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Título del proyecto:

ANALYSIS AND DESIGN OF A VERTICAL AXIS WIND TURBINE

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1. **INTRODUCTION**

The function of vertical axis wind turbine is converted the wind power to electricity. Particularly this type of turbine has the main rotor shaft arranged vertically. For it a power study is made in which the size of the wind turbine is defined.

Nowadays there are several types of vertical axis wind turbine: Sabonius, Darrieus and Giromill.

The Sabonius turbine is one of the simplest turbines. Looking down on the rotor from above, a two-scoap machine would look like a ¨S¨ shape in cross section. Sabonius turbines are used whenever cost is much more important than efficiency.

The Darrieus turbine consists of a number of curved and vertical aerofoils which are attached to the central mast by horizontal supports. The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses.

The giromill turbine is a subtype of Darrieus turbine, this turbine has a straight blades. This turbine is the type of wind turbine that I am designing. It is typically formed by two or three vertical aerofoils but these aren't the only options. Giromill turbine is cheaper and easier to build than a standard Darrieus turbine, but also requires strong winds (or a motor) to start. However, they work well in turbulent wind conditions and are an affordable option where a standard horizontal axis windmill type turbine is unsuitable.

One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective. The Giromill blade design is much simpler to build, but results in a more massive structure than the traditional arrangement, and requires stronger blades, for reasons outlined above.

The disadvantage of this type of wind turbine is the performance that present. They have a low performance, because to turn all the wind energy to electrical energy is impossible, but sometimes this solution is cheaper than to take the electrical network to the wiring, the cost of kW·generated h is minor that in the case of contracting the

services of a company. And it is a process of transformation of energy that does not cause environmental damages.

2. AIMS OF THE PROJECT

The main objective of this project is to design a new vertical axis wind turbine, specifically one Giromill wind turbine.

The project development requires performing a previous study of the vertical axis wind turbines currently development. This study has to be performed before starting to design the wind turbine.

Other very important aim is the development of a new vertical axis wind turbine. The after analyses that will result in the final design of the wind turbine will be made from this first design.

The project requires performing the analysis of efforts and the analysis of performance. These analyses will be made with the help of the softwares Gambit and Fluent. The final design of the vertical axis wind turbine will be made from the results obtained in these analyses.

Finally the main objective of this project is the design of the vertical axis wind turbine based on the results obtained in the analysis of efforts and performance performed on the first design of the wind turbine. This final design will be carried out with SolidWorks.

3. REVIEW OF LITERATURE

3.1. Giromill rotor

3.1.1. Historical background

The straight-bladed wind turbine, also named Giromill or H-rotor, is a type of vertical axis wind turbine developed by Georges Darrieus in 1927.

This kind of VAWT has been studied by the Musgrove's research team in the United Kingdom during the '80.

In these turbines the "egg beater" blades of the common Darrieus are replaced with straight vertical blade sections attached to the central tower with horizontal supports. These turbines usually have 2 or 3 vertical airfoils. The Giromill blade design is much simpler to build, but results in a more massive structure than the traditional arrangement and requires stronger blades.

In these turbines the generator is located at the bottom of the tower and so it can be heavier and bigger than a common generator of a HAWT and the tower can have a lighter structure.

While it is cheaper and easier to build than a standard Darrieus turbine, the Giromill is less efficient and requires motors to start. However these turbines work well in turbulent wind conditions and represent a good option in those area where a HAWT is unsuitable.

3.1.2. Parts of the rotor

The structure of all Giromill rotors can be splitted in three components:

- **Central axis of rotation:** This component is also called central mast. This is in the middle of the rotor. The other components of the rotor rotate around it. Generally it is metallic and its section is circular.

- **Blades:** In Giromill rotors the blades are vertical airfoils like in the Darrieus rotors, but in Giromill rotors the blades are straight. The main function of the blades is spin by the action of the wind. The blades are fixed and are connected to the rotor shaft, which rotates with them in the wind.

The number of blades is a significant issue. You generally have a decision between two and three blades, but these aren't the only options. These machines may suffer some efficiency loss, but adding more blades means that

the machine is dealing with more drag. The VAWTs with large numbers of blade define rotation speeds relatively low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor in Darrieus wind turbine. The disadvantage to adding more blades is the cost.

