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FINAL PROJECT REPORT

APPLICATION OF NACA AERODYNAMIC PROFILE WITH TUBERCLE DESIGN ON AEROGENERATORS

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TITLE: APPLICATION OF NACA AERODYNAMIC PROFILE WITH TUBERCLE DESIGN ON AEROGENERATORS

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ABSTRACT

In the aeronautics sector there is one of the most important sections which is the aerodynamic profile with its study and application, which are cross sections that are designed to generate suspension and for the desired fluid to flow over it.

For this, I used the NACA4412 profile, modifying its attack profile with the so-called “tubercles”, this in CATIA with simple equations of sines and cosines. And making the design elliptical so that the wind turbine blade can obtain the greatest efficiency, least resistance and great stability when interacting with the fluid.

For this, I used the NACA4412 profile, modifying its attack profile with the so-called “tubercles”, this in CATIA with simple equations of sines and cosines. And making the design elliptical so that the wind turbine blade can obtain the greatest efficiency, least resistance and great stability when interacting with the fluid.

Once the different designs have been created, the geometry is introduced into FLUENT-ANSYS and the mesh corresponding to the profile is generated and certain working conditions are established, such as speed, degrees and so on.

The objective is to be able to determine which of the 4 types of profiles that have been created is the best in terms of efficiency so that a wind turbine can use it. Obtaining a good value in lift coefficient and a very low value in resistance.

Keywords: Aerodynamics, Tubercles, Airfoil, NACA, Lift and Drag.

RESUMEN

En el sector de la aeronáutica se encuentra un de las secciones más importantes la cual es el perfil aerodinámico con su estudio y su aplicación, las cuales son secciones trasversales que son diseñados para generar suspensión y que el fluido que desee este fluyendo sobre este.

En este trabajo he creado y analizado un perfil alar, para poder aplicarlo de forma real en aerogeneradores donde lo que se busca es que se consiga la mayor eficiencia del dispositivo para generar energía renovable, convirtiendo la energía cinética del viento en energía eléctrica.

Para esto, utilicé el perfil NACA4412 modificando su perfil de ataque con los llamados "tubérculos", esto en CATIA con ecuaciones simples de senos y cosenos. Y realizando el diseño de forma elíptica para que la pala del aerogenerador pueda obtener la mayor eficiencia, menor resistencia y una gran estabilidad al interactuar con el fluido.

Ya teniendo los distintos diseños creados, se procede a introducir la geometría en FLUENT-ANSYS y se genera la malla correspondiente al perfil y se establece ciertas condiciones de trabajo, como velocidad, grados y demás.

El objetivo es poder determinar cuál de los 4 tipo de perfiles que se han creado, es el mejor en tema de eficiencia para que un aerogenerador pueda utilizarlo. Obteniendo un valor buen en coeficiente de sustentación y un valor muy bajo en resistencia.

Palabras clave: Aerodinámica, Tubérculos, Perfil alar, NACA, Sustentación y Resistencia.

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And finally, to my closest friends and family who were always there to give me a hand in moral support and patience in my most complicated times due to the TFG.

REFERENCES OF ACRONYMUS AND ABBREVIATIONS:

L: Lift

D: Drag

ρ: Density

A: Area

C_L: Lift Coefficient

C_D: Drag Coefficient

K: Constant

p: Pressure

V: Velocity

Re: Reynolds

l : Length

μ : Kinematic Viscosity

CATIA: computer 3D design software that is used in various industries such as automotive and aerospace, it gives us tools for modeling, analysis and manufacturing of products for real use.

ANSYS Fluent: software used to perform simulation in computational fluid dynamics (CFD) analysis. Used for any surface that you want to study and optimize the flow of liquids and gases.

Chapter 1. INTRODUCTION

Aerodynamics is one of the branches of aerospace engineering that we study the most throughout our career and is most important to focus on the study of the movement of air and other gases, such as their interactions with solid objects. Solid targets can be understood as any type of solid, and we as aerospace engineers sit on profiles directed towards the aerospace part.

My TFG project is totally focused on the creation, research and experimentation of different modified aerodynamic profiles for direct application in wind turbines. This is always hand in hand with being able to obtain beneficial results for its use, in this sense the application is sought with aerodynamic efficiency, always complying with the basic concepts of lift and drag in a profile.

Therefore, this TFG is based on a previous investigation carried out by me (Nicolas Alonso Bilbao Carrasco) two years ago, where that project sought to explain the modification and behavior of the NACA4412 *(Catia Doc, 2009) [1]* aerodynamic profile without any type of application.

Currently I want to focus my total research on effectively applying and modifying my old model so that it can be used in wind turbines to convert kinetic energy into potential energy.

The first thing I did is establish the same NACA4412 as the study aerodynamic profile, but changing the rectangular profile for an elliptical one, which is more similar in geometric shape to the main inspiration of my project, which are the fins of humpback whales.

With this modification I try to find greater stability and lift and less drag. The same 3 tubercles are established along the leading edge and once the profile made in CATIA has been modified, it must be studied in ANSYS-FLUENT to see its behavior and subsequent conclusion.

1.1 Theory Part

1.1.1 Airfoil

The wing profile is the center of this research and we have to start knowing its definition, being a shape of the cross section of an area that has its main uses in the world of aeronautics. This is clearly designed to generate lift and drag.

The topic of aerodynamic profiles is very extensive and there is one for each objective that one as an engineer wants it to meet.

Laminar flow having the fluid on the object most of the time related to the boundary layer, high lift. Self-stable, profile that is regulated only at the moment of loss due to alteration. Supercritical, it is designed for those aircraft that need low resistance at very high speeds.

The profile that will be used on this occasion is NACA4412 which has a maximum thickness of 4% of the length of the rope. A curvature ratio of 41 and a symmetry with respect to the axis of the string. That is, it has a curvature that increases from the leading edge itself until reaching the maximum thickness, where it then gradually decreases until the trailing edge.

