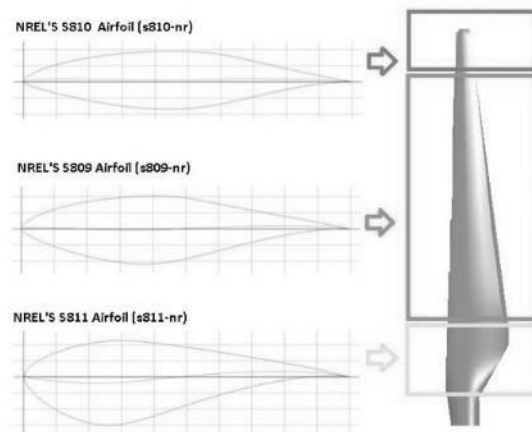


Figure 2. Wing airfoil's for variable chord blade design.

Once a previous investigation and search of studies on types of NACA and NREL airfoil [5], figure 2, is performed by means of a predictor of aerodynamic coefficient curves known as Javafoil® [6], the following aerodynamic coefficient curves, this with In order to evaluate the coupling capacity of these airfoil, be part of a single blade and see that ad design attack angle use.

Reynolds Number

To make a prediction of the aerodynamic coefficients, the calculation of the associated

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Reynolds number is carried out, in order to configure the simulation in Javafoil®.

$$Re = \frac{V C m \rho}{\eta} \quad (4)$$

Table 1. Reynolds Number calculation.

P (kg/m ³)	C (m)	η (N·s/m ²)	V (m/s)	Re
1.087	0.081	1.85 x10 ⁻⁵	30	140000

As it is a subsonic aerodynamic application, a wind speed of 30 m/s is used, in order to be able to develop future experimental tests in a real wind tunnel, which allow to evaluate the simulation results obtained with CFD.

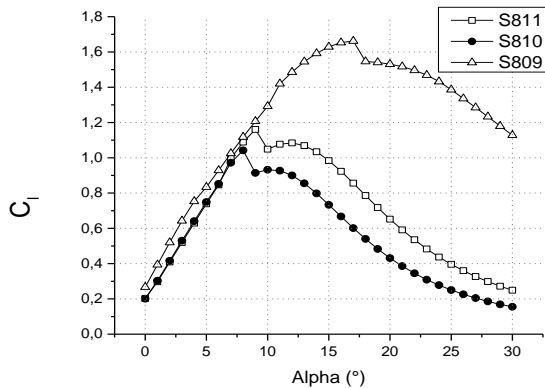


Figure 3: Lift Coefficient for NREL airfoil S809, S810, S811 using JavaFoil® with Reynold's number = 140000.

The curves obtained by the Javafoil® predictor software, shows that these airfoil have a similar behavior for (α) attack angles from 0° to 7°.

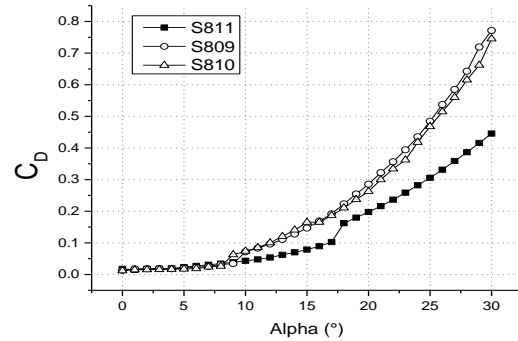


Figure 4. Drag coefficient for NREL airfoil's S809, S810, S811 using JavaFoil with Reynold's number = 140000.

The predictor shows quite distant values between the moment coefficient associated with the S811 airfoil, with respect to the other airfoil (S809 and S810), which indicates a relatively similar behavior for angles between 0° and 5°, therefore decides to take an Alpha Design Angle in this interval with a value of α_d = 5.5, with an associated design lift coefficient of C_{ld} = 0.795.

We start from the limitation that the radius of the blade can not be more than 1 m, so it is desired to perform future tests in a real wind tunnel, which has 2 m in height, also that the associated electric generator to use It has blades of a similar size, close to 1 m radius, so the equations related to the calculation of the energy and radius of the wind rotor described in [4], will not be taken into account for this part of the study, since from there the radius of the blade to be constructed was defined according to the required energy.