- Radial arms: These components are horizontal supports which attach the blades to the central axis of rotation. It can be attached to the blades and to the central mast by welding or by means of a screwed union.
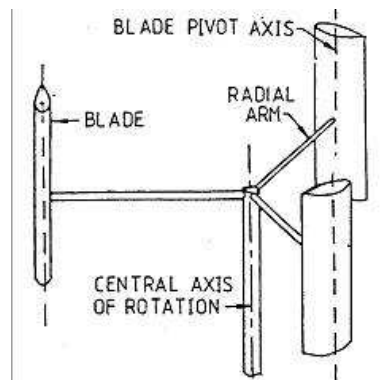
Figure 3.1.
Parts of the rotor

3.1.3. How Darrieus rotor works

The working principle of Darrieus rotor can be simplified as below. First, assume that the retarded wind in front of the rotor still remains straight. When the blades are moving much faster compare to the original undisturbed wind speed i.e. ratio of blade speed to free stream wind speed, tsr > 3, the picture above shows the velocity vector of the airfoil blades at different angular position. With such a high tsr, the airfoils will be 'cutting through' the wind with small angle of attack. The resulting lift force always assists the rotor rotation while the drag force always opposes the rotation. As the lift zeroing at the left side (0 degree) and right side (180 degree) where the symmetrical airfoil moves paralleled to wind, the torque changes to negative around these position. At the near front (90 degree) and far back (270 degree) position, the lift component is much higher than the drag component, so positive torque is produced. The total torque per revolution will be positive with a good set of airfoils so the rotor will accelerate at the right direction.

During start-up, the starting torque depends on the angular position of rotor with respect to the wind direction, so the rotor might rotate at the right direction straight away or wobble a bit before starting. Normally, the rotor will need some form of assistance to reach higher revolutions before it begins to rotate by itself as the Darrieus rotor has very low torque at low tsr which can be easily worsened (till negative) by friction in the system.

To summarize the operation way of a Giromill VAWT is not different from that of a common Darrieus turbine. The wind hits the blades and its velocity is split in lift and drag component. The resultant vector sum of these two components of the velocity makes the turbine rotate. The swept area of a Giromill wind turbine is given by the length of the blades multiplied for the rotor diameter.
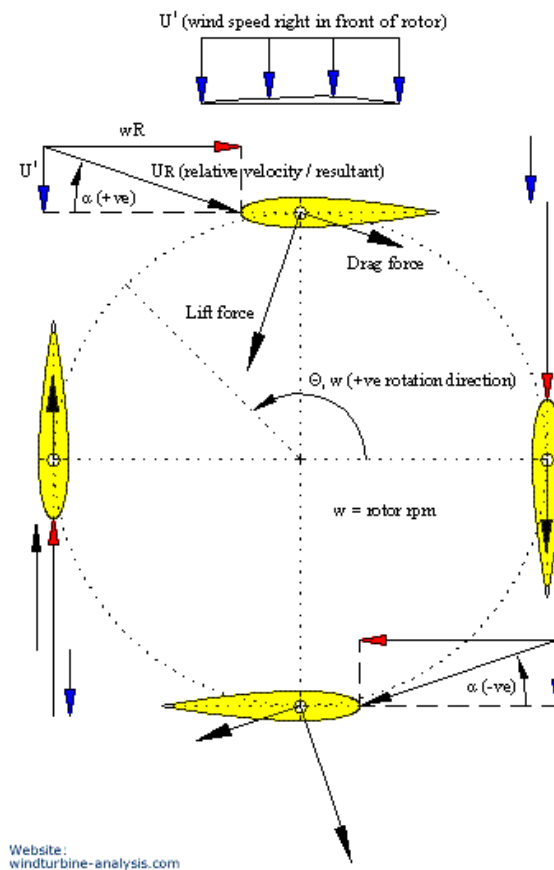
Figure 3.2.
How Darrieus rotor work

Below I add other figure which shows the direction of rotation of the rotor due to wind speed.
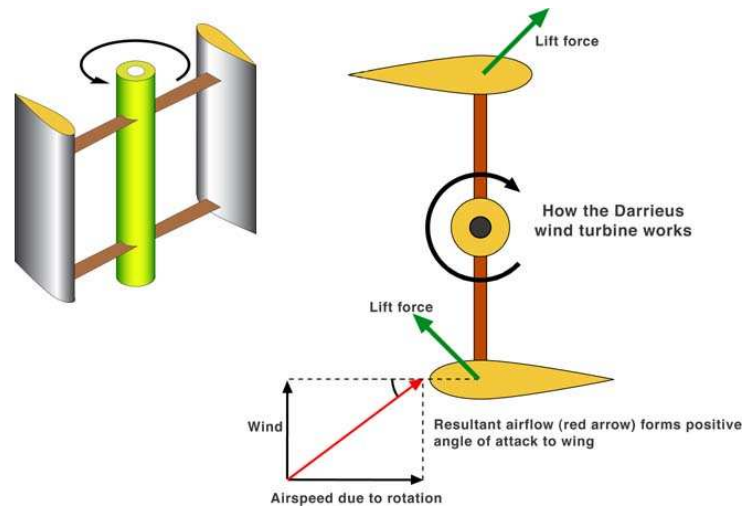
Figure 3.3.