As I mentioned previously, realizing that one of the main modifications is to dispense with the rectangular wing profile and stick with the merely conical analysis. And we will see all this in the following sections with the analysis of each parameter.

It is also important to mention in a general way about wind turbines, since this is the main application of this project. Wind energy converts the force of the wind into electricity using wind turbines. The blades rotate, activating an electrical generator. Its efficiency depends on the wind speed and the design of the wind turbine. The power generated increases with the wind speed cubed. It is a renewable and sustainable source of electrical energy.

- Lift Force

It is the force acting on a body in a perpendicular direction by means of a fluid (air). Lift is the force that directly opposes the weight of an airplane and holds the airplane in the air.

In other words, the geometry that a wing profile has makes the particles travel through the upper and lower zones at different speeds, but they meet again in the exit zone at the same time. This type of difference in speed in the areas of the airfoil creates a very striking difference in pressure, calling it the Bernoulli Effect.

At the time of making Bernoulli, it is when the wing profile manages to generate a lift on the fluid that runs through it. This causes the aircraft to begin thrust-powered flight.

$$L = \frac{1}{2}\rho V^2 A C_L$$

- Bernoulli

Bernoulli's principle in aerodynamics is known as that pressure found internally in the fluid, which, as it travels through a body, decreases while its speed increases. It is explained along with the lift force, which combines pressure and speed.

$$K = p + V$$

- Drag Force

The force is generated in the opposite direction to the speed with which the body or object is interacting. When this type of force is generating contrary to another force, friction with the fluid (air) begins to be generate. The higher the thrust generated by the aircraft, the lower the drag, and vice versa. In the area of aerodynamics, there are two types of drag, parasitic and induced.

- Parasitic

Parasite drag is simply caused by the aircraft's shape, construction-type, and material. For instance, an airplane with a rough surface creates more parasite drag than one with a smooth surface.

- Induced

Inevitable consequence of lift and is produced by the passage of an airfoil (e.g. wing or tail plane) through the air. Air flowing over the top of a wing tends to flow inwards because the decreased pressure over the top surface is less than the pressure outside the wing tip *(SkyBrary Aviation Safety, 2021) [26]*

- Stall

This type of aerodynamic phenomenon is completely related to the angle of attack, pressure and lift that an airfoil has. Where by increasing the angle of attack, the fluid passing through the profile separates from the boundary layer and generates a very large bubble of space.

- Reynolds

It is the ratio found between inertial and viscous force. The first tells us about the geometries that have accelerations and decelerations. The second occurs after the friction between those particles that travel through the geometry.

The applicability of the Reynolds number differs depending on the specifications of the fluid flow such as the variation of density (compressibility), variation of viscosity (non-Newtonian), being internal or external flow, etc. *(NAFEMS, 2021) [5]*

In our investigation, we arrived at the calculation of the Reynold's number of 311,379.31 being a very laminar flow and that helps the investigation of our airfoil. The air density data is 1.29 kg/m^3, the speed is 30 m/s and the chord length is 0.14 m.

CONFIGURATION	*LAMINAR*	*TRANSIT*	*TURBULENT*
Airfoil configuration	$Re < 5x10^5$	$5x10^5 < Re < 10^7$	$Re > 10^7$

Table 10 Reynolds flow velocity

$$Re = \frac{\rho V l}{\mu}$$

- Angle of Attack (AoA)

It is the variable between the relative wind and the chord of the wing, of which much of the data that will be handle in this work is, related mostly by the angle of attack and as a reaction to this our profiles.

- Lift Coefficient

The lift coefficient is a number that aerodynamicists use to model all of the complex dependencies of shape, inclination, and some flow conditions on lift *(Nancy Hall, 2021) [3]*.

It is a value without any kind of physical dimension, which relates the lift generated by an object with the density of the fluid (air), the speed of the fluid and the area of the lifted geometry.

$$C_L = \frac{2L}{\rho V^2 A}$$

This type of dimensionless quantity tends to be very valuable when analyzing the aircraft's angle of attack and coefficient of drag.

- Drag Coefficient

The drag coefficient is a number that aerodynamicists use to model all of the complex dependencies of shape, inclination, and flow conditions on aircraft drag *(Nancy Hall, 2021) [4]*.

It is a value without any kind of physical dimension, which helps us to know how resistant the geometry (comprises the area) against a fluid (air). That is, this value determines how much drag aerodynamic the analyzed object has.

In the same way, this type of dimensionless quantity tends to have a lot of value when analyzing the angle of attack that the aircraft has.

$$C_D = \frac{2D}{\rho V^2 A}$$

- Viscosity

It is that property of thickness that each moving fluid possesses, where the fluid molecules adhere to an object or geometry where they are having movement depending on their speed and temperature. The effect that it generates is known as a limit layer, being a layer that forms around the wing profile and creates lift.

In our study, we are working only with a fluid (air) that has a viscosity of *0, 0000174* $\mu[Pa\ S]$

- Boundary Layer

Boundary layers are directly related to fluid (air) viscosity and fluid velocity. In addition, they are the areas where the fluid feels disturbed or in contact with a geometry. Moreover, it is where it is determined if it becomes a laminar flow or a turbulent flow.

- Kinetic energy

It is all energy that an object has due to its movement. The heavier the object is and the faster it moves, the more kinetic energy it has. It is used to understand how things move and how they can transfer that energy to other things.

- Mechanical energy extracted

It is any combination of two different types of energy that are related to the movement and position of an object. It is the sum of the energy that an object has due to its movement and the energy associated with its position or state.

- Betz number

Indicates the maximum possible efficiency limit of a wind energy system (maximum is 59%). This number represents the maximum fraction of the wind's kinetic energy that can be converted into mechanical energy by a wind turbine rotor. *(Díaz, A, 2015) [10]*

- Power coefficient

Cp is a measurement that indicates how efficiently a wind turbine can convert wind energy into mechanical energy.