Once a radius of 700 mm is defined, a table of equations is made, where we can obtain the value of the chord and the angle of inclination of each airfoil, which are calculated according to the Total radius, with the use of some constants recommended by some authors, associated with the type of NREL airfoil, as for example in the case of a TSR or λ_d in the book of H.D. Lysen recommends for these types of airfoil an λ_d = 6 with a number of blades or B = 3, we would have:

$$R = 700 \text{ mm} \quad (5)$$

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$$\lambda_{rd} = \lambda_d \frac{r}{R} \quad (6)$$

$$\phi = \frac{2}{3} \tan^{-1}\left(\frac{1}{\lambda_{rd}}\right) \quad (7)$$

$$\beta = \phi - \alpha_d \quad (8)$$

Once the airfoil of the blade are created from the design equations described, the CAD design of the blade is created, this with the aim of generating a solid, from the union of the sketches.

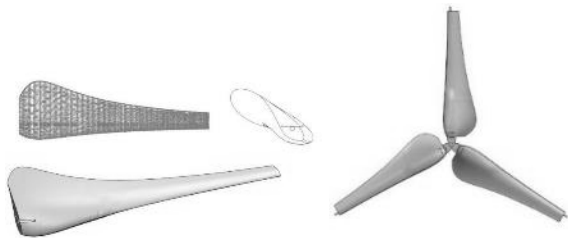


Figure 5. CAD design of the variable winding blade by importing the coordinate values of airfoil.

3.2. CAD Design of Tips

Once several types of tips have been analyzed in previous studies (Figure 6), it is possible to appreciate that several of the study points to design must have geometric characteristics that generate useful vortices, but that do not damage the operation of the blade, that is to say that instead of damaging its aerodynamic behavior, allow an advantage of the vortex phenomenon, this without significantly increasing the induced drag. Below are several tip geometries, which were used as design cues [7].

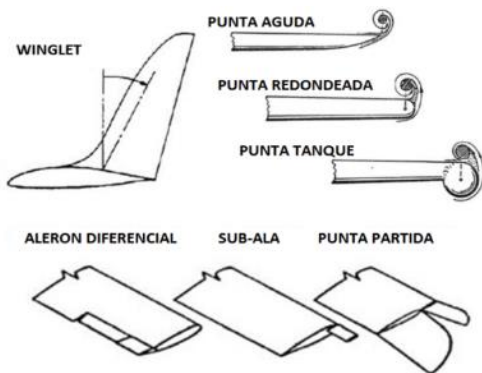


Figure 6. Forms of tips for wings of aircraft and helicopter rotors, and typical behavior of pointed vortices [7].

In Figure 7, there are several types of tips for wings of aircraft and blades of helicopters, among which stand out the split ends types Split, rounded, straight, and type Winglet.

Real Applications

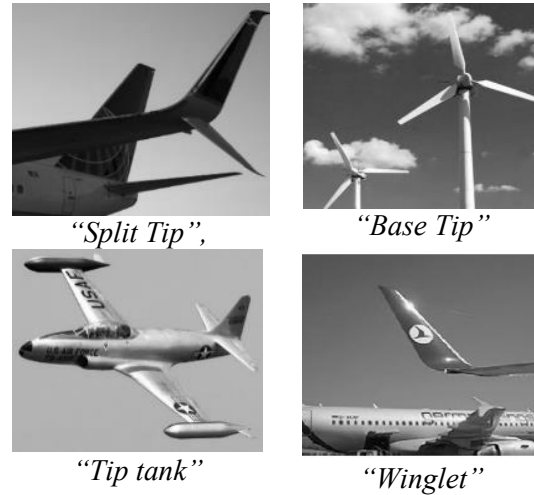


Figure 7. Forms of tips for wings in aircraft and wind turbines [7]

Therefore, the idea of developing 5 representative Tips of these forms, which occupy 3% of the final distance of the tip of the blade as shown below (Figure 8).