Rotational direction of the rotor

One problem with the design is that the angle of attack changes as the turbine spins, so each blade generates its maximum torque at two points on its cycle (front and back of the to a sinusoidal power cycle that complicates design.

Another problem arises because the majority of the mass of the rotating mechanism is at the periphery rather than at the hub, as it is with a propeller. This leads to very high centrifugal stresses on the mechanism, which must be stronger and heavier than otherwise to withstand them. The most common shape is the one similar to an egg-beater, which can avoid in part this problem, having most of the rotating mass not far from the axis.

3.2. The effect of number of blades

The number of blades is a significant issue. You generally have a decision between two and three blades, but these aren't the only options. The benefit of adding more blades depends on a trade off between the various required performance characteristics and manufacturing costs.

These machines may suffer some efficiency loss, but adding more blades means that the machine is dealing with more drag. The VAWTs with large numbers of blade define rotation speeds relatively low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor in Darreus wind turbine

The disadvantage to adding more blades is the cost.

Other parameters that may be affected by the number of blades include, rotor weight and balance, structural loading, torque ripple, starting torque, and fatigue resistance. It should be noted here that the number of blades was increased, but the chord of those blades was not reduced so the solidity rises substantially.

Particularly I have chosen design a vertical axis wind turbine with three blades.

3.3. Theory of aerodynamics

From an aerodynamic point of view, the different VAWT, have a number of aspects in common that distinguish them from the HAWT.

The blades of a VAWT rotate on a rotational surface whose axis is at right angle to the wind direction. The aerodynamic angle of attack of the blades varies constantly during the rotation. Moreover, one blade moves on the downwind side of the other blade in the range of 180° to 360° of rotational angle so that the wind speed in this area is already reduced due to the energy extracted by the upwind blades. Hence, power generation is less in the downwind sector of rotation. Consideration of the flow velocities and aerodynamic forces shows that, nevertheless, a torque is produced in this way which is caused by the lift forces. The breaking torque of the drag forces in much lower, by comparison.

In one revolution, a single rotor blade generates a mean positive torque but there are also short sections with negative torque. The calculated variation of the total torque also shows the reduction in positive torque on the downwind side.

The alternation of the torque with the revolution can be balanced with three rotor blades, to such an extent that the alternating variation becomes an increasing and decreasing torque which is positive throughout. However, torque can only develop in a vertical axis rotor if there is circumferential speed: the vertical axis rotor is usually not self starting.

The qualitative discussion of the flow conditions at the vertical axis rotor shows that the mathematical treatment must be more complex than with propeller type. This means that the range of physical and mathematical models for calculating the generation of power and the loading is also wider.

Various approaches, with a variety of weightings of the parameters involved have been published in the literature. Most authors specify values of 0,40 to 0,42 for the maximum Cp for the Darrieus type wind turbine.

In order to analyze the aerodynamics of a rotor and to get information about its power generation, it's necessary to start by considering that a wind turbine works converting the kinetic energy of a wind flow in electricity, following several steps:
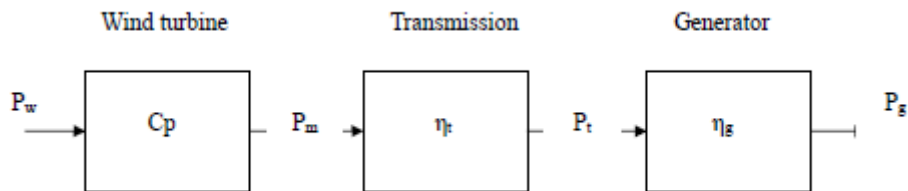
Figure 3.4.

Conversion process of energy

From the wind flow the turbine gets the energy to rotate the blades. The energy produced by this rotations is given to the main shaft (or to a gearbox, if it is present) and from here to the electrical generator, that provide the electricity to the grid.

3.4. Power in the wind

Another point to consider during the design of any wind turbine is how calculate the wind power in the blades. But the available wind power is different from the usable wind power. Firstly I show the expression to calculate the available wind power:

$$P = \frac{1}{2} G A V^3 \qquad\qquad [3.1.]$$

P = Wind power in watts

G = Air density in kg/m^3

A = area perpendicular to the wind direction formed by the rotor in m^2

V = wind speed in m/s

The expression to calculate the usable wind power is:

$$P= \frac{1}{2} \, G \, A \, V^3 \, C_p \qquad\qquad \text{[3.2.]}$$

In this expression C_p is the power coefficient that depends on the type of machine and for each variable in turn to the relationship between the peripheral speed of the blades and wind speed.