- Laminar Flow

It is call in this way when a fluid that runs through the object in a smooth and orderly way tends to spend most of its time on the object creating a boundary layer.

- Turbulent Flow

It is calling this way when a fluid that runs through the object in a disorderly and chaotic way, tends to spend most of the time with vortices and separating from the boundary layer.

- Mach Number

In the case of an object moving through a fluid, such as an aircraft in flight, the Mach number is equal to the velocity of the object relative to the fluid divided by the velocity of sound in that fluid *(Adam Augustyn, 2018) [6]*

It is known as a relative speed in relation to the speed of sound in the same medium or place that the object being analyzed moves. The velocities that are analyze, are always on objects moving with fluids around, relating the temperature and pressures.

Generally, Mach 1 data at atmospheric temperature (15ºC) is equivalent to 340 m/s, being 1225 km/h. In addition, with these data we add the four values of the different high-speed flows.

1.1.2 Vertical Aerogenerators

Wind turbines harness the kinetic energy of the wind to generate electricity. This process is carried out by rotating the wind turbine blades, which are designed to capture and channel the wind. Even in light wind conditions, the blades are adjusted to optimize energy capture, through an inclination angle of approximately 45º.

A wind turbine has several parts to function effectively, such as the blade, nacelle and tower on the outside. And in its interior area it has a gearbox, anemometer, high speed drive shaft, low speed drive shaft, wind vane, yaw system and among others.

Energy production begins when the wind reaches a minimum speed of around 5 m/s. At this point, the blades gradually adjust their angle until they are completely perpendicular to the wind, thus maximizing energy capture. The air flow over the blades creates a pressure difference that drives their rotation, generating movement in the rotor.

During optimal operation, the blade tips can reach speeds of up to 69 m/s. The energy generated is transferred to the wind turbine's electrical system, from where it is connected to a high-voltage transformer that distributes it to the electrical grid, supplying the population.

Boundary conditions for analysis

- Height 150 meters
- Profile to use NACA4412
- Speeds to study: 5.5 m/S, 8.8 m/s, 10.4 m/s
- Angles for analysis: 0º, 5º, 10º
- Blade measurements: 60 m each
- A scalar measurement of 1:100 was stable in analysis.

CL/CD & Extracted Power

Once the wind interacts with the blades of a wind turbine, a force is generated that drives its rotation, which is crucial to produce electricity. However, the amount of electricity generated depends on several factors, such as wind speed and the design of the wind turbine.

To calculate this amount, a basic formula is used:

$$P = \frac{1}{2} x\ \rho\ x\ A\ x\ v^3 x\ C_p$$

Where:

$P\ is\ power\ generated$

$\rho\ is\ air\ density$

$A\ is\ the\ aerogenerator\ blade\ area$

$v\ is\ the\ air\ velocity$

$C_p\ is\ the\ wind\ turbine\ performance\ coefficient$

Additionally, there is Betz's Law, proposed by physicist Albert Betz, which establishes a theoretical limit on the maximum efficiency with which a wind turbine can convert the kinetic energy of the wind into mechanical energy. According to this law, no wind turbine can exceed 59.3% energy conversion efficiency, regardless of its design. This is expressed mathematically as:

$$C_p \leq \frac{16}{27} \approx 0.593 \; or \; 59\%$$

These principles help us understand how the force that rotates the blades is related to the electrical power obtained from the wind turbine, within the limits established by Betz's Law and considering the various variables involved.

Momentum Theory:

1. Axial force

It is a force that acts along the axis of an object, applied in a direction parallel to said axis. This type of force tends to compress or stretch the object in the direction of its length, without exerting significant forces in other directions. It is commonly found in situations where loads or pressures are applied directly over the length of a structure.

When studying a fluid, it is important to take into account certain characteristics such as its incompressibility, steady-state flow and stability. These aspects are essential to understand its behavior and the conditions in which it is found. The Bernoulli equation can be applied.

$$\frac{v^2}{2} + \frac{P}{\rho} + gz = constant$$

$$P1 + \frac{1}{2}\rho V1^2 = P2 + \frac{1}{2}\rho V2^2$$

$$P3 + \frac{1}{2}\rho V3^2 = P4 + \frac{1}{2}\rho V4^2$$

The flow will vary throughout its passage through the turbine, so there is a change in speed and a pressure drop and it is completely related to the axial force already mentioned.

Therefore, we define this axillary thrust with the following formulas:

$$dFx = (P3 - P2)dA$$

$$dFx = \frac{1}{2}\rho(V1^2 - V4^{2)}dA$$

Induction term is the process by which a time-varying magnetic field generates an electric current in a conductor. This phenomenon is fundamental in the production of electricity in electrical generators and in the operation of transformers.

$$n = \frac{V1 - V2}{V1}$$

$$V2 = V1(1 - a)$$

$$V2 = V3 = \frac{V1 - V4}{2}$$

Therefore:

$$V4 = V1(1 - 2a)$$

Returning to the first axial thrust formula, we substitute and we will have:

$$dFx = 4\pi\rho V1^2 a(1 - a)dr$$

And if you want to know how to correct the loss that occurs at the tips of the blades of each wind turbine, you have to add an F to the previous formula.

Torque

Torque is a measure of the tendency of a force to rotate an object about a specific point or axis. It can be visualized as the force that causes a rotation in an object. Essentially, torque depends on the magnitude of the applied force and the distance from the point of application to the point of rotation, with greater distance producing greater torque for a given force and such rotation will result in additional energy loss.

Inertia of an annular moment is:

$$I = mr^2$$

Torque at an annular moment is:

$$T = \frac{dL}{am} = \frac{dm}{at} r^2 \omega$$

2. Blade element

A blade element refers to a part or component used in the construction of a propeller blade, whether in the context of wind turbines, fans or other similar applications. These elements are designed to capture the kinetic energy of the wind and convert it into mechanical energy, usually in the form of rotation. Each blade element can have different shapes and sizes, but its main function is to generate force from the wind.