- **Tip 1**, Tip "Split-tip" 1: This tip, is characterized by a split point shape at 11.25 ° between sub-points. (Figure 8)
- **Tip 2**, Tip "Split-tip" 2: This tip has a split point shape with 22.5 ° between sub-points, and is characterized by starting its partition at the end of the base point. (Figure 8)
- **Tip 3**, Base Tip: This is characterized by presenting a normal tip shape without modification geometry; therefore it is defined as base tip. (Figure 8)
- **Tip 4**, tip "Tip-Tank": This tip has a rounded shape or bulb, is characterized by generating more circular vortices and is used as a storage tank for fuel in aerobatic aircraft hence its name. (Figure 8)

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- **Tip 5, Tip "Winglet":** This tip is characterized by presenting an L shape at the end of the tip on wings of aircraft, it generally has angles of inclination between 45° to 90° , it is also known to reduce the effect in a large percentage of tip vortex. (Figure 8)

Once the Tips to be evaluated have been defined, the following CAD designs of interchangeable tips for a variable winding blade for a wind rotor are obtained.

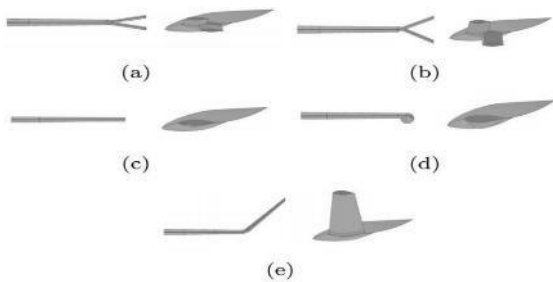


Figure 8. CAD designs of Tips to Simulate.

- a) Tip type Split-tip with separation angle of $11,25^\circ$
- b) Tip type Split-tip with separation angle of $22,5^\circ$
- c) Base tip without modification
- d) Tip type Tip-tank
- e) Tip type Winglet with angle of inclination of 45° .

To achieve CFD simulation of the blade in a virtual wind tunnel, is necessary to use a specialized software that uses MEF (finite element method), capable of generating a dynamic fluid analysis, after a previous review of works of this type, it is decided to use ANSYS16®, with its Workbench and Solver CFX environment, (Figure 9). Which allows to quickly configure the simulation conditions as well as the turbulence models that in our case will be K- ϵ .

3.3. Mesh Convergence and Simulation

In order to define the finite element size suitable for a CFD simulation, it is necessary to pre-simulate Figure, with several element sizes until a steady value can be seen in the lift coefficient values.

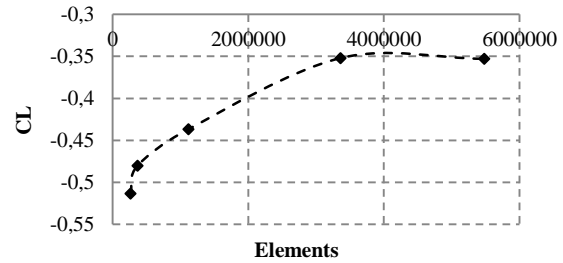


Figure 9. CL with $\alpha = 0^\circ$ vs. numbers of elements in the surface of the blade.

For mesh with element size of 1 and 0.8 mm, it can be seen that the values of the CL (Figure 9), have a more stable value, so it is decided to use an element size on the blade surface of 1 mm. In order to obtain more precise simulation results, the mesh with body influence is performed, which allows locating smaller elements in selected areas of interest, such as in the vicinity of the blade, which increases the number of elements of 3.3×10^6 to 5.8×10^6 (Figure 10).

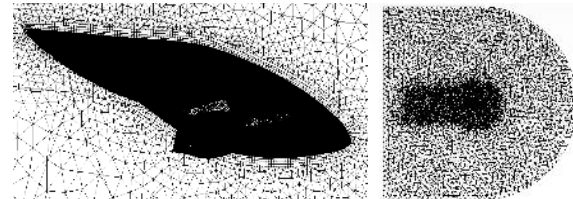


Figure 10. Mesh with inflation of 4 layers and element size of 1 mm on the surface of the blade.

The mesh of the domain (Figure 11), is one that surrounds the structure to analyze, it was necessary to find a way to build one in which you could see behavior in detail in the fluid in the vicinity of the cross and thus obtain normal forces, with an acceptable precision.