Formula:

$$V_v = \Omega r + \frac{1}{2} \omega r$$

$\boldsymbol{\alpha\ attack\ angle}$

$\boldsymbol{\theta\ angle\ that\ indicates\ the\ direction\ of\ the\ string\ with\ respect}$

$\boldsymbol{to\ the\ plane\ of\ rotation\ of\ the\ rotor}$

$\boldsymbol{\phi\ angle\ indicating\ the\ direction\ of\ relative\ velocity}$

$$\alpha = \phi - \theta$$

The relative speed is seen in these formulas with each different angle:

$$Vsin\phi = V1(1-a)$$

$$v\cos\phi = \Omega r(1-a')$$

Forces such as LIFT and DRAG will always depend on the type of profile, angle of attack and relative speed, therefore, we will use this graph

Formulas:

$$L = \frac{1}{2}\rho V^2 cCl$$

$$L = \frac{1}{2}\rho V^2 cCd$$

1.2 Project Objectives

1.2.1 General Objectives

Being able to obtain improved results with modifications after the initial analysis in the first project. With these improvements, you will achieve real-life application in wind turbines with the tubercles on the leading edge and to be able to have a racket that gives us aerodynamic efficiency.

1.2.2 Specifics Objectives

- Create three equations, which help make modifications to the leading edge.
- Create the different modifications for the 3 models of the NACA4412 with an elliptical shape, and each one with its different tubercles.
- Create a geometrically clean mesh over the object with complete precision in fulfilling the specific requirements of the project.
- Make the perfect and appropriate boundary conditions for each model, and thus be able to carry out an analysis under efficient conditions.
- Thoroughly analyze each aspect of the 3 models created, creating a conclusion and obtaining the model with the greatest chance of being useful in real life.
- Research about wind turbines and their use
- Find the real future use in different applications, which we will focus on wind turbines.

1.3 History

This work was born out of the curiosity of how humpback whales, this being the first historical reference, can swim with the momentum and maneuverability of their lateral fins. Then we focus on issues of aerodynamics and fluid mechanics, which is the main factor that makes this body movement capable.

The morphology of whale fins is similar to an aerodynamic profile which acts on lift, drag and more. But the most interesting area as a historical precedent is that the fins are not a smooth aerodynamic profile, but rather have tubercles, which are mainly responsible for greater lift, balance and less drag in these animals.

With my work done previously (inspiration) it is about impeccably improving and resembling these fins as much as possible with some NACA model so that its efficiency can be fruitfully used with real life applications (wind turbines).

And since in this statement we can have an idea of how it will come to be affirmed or not in real life. “Its lift can be up to 6% greater than that of other types of fins without these protuberances” *(Frank E. Fish, 2011) [12]*

The second historical fact that I have to be able to develop this new work is the analysis and research of wind turbines and their use of simple blades for the conversion of kinetic energy to potential energy. Since the 80s, wind turbines began to be developed to obtain sustainable energy, but complete efficiency has not been achieved, since the vast majority of wind turbines have an efficiency of 40% to 50%, the maximum possible being obtained 60%.

Currently, one of the most valued companies for comparison purposes is Siemens Gamesa *(Siemens, 2022) [7]*. Renewable Energy since it is a leader in the wind energy sector worldwide and has installed numerous wind turbines in Spain, among which is the SG 3.4-132 model. This model is recognized for its efficiency and its ability to adapt to the different wind conditions in various regions of Spain. However, it is important to keep in mind that technology in the field of wind turbines is constantly evolving, and that is why we hope to contribute with our new blades.

So, with the tubercles that I generated in the profile, after extensive research, the airfoil can interact more effectively with the air, resulting in a greater ability to generate lift. This leads to an increase in performance and efficiency. When we compare a wind turbine with unmodified blades to one that has the aforementioned modifications to the tuber, we observe significant differences in the percentage data. These differences reflect a greater effect on the movement of air that remains attached to the airfoil for longer, resulting in higher energy generation.

1.4 Difficulties approach or statement

This project has several antecedents, where the most important is the TFG presented by the author Nicolas Alonso Bilbao Carrasco two years ago where some modifications were made to a rectangular NACA4412 profile and analyzed in depth, where the main objective was to considerably increase the capacity . of the new airfoil to stay in the air, using the new variable adjustments required.

At the time when that project was presented, there was no real application where it could be demonstrated that this new creation could work fruitfully in some type of aeronautical device.

After months, thinking about what project I could do to present on this occasion, I decided to focus on my old TFG work and be able to give it a real application, a way to demonstrate that after these years I have been able to learn and expand my knowledge in engineering career and its applications.

Following the review in the first delivery of the work, I have had to redesign and change some aspects of the initial conditions so that the final objective is achieved and to be able to meet the expectations of the expected efficiency of 59%.

After making subsequent adjustments, already mentioned, the profile managed to meet the established expectations. Special attention was paid to the optimization of variable parameters and the refinement of the airfoil design. The main objective was to achieve improved and favorable results (lift, drag and Betz Number), through the comparison and correlation of various designs generated from the NACA4412 profile. Since this study was based on the modification of a previously developed and analyzed design (NACA4412), it is anticipated that this type of experimentation will facilitate future applications in subsequent wind turbines with conventional blades.

Chapter 2. CFD

2.1 Original Wing

The original wing profile of the NACA4412 model is the basis of the project, developing it in an elliptical shape and transforming the leading edge with those oscillations. The reason why choosing an elliptical shape over a rectangular one is for the simple fact that the greatest effectiveness for the objective of this project is the stability of the profile and that happens with a conical shape. Furthermore, we already have a previous analysis of a rectangular shape where it is observed in detail that the support is not what was expected.

2.1.1 Specifications airfoil

The wing profile has different measurements, chord area and wingspan. These measurements were created so that, in their subsequent analysis in the real wind tunnel, they do not have to be modify.

Taper Wing Scale (1:100) NACA4412:

- Chord Zone 1: 200 mm
- Chord Zone 2: 72 mm
- Wing Span: 600 mm

2.1.2 Torsion

This work does not mention the use or design of a torsion blade, which is a crucial phenomenon. But due to the fact that this TFG comes from the hand of one already made a few years ago that had the same characteristics and/or objectives, but a different design. The aim is to improve with this new one, but following the profile structure line without excessive changes.

Clearly in the future it is not ruled out to be able to make this improvement, since the twisting in the blades of a wind turbine is a crucial phenomenon that occurs as a result of the combination of various aerodynamic and structural factors. This twist refers to the blades' ability to twist slightly in response to wind forces.

Simply reducing what torque is used for in aerodynamics is that their blades are kept at the best or most optimal angle of attack and thus when the wind hits the blade, it readjusts in direction to maximize the capture of wind energy.

This continuous adjustment of the angle of attack is essential to ensure efficient conversion of the kinetic energy of the wind into mechanical energy, which is then transformed into electricity through the generator.

2.1.3 Cl vs. Cd

The first thing we are going to do is define those angles that we are going to analyze, since the importance of the different angles is to have and know the movement that the wind turbine will have when receiving the wind at different speeds.

The 3 angles to be analyzed will be -5º, 0º, 10º since they tend to be the most common variations of current wind turbines such as the Siemens Gamesa SG 3.4-132, which is one of the most current and most used in Spanish territory.

Then it is important to know that the cl and cd will also be affected at the different speeds, which will be 5.5 m/s; 8.8 m/s; and 10.4 m/s.

So after this brief explanation, the graphs that will be shown from this moment on are of both coefficients with different leading edge models, but the same angle and speed with respect to each other.

The observed efficiency of the unaltered wing is 1.25 and is generally considered the critical factor, until stall due to an increase in angle of attack (AoA) occurs.

The drag coefficient of the profile is 0.045, which is relatively low, but since it is positive and constantly increasing, it becomes aerodynamically efficient. The pressure exerted across the entire area of the unmodified airfoil tends to be greatest at the leading edge. Furthermore, this pressure pattern does not usually change significantly with variations in the angle of the leading edge.

2.1.4 Mesh

- Symmetric mesh type

The efficiency of symmetry modeling is optimized with the computational simulation of physical phenomena; mesh optimization is essential to guarantee accurate results and computational efficiency. For a profile I have done the most appropriate, symmetrical meshing in Fluent ANSYS and it emerges as a crucial technique that reduces the calculation time and the necessary resources, while maintaining the accuracy of the model. *(González, A. y. N., Miguel, L., Megías, G., García, N., Igeño, Q., & Manuel, P, s/f) [11]*

- Definition of Geometry and Plane of Symmetry

Before delving into the meshing process, it is essential to precisely define the geometry of the problem and the symmetry plane. This plane, which divides the geometry into equal parts, serves as a reference axis for the symmetry of the model.

- Symmetry Boundary Conditions

Once the symmetry plane is established, the appropriate boundary conditions must be defined in Fluent ANSYS to reflect this symmetry. This involves treating the symmetry plane as a wall and applying boundary conditions that capture the symmetric behavior of the phenomenon under study.

- Mesh Generation

The meshing process is carried out with the objective of creating a mesh that reflects the symmetry of the defined geometry. Using the tools provided by Fluent ANSYS, the density and quality of the mesh is controlled to ensure an accurate and efficient representation of the model.

- Simulation Configuration

Once the meshing is completed, the simulation parameters are configured, such as the turbulence model, fluid properties, and initial and boundary conditions. These parameters are adjusted according to the specifications of the problem under study.

- Running the Simulation

With everything configured correctly, the simulation is run in Fluent ANSYS. During this process, the software takes advantage of symmetrical meshing and defined boundary conditions to solve the problem efficiently, significantly reducing calculation time.

2.1.5 Aerodynamic Effectiveness

After the first analysis of this NACA model, a correct aerodynamic effectiveness can be confirmed, the design is made so that the lift is much greater than the drag. In addition, it is concluded that both coefficients (lift and drag) have a positive trend each time the angle is greater.

Drag and lift coefficients are closely related to speed parameters and Mach number. The pressure, temperature and velocity contours and vector graphics around our airfoil are correctly justified.

It is important to know the type of object where this aerodynamic profile would be used, in a way we will understand the data that we have obtained after the analysis in graphs of Cd vs. Cl, pressures and velocities. Following high lift, low drag and low speed for an aircraft it is understand that this type of airfoil is use for small aircraft, low weight and low aerodynamic impact on thrust.

2.1.6 Theory of turbulent flow and adhesive flow

Aerodynamics in the profiles is fundamental in the design of aircraft wings. So we know there are fluid dynamic phenomena, turbulent flow and adhesive flow. These have very important roles in the analysis and generation of lift along with flow resistance.

- Turbulence flow in the profile

Turbulence flow occurs when eddies and vortices are generated in an aerodynamic profile anywhere on the object as the flow passes through.

This turbulence can be beneficial or not, this depends on the objective for using the profile. Because if there is more turbulence in an airfoil, lift increases by creating a low pressure region at the top of the wing.

- Adhesive flow in the profile

It is the boundary layer of fluid that adheres along the airfoil due to viscous force.

This adhesive boundary layer is essential for the generation of lift, since it allows good performance of the fluid with the aerodynamic profile.

Controlling this boundary layer is very important to minimize flow resistance and maximize lift.

- Interaction between Turbulence and Adhesive Flow

In an airfoil, turbulence and adhesive flow interact in a complex manner. Turbulence can help keep the flow attached to the wing surface longer, increasing lift. Furthermore, the adhesive boundary layer can influence the distribution of turbulence along the profile, thus affecting its overall aerodynamic behavior.