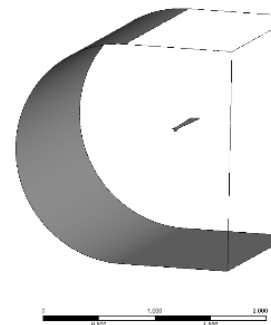


Figure 11. 3D Simulation Domain.

This 3D mesh (Figure 10), results after several attempts of meshing by means of ANSYS ICEM, obtaining the best results with the following parameters: Element = triangular, with Inflation ("inflation") from the surface of the blade, number of layers = 4, layer height = 1 mm, mesh option with body influence, achieving element sizes of 1 mm on the whole surface of the blade, 10 mm in the vicinity of the blade and 50 mm in the walls of the domain, creating a final mesh of blade with tip and domain of 6×10^6 elements and 1.2×10^6 nodes approximately, obtaining the following curves of aerodynamic coefficients, making the change of the direction of the fluid, emulating in this way the turn of the blade or angle of attack, with the speed components, in the configuration properties of the INLET region.

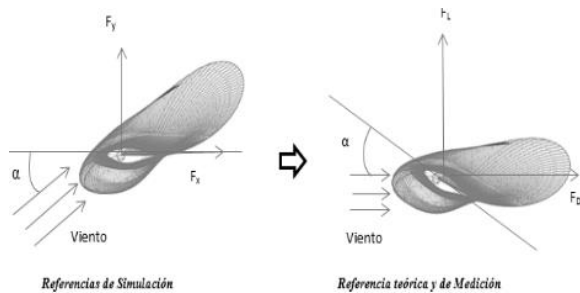


Figure 12. Reference for forces in Simulation and theory.

In simulation, the blade remains static and the fluid changes its direction (Figure12), experimentally the fluid maintains the direction constant, and the blade varies the angle of attack, therefore the simulated values must be adjusted (9) and (10) to be able to be compared with future experimental works.

$$fL = Fy \cos(\alpha) - Fx \sin(\alpha) \quad fD = Fy \sin(\alpha) - Fx \cos(\alpha) \quad (9)$$

$$C_L = \frac{fL}{\frac{1}{2} \rho * V^2 * A} \quad C_D = \frac{fD}{\frac{1}{2} \rho * V^2 * A} \quad (10)$$

The highest lift values are presented in the Split-tip of 45° Figure 9, with respect to the tip the base tip, a lower value is observed for positive angles, which indicates that all the

simulated tip devices have an increase of sustentation with respect to the base tip with the exception of Tip-tank, where lower values of this coefficient are observed for positive attack angles (Figure 13).

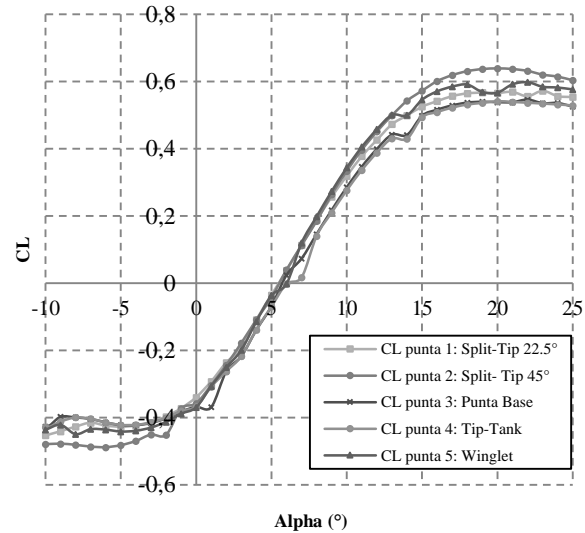


Figure 13. Simulated Lift Coefficient curves with CFX and turbulence model k-epsilon.

The lift coefficient values in Table 3, for $\alpha = 10^\circ$, show to the Tip 5 and Tip 2 with lift values higher by 20% and 16% with respect to the base tip, for $\alpha = 15^\circ$ they show Tip 2 and Tip 5 with higher lift values by 14% and 9% respectively, which indicates that this type of tips have an increase in lift with respect to the blade with a base tip as a function of the angle of attack α .