2.2 Optimization with different formulas

We have an elliptical NACA 4412 where three modifications have been made, these modifications following some equations as a first step to be able to make these changes to the leading edge.

These equations will help to have uniform undulations throughout the wing profile, these being very similar to the fins of humpback whales, where great lift is sought, very little drag and good use in wind turbines as the main application.

After studying the NACA4412 profile without alterations, it has been determined that its aerodynamic efficiency is notable. The lift generation capacity is high and the resistance is favorable, which makes it an aerodynamic profile with low drag.

The equations associated with the cutting angle at the leading-edge change depending on the depth and width throughout the entire length of the profile.

The three equations with which I had support for this first optimization are:

a=10*sin(10*PI*1rad*b) +10

a=20*sin(20*PI*1rad*b) +20

a=20*sin(40*PI*1rad*b) +20

2.2.1 First Equation

With the first equation a=10*sin(10*PI*1rad*b) +10 to be able to modify the leading edge of our NACA4412 profile, we get the following wavy shapes with a slight, smooth and very well distributed shape. It is important to remember that with this type of undulations on the leading edge they have a uniform depth of about 10 mm that extends until reaching the edges of the profile.

The generation of these curves in CATIA is very simple, as long as you are clear about where the created formula would be generated, depending on the position axis and the same with the “sweep” tool to be able to outline this indicated section in a uniform and smooth manner.

The smooth and uniform completion of the design helps the fluid (air) to remain adhered to the walls for longer and follow the lift line until reaching the trailing edge, thus creating greater efficiency and lower resistance.

2.2.2 Second Equation

With the second equation (a=20*sin(20*PI*1rad*b) +20) to be able to modify the leading edge of our NACA4412 profile, the result is the following slightly, soft and deeper wavy shapes. Where the air cut is partial and does not allow the fluid to pass homogeneously through the analyzed object.

The cutting angle of each termination is much more pronounced, where in the end the conclusion is reached that instead of generating greater lift, what it produces is much greater resistance and pressure than the rest of the designs.

Therefore, having a high resistance and pressure, the modified profile immediately generates a formation of turbulent fluid before reaching the trailing edge, which does not help the lift to be significant and becomes a problem when needs aerodynamic efficiency.

2.2.3 Third Equation

With the third equation (a=20*sin (40*PI*1rad*b) +20) to be able to modify the leading edge of our NACA4412 profile, we get the following wavy, soft and deeper shapes. Where the air cut-off is total and does not allow the fluid to pass in any way through the analyzed object.

Furthermore, it results in a design that is completely contrary to the first, being a very smooth and correctly distributed design, respecting the leading edges and profiles.

This formula does not help to generate a smooth curve so that the fluid can pass lightly and without drag problems and generate adequate lift.

After the generation of this type of design on the leading edge, the Cl vs Cd graphs show us what was expected, a very high CD and a very low CL.

2.2.4 Comparison

In this section we will carry out the study of each design and/or model that has been generated, in order to find the one that has aerodynamic efficiency when used in the real undo. The main objective of this work is to find that design that helps a wind turbine to take advantage of almost 60% of its energy extraction to convert it into power.

It is very important to know that there are three angles of attack (those that the blades rotate depending on the wind at the time of use) and the different speeds that will be 3 (those speeds that are within the range of use of a wind turbine)

These three modified NACA 4412 profiles have the same Reynolds number so that the fluid does not have any alteration at the time of object analysis.

In addition, we have to take into account those graphs that are made through vectors and pressure or velocity contours. These are always related to the fluid becoming laminar most of the time so that the aerodynamic effectiveness is positive.

In the same way, we can know what the biggest error is in each design and improve after some other experimentation and/or idea.

2.2.4.1 Angle 0 Degree

We will start with the profile at 0 degrees, the different models and speeds. Each table comes with data extracted from the analysis carried out in ANSYS-FLUENT where the lift and drag of each profile has been assessed in the different situations submitted.

These situations come hand in hand with actions that will be carried out in a real way in the near future with wind turbines, for the same reason 3 angles were thought of and that none of these are negative, since a negative angle of attack is not beneficial for the efficient operation of a wind turbine, since it reduces the capacity to harness wind energy and can exert excessive forces on the turbine structure.

The three models shown in the tables are 0 mm (regular), 10 mm, 20 mm and 40 mm. This refers to the depths of the corrugations in each design in the leading edge area.

Model	Velocity	Lift	Drag	Efi.
0 mm	5,5 m/s	1	0,15	6,66
10 mm	5,5 m/s	0,42	0,018	23,30
20 mm	5,5 m/s	0,3	0,014	21,42
40 mm	5,5 m/s	0,35	0,0085	41,17

Table 1 0º 5,5 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	8,8 m/s	1,05	0,2	5,25
10 mm	8,8 m/s	0,43	0,018	23,88
20 mm	8,8 m/s	0,30	0,014	21,43
40 mm	8,8 m/s	0,37	0,04	9,25

Table 2 0º 8,8 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	10,4 m/s	1,1	0,15	7,33
10 mm	10,4 m/s	0,42	0,019	22,10
20 mm	10,4 m/s	0,42	0,033	12,72
40 mm	10,4 m/s	0,08	0,04	2

Table 3 0º 10,4 m/s

In the three graphs a clear advantage is observed in the operation of the leading edge of the first modified model knowing that the resistance becomes negative. Likewise, if we only look at the figure created by the CL vs CD graphs, they are very similar in their behavior with the fluid, so at a degree like 0º it is more complicated to make an efficiency decision, so we must follow investigating with the rest of the angles of attack.

Furthermore, what we have to take into account is knowing when the fluid will or will not separate from the profile wall, since a boundary layer has to form where turbulence and drag will subsequently occur. But it is understood that in this situation precisely there is no such notable separation.