Table 2. Simulated lift coefficients with $\alpha = 10^\circ, 15^\circ$

Tip	CL($\alpha=10^\circ$)	CL($\alpha=15^\circ$)
1	0,318	0,525
2	0,333	0,572
3	0,285	0,498
4	0,275	0,493
5	0,343	0,545

The lift values for $\alpha = 10^\circ$ Table 3, show Tip 5 and Tip 2 with CL values higher by 20% and 16% with respect to the base tip, for $\alpha = 15^\circ$, Punta 2 and Punta 5 present lift values greater by 14% and 9%, which indicates the

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incidence of this coefficient before changes in attack angle α .

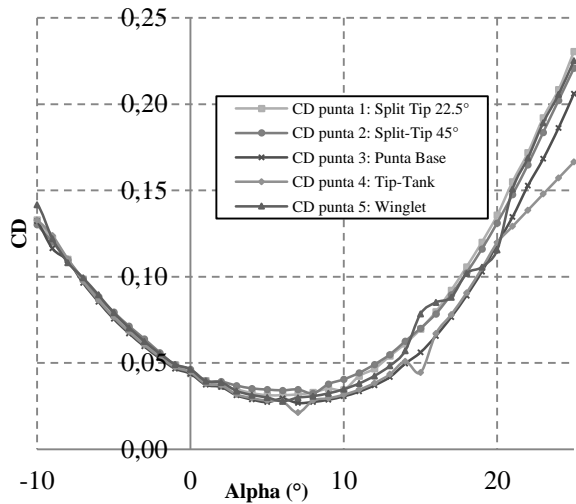


Figure 14. Curves of Drag coefficients simulated with CFX and turbulence model k-ε.

In Figure 14, there is an increase in the drag coefficient with positive angles $\alpha > 6^\circ$, with the Split-Tip and Winglet tips having the highest simulated drag coefficient with respect to the base tip.

Table 3. Drag coefficients in device, and $\alpha = 5^\circ, 10^\circ, 15^\circ$.

Tip	CD($\alpha=5^\circ$)	CD($\alpha=10^\circ$)	CD($\alpha=15^\circ$)
1	0,031	0,034	0,069
2	0,034	0,040	0,070
3	0,027	0,030	0,056
4	0,028	0,031	0,056
5	0,029	0,034	0,078

The coefficient of drag for $\alpha = 5^\circ$ (Table 4), increases in all devices, the highest values are presented in Tip 2 and Tip 1, with increases in drag of 25% and 14% with respect to Tip 3 (base Tip), with $\alpha = 10^\circ$ this increase in Tip 5 was 7%, and 3% for Tip 4. The relationship CL/CD (Figure15), allow to appreciate the value of the angle of attack in which the best aerodynamic performance, the modifications between devices are reflected in these curves, the Tip Winglet presented the highest ratio, followed by the

Tip 3, which indicates that the best aerodynamic performance is given in the blade with Winglet tip, with an angle $\alpha = 10^\circ$.

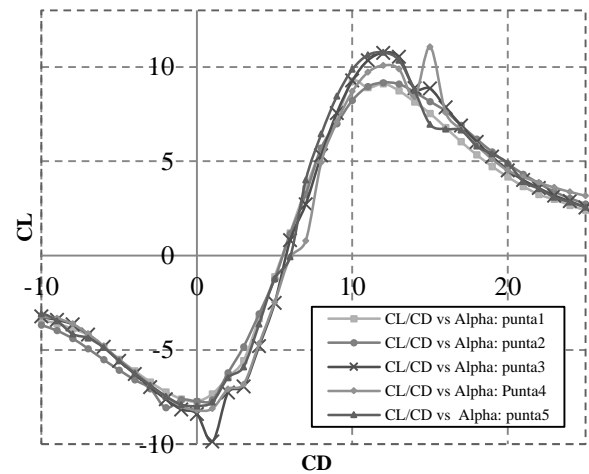


Figure 15. CL / CD curves simulated with CFX and turbulence model k-ε.

The CL / CD ratio decreases in most tip devices with the exception of Tip 5 (Table 5), which presents a 6% increase with respect to Tip 3 for an angle $\alpha = 10^\circ$. This indicates that this device has a better aerodynamic performance and can be used to increase efficiency in HAWT rotors, however this increase is susceptible to the angle of incidence of the wind.