It is correct to comment that the profile with leading edge without modified design behaves really well, generating a lot of lift but managing to have little resistance against the fluid. It is correct to comment that the model with the modification of the first equation achieves greater efficiency over the rest, as long as the speed is between 8.8 m/s and 10.4 m/s. The first modified model achieves high lift and low drag, which is actually what is sought because I considered it as exceptional efficiency where it implies that the wind turbine blades experience a net force in the opposite direction to the wind.

2.2.4.2 Angle 5 Degree

The analysis is based on the aerodynamic profile with an angle of attack (AOA) of 5º, it can be imagined that the wind turbine blade has varied its position according to the axis in order to obtain the best lift according to speeds at that moment.

It is based on the tables with the different blade models and speeds but with the same angle of attack, which will help to verify the best aerodynamic efficiency compared to the rest.

Model	Velocity	Lift	Drag	Efi.
0 mm	5,5 m/s	0,35	0,1	3,50
10 mm	5,5 m/s	0,3	0,04	7,50
20 mm	5,5 m/s	0,4	0,1	4,00
40 mm	5,5 m/s	0,2	0,18	51,11

Table 4 5º 5,5 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	8,8 m/s	0,2	0,03	6,66
10 mm	8,8 m/s	0,4	0,09	4,44
20 mm	8,8 m/s	0,19	0,32	0,59
40 mm	8,8 m/s	0,2	0,40	0,50

Table 5 5º 8,8 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	10,4 m/s	0,4	0,04	10,00
10 mm	10,4 m/s	0,52	0,0128	40,62
20 mm	10,4 m/s	0,25	0,02	12,50
40 mm	10,4 m/s	0,35	0,04	8,75

Table 6 5º 10,4 m/s

With this second analysis and study, a very similar comparison to grade 0º is observed, since it is seen without problems in the 4 designs that the one that predominates in having greater lift and less resistance to fluids is the first modified design.

It is important to highlight that it is the model that has less roughness, greater smoothness and better finishes so that the fluid and waves with a depth of 10 mm can pass through the object and adhere to its body.

It must be taken into account that the higher the aerodynamic coefficient, the lower the aerodynamic efficiency, which is why the famous turbulence that can be seen at the trailing edge of the same profile is generated. So, with this conclusion, when these turbulences are generated, it is when a very rapid separation of the fluid from the walls of the aerodynamic profile occurs, generating a profile that is not very usable in the aeronautical world.

The last two graphs being very similar, and the first very different from the rest. It is concluded that the 5º angle of attack of the 10 mm profile may work better at medium or high speed, but I can rule out that the same profile also works correctly at minimum speeds.

A great performance of the first equation is repeated in the model with the high speeds of 8.8 m/s and 10.4 m/s in this AOA. So, we consider it as a characteristic and one of the first conclusions about the model and its behavior.

It would be very interesting to be able to verify it in a real way in a wind tunnel or with the construction of a scale model.

2.2.4.3 Angle 10 Degree

This last analysis for the aerodynamic profile with an AoA of 10º I intend to subject the profile at a different angle to see its reaction and know the lift and drag.

It is curious how wind turbines operate, where they have to rotate up to a certain angle to extract the greatest benefit in terms of power or energy, and at the same time not overexert it so as not to break the structure due to the angles. and high speeds.

In this sense, a great similarity is observed with the lift and resistance in the models (a=10*sin (10*PI*1rad*b) +10) and (a=10*sin (20*PI*1rad*b) +10) designed and modified, since it is understood that having the undulations between 10 mm and 20 mm are almost perfect for this angle.

It is also very important to note that at a greater angle of attack (10º) and at a higher speed 8.8 m/s or 10.4 m/s the lift is much better in both models. The first design (a=10*sin (10*PI*1rad*b) +10) is still indicated, but the second model (a=20*sin(20*PI*1rad*b) +20) could be investigated more in depth to find some other type of benefit in another area of the industry.

It is observed that the greatest efficiencies given by the CD VS CL data are with the models of the first equation and second equation. Knowing first-hand a great speed ratio of 5.5 m/s and 8.8 m/s. Therefore, it is understood when analyzing the model or case that this AOA acts better at low speeds.

Model	Velocity	Lift	Drag	Efi.
0 mm	5,5 m/s	0,01	0,18	0,05
10 mm	5,5 m/s	0,9	0,1	9,00
20 mm	5,5 m/s	1,12	0,12	9,33
40 mm	5,5 m/s	0,99	0,15	6,60

Table 7 10º 5,5 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	8,8 m/s	0,3	0,009	33,33
10 mm	8,8 m/s	1	0,02	50,00
20 mm	8,8 m/s	1,23	0,12	10,25
40 mm	8,8 m/s	1,02	0,1	10,20

Table 8 10º 8,8 m/s

Model	Velocity	Lift	Drag	Efi.
0 mm	10,4 m/s	1,99	0,21	9,47
10 mm	10,4 m/s	2,09	0,40	5,22
20 mm	10,4 m/s	1,8	0,2	9
40 mm	10,4 m/s	0,5	0,08	6,25

Table 9 10º 10,4 m/s

As soon as you have the 10mm model and an angle of attack of 10º, the best you can have been either low speeds such as 5.5 m/s, which is when the wind turbine just begins to rotate, or at high speeds 10, 4 m/s, which is the maximum limit that it has, and this because the Drag coefficient has negative and very low numbers. Which tells us that the turbulence is lower and the adhesion in the profile (fluid) is very long, generating greater efficiency.

What the values obtained by the CDF also tell us is that the adhesion that the fluid has on the profile is better at these low speeds. And the resistance has been equally low at those speeds, the only thing is that it is not yet possible to know exactly the moment of release of the fluid from the body in the corresponding axis.

2.2.5 Conclusion Cl vs Cd

After having visually analyzed with graphics and vectors the three models created from the NACA4412 profile and modified the leading edge with these undulations and having a conical type wing or wing profile, he was able to reach the conclusion that the model that best fits adapt to the work of a wind turbine and its effectiveness through the flow of air is the first modified model, which is the equation:

(a=10*sin (10*PI*1rad*b) +10).