Table 4. CL / CD relation for $\alpha = 5^\circ, 10^\circ, 15^\circ$.

Tip	CL/CD ($\alpha=10^\circ$)	CL/CD ($\alpha=15^\circ$)
1	9,227	7,541
2	8,225	8,165
3	9,273	8,857
4	8,700	6,900
5	9,871	6,958

The use of specialized software that uses MEF, through the Solver CFX, allows CFD simulations to be obtained, obtaining the behavior of the velocity of the fluid, once it crosses the different points of the designed blade, then vortex regions are used, very used in post CFD processing, which allow to show areas where this phenomenon is generated. (Figure16).

Velocity contours in Vortex Region.

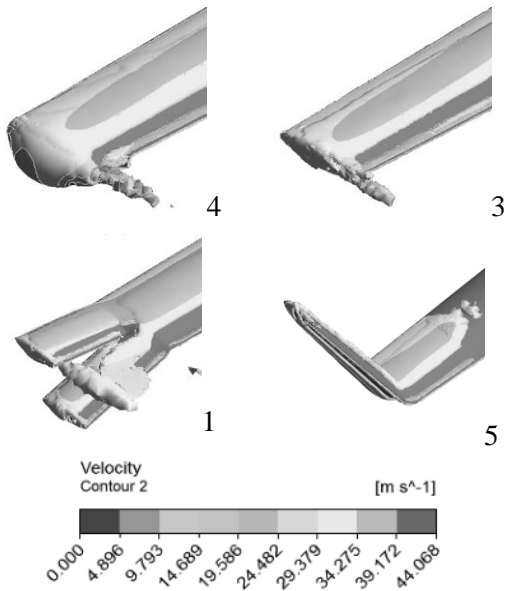


Figure 17. 3D Contours of velocity in vortex region (isometric view).

In Figure 18, we can see the more rounded vortex region obtained by post processing of the 5 simulated tips, this tip called Tip-tank, has aerodynamic coefficient curves very similar to the base tip, tip3. With the exception that you can see a very rounded and more concentrated vortex.

Velocity contours in Vortex Region.

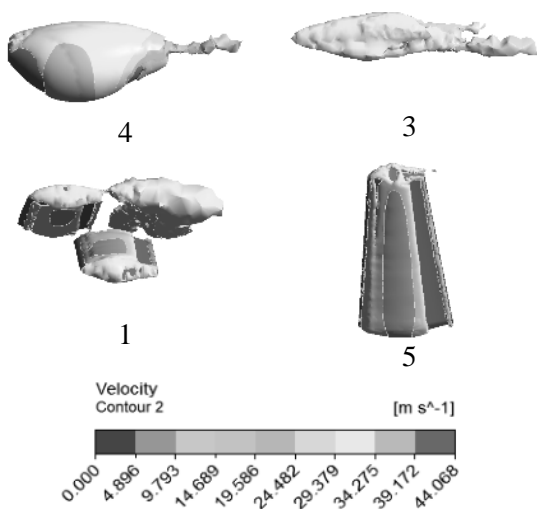


Figure 18. 3D Contours of velocity of velocity in vortex region (side view).

Conclusions

The tip devices generate different forms of turbulence according to their geometry, this can be measured through the changes in the aerodynamic coefficient curves by means of CFX, the drag curve shows that the Split-tip points have a greater magnitude, highlighting the Winglet Point and Split-Tip tip with lift values greater than 20% and 16% with respect to the base tip, the highest CL / CD ratio in the Winglet tip was 6% with $\alpha = 10^\circ$.

The Post-processing of ANSYS allows to appreciate by means of planes of contours and plane of vectors the magnitudes and directions of the variables of speed and pressure that are generally very used in the design and evaluation of aeronautical devices, with these planes it was possible to appreciate the formation of circular vortices when the tip device is also circular Tip 4 (Tip-tank), the use of double Winglet or Split-tip, is not more efficient with respect to the base tip although this increases the lift by 10% also increases the drag by about 30%

The shapes in the regions of vortex obtained by simulation, allow appreciating notable differences, in Tip 5 where the smallest diameter of vortex region is observed, with a reduction of 84% with respect to the Base Tip (Tip 3) and in the Tip 2 a diameter of 83% greater is observed.

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