It acts perfectly at low speeds and medium speeds, which means that at 5.5 m/s and 8.8 m/s it is a safe bet that all the efficiency that can be understood in terms of converted energy will be extracted.

If we simply compare the conventional model without any modification and the first second modified model, it can be said that there is no point in continuing to use or manufacture the current models, the efficiency is much higher and the survey results are very high.

And it is very important for these last conclusions to focus carefully on the Lift and Drag tables and analyze each angle and speed, the only times that my conclusion is refuted in a very pointed way is with the 40mm model at low speed at 0º and 5º, while that the rest of the data is clear and concise when choosing a promising and futuristic design with a technology that will undoubtedly completely change the way of seeing and converting the efficiency obtained into energy for use in the cleanest way possible.

Chapter 3. Conclusion Project

To make a final reflection in this section of conclusions of the work and the behavior of the different angles of attack and designs, it is very important to remember that turbulence flow and adhesive flow are critical components in the aerodynamics of the wing profiles, Therefore, understanding how these phenomena interact with wing geometry is essential to designing efficient, high-performance aircraft wings. The control and optimization of turbulence and the adhesive boundary layer are key research areas in aeronautical engineering and applied aerodynamics and more so that a wind turbine (application) can have much more efficient performance than current ones.

It is very important to emphasize that the only model that gives us high efficiency is the 10mm model in the first equation. It is also correct to say that if we find a middle point between the 10mm and 20mm models, it could be that it works better at those angles and speeds. that the 10 mm model is surpassed by another body. And this can simply be verified in future work, which I do not find of great need.

We also conclude that this figure already analyzed is transformed into benefits such as energy efficiency, performance in different wind conditions, reduction in the cost of operation and maintenance, lower environmental impact and longer useful life of the wind turbine.

And in the same way, having a very high and good efficiency, some very important points are added, which are the resistance and durability of the material with which we are working or carrying out this wind turbine work. Since having a very high efficiency, it is understood that when analyzing the useful life of the blades it can be said that they have been used to the maximum and it becomes lower expenses for the company.

Chapter 4. Future Work

It is very important to be able to be clear about the improvements or future work that will be carried out with this type of blades for wind turbines, so those situations must be carried out in order to find an improvement for their use and manufacturing.

Torque in the Blades

There are four very clear points to be able to use this type of feature and design in wind turbine blades in the future, of which clearly if used will help the performance of the wind turbines on a percentage basis.

- Aerodynamic performance optimization;

This is generated with the contact that the surface area has, with the wind speed and angle direction being the main ones responsible for making the design work, seeking an optimization of the aerodynamic work. This is usually designed into the blades, although there is a higher cost than normal ones.

- Reduction of dynamic loads;

This is an issue that crucially interferes with the aerodynamic issue and how the loads developed by speed, angle of attack and profile design act. It is curious that it is an issue that has to have a lot of control because it becomes beneficial in the production of energy and the continuous economic improvement of wind systems.

- Improved stability;

The issue of stability related to torque is very important and complex, since if there is no torque in some final part of the wing surface, it may undergo certain changes in its aerodynamics. So in this work it is something that I needed to specify and test, but for a reason of sticking to the previous work and the not so changing improvements on the profile.

Reduction of the carbon footprint

It is necessary to considerably reduce the environmental impact on the manufacturing of wind turbines where it is vital to continue ensuring ecological sustainability in the near or distant future. And in this section you will know how this will be achieved with a totally comprehensive approach that includes the following:

- Selection of Sustainable Materials

Interesting and important section to be able to find the correct and fully recyclable materials to avoid a continuous attack on environmental health. Likewise, what is meant is that no new material introduced for use in manufacturing considerably affects its wind performance.

What we have to seek and conserve in conjunction with this section of reducing the carbon footprint is environmental sustainability, a considerable reduction in emissions and conservation of resources, which is the recycling of resources already used in other industries.

Therefore, we have the following important and concise points that can be taken as very important future steps from which we can start to generate this new era of wind production.

- Recycled Fiberglass
- Recycled Carbon Fiber Composites
- Natural Composite Materials
- Biodegradable Polymers
- Hybrid Materials

- Efficient Manufacturing Processes and Renewable Energy in Manufacturing

One of the great possibilities to achieve this efficiency while respecting the environment is with 3D printing and its automation, helping in an exemplary way to reduce the use of energy and waste of materials when mass manufacturing blades or other corresponding parts. with the industry.

If in the future we want to make this important change, it is best that it be a complete change and not only in terms of materials, since we know that we can manufacture using or providing the use of totally renewable energy with the help of nearby wind energy. to the industrial plant or the same solar panel fields that would help in the manufacturing of each material or important part of a wind turbine.

What we are trying to create is for it to be a totally renewable cycle, where we know that the carbon footprint reduction is achieved in any section of manufacturing, from obtaining the material, reusing the material and manufacturing the material.

Once this stage is achieved, the majority of the population will be made aware of this type of renewable energy actions and it will be more supported by different sectors.

- Recycling after use and end-of-life management

It is completely important to be aware that when designing the blades or parts of the wind turbines, we take into account that in the near future, at the end of their useful life when the time or hours of use comes, it will be possible to obtain almost 100% recycling of each material. It is possible that not all pieces can be recycled due to material and durability issues, but the greater the recovery the better.

So I am clear that very important control will have to be carried out at the time of recycling and create a program that endorses and manages with experts the issue of recycling parts in the same industry or in a completely different one.

With this correct management we will know which part and which material can be reused without problems after having spent a few hours or time of use in the wind sector. Therefore, there will be materials already mentioned that can be recycled more than once with correct management and administration, such as fiberglass, which is a material completely suitable for the manufacture of the majority of sections of a blade.

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