To calculate the wind speed exist this expression:

$$V=V_0(h/h_0)^n \qquad\qquad \text{[3.3.]}$$

V is the wind speed at height h above ground in m/s

V_0 is the known wind speed at a height h_0 m/s

h is the height at you want to calculate the wind speed in m

h_0 is the reference height in m

n is the value which depends on the terrain roughness:

-Smooth (sea, sand, snow): 0.10-0.13

-Moderately rugose: 0.13-0.20

-Rugose (forest, neighborhoods): 0.20-0.27

- Very rugose (cities, tall buildings): 0.27-0.40

Below I show a map with annual wind mean speed at 25 m above ground level in United Kingdom:

Figure 3.5.

Annual mean Wind Speed

3.5. Power coefficient

The power output of a wind turbine rotor changes with the rpm so the rotor performance is normally presented in power coefficient versus tip to wind speed ratio graph. Sometimes, the same information is also expressed in form of torque coefficient vs. tip speed ratio curve. For a Darrieus wind turbine:

The power coefficient is defined as:

$$Cp = \frac{P}{\frac{1}{2}\rho U^3 A} \qquad [\mathbf{3.4.}]$$

Where P = rotor power

The tip to wind speed ratio, or tip speed ratio, or tsr is defined as:

$$\lambda = \frac{wR}{U} \qquad\qquad [\mathbf{3.5.}]$$

Where R = maximum rotor radius

w = rotor rpm

The torque coefficient is defined as:

$$Ct = \frac{T}{\frac{1}{2}\rho U^3 A} \qquad\qquad [\mathbf{3.6.}]$$

Where T = rotor torque

The relation between these two coefficients is:

$$Ct = \frac{T}{\frac{1}{2}\rho U^2 AR} * \frac{w}{w} * \frac{1}{\frac{U}{U}} = \frac{Tw}{\frac{1}{2}\rho U^3 A * \frac{wR}{U}} = \frac{P}{\frac{1}{2}\rho U^3 A \lambda}$$

$$Ct = \frac{Cp}{\lambda} \qquad\qquad [\mathbf{3.7.}]$$

In this project the torque coefficient will be calculated with the analysis carried out in Fluent.

3.6. Betz´s law

Betz's law is a theory about the maximum possible energy to be derived from a "hydraulic wind engine", or a wind turbine such as the Éolienne Bollée (patented in 1868), the Eclipse Windmill (developed in 1867), and the Aermotor (first appeared in 1888 to pump water for cattle, and is still in production). Decades before the advent of the modern 3-blade wind turbine that generates electricity, Betz's law was developed in 1919 by the German physicist Albert Betz. According to Betz's law, no turbine can

capture more than 59.3 percent of the kinetic energy in wind. The ideal or maximum theoretical efficiency n max (also called power coefficient) of a wind turbine is the ratio of maximum power obtained from the wind to the total power available in the wind. The factor 0.593 is known as Betz's coefficient (from the name of the man who first derived it). It is the maximum fraction of the power in a wind stream that can be extracted. The power coefficient is defined as:

$$power\ coefficient = Cp = \frac{power\ output\ from\ wind\ machine}{power\ available\ in\ wind} \qquad [\mathbf{3.8.}]$$

4. DESIGN PROCESS

4. 1. Introduction

The type of aerofoils that I have studied to apply in my wind turbine is a four-digit NACA wing section. In this type of NACAs aerofoils the first digit describing maximum camber as percentage of the chord, the second digit describing the distance of maximum camber from the airfoil leading edge in tens of percents of the chord and the last two describing maximum thickness of the airfoil as percent of the chord.

Particularly the NACAs aerofoils that I have analyzed in my project are symmetrical 4-digit NACAs aerofoils. The main characteristic of these NACAs is that their first two digits are 0. The formula for the shape of a NACA 00xx foil, with "xx" being replaced by the percentage of thickness to chord, is:

$$y = \frac{t}{0.2}c \left[0.2969 \times \sqrt{\frac{x}{c}} - 0.1260 \left(\frac{x}{c}\right) - 0.3516 \left(\frac{x}{c}\right)^2 + 0.2843 \left(\frac{x}{c}\right)^3 - 0.1015 \left(\frac{x}{c}\right)^4 \right] ; \textbf{4.1.]}$$

where:

    c is the chord length

    x is the position along the chord from 0 to c

    y is the half thickness at a given value of x (centerline to surface)

    t is the maximum thickness as a fraction of the chord (so 100 t gives the last two digits in the NACA 4-digit denomination)

This formula will be very important to draw the airfoils in Gambit by the coordinates generated by one generator of points.

Exactly I have analyzed the behavior in 2D of these three symmetrical NACAs airfoils: NACA 0012, NACA 0015 and NACA 0020. I have chosen these three NACAs because they have given good results in previous studies carried out about Giromill turbines.

4.2. Gambit

4.2.1. Geometry

First of all, I have drawn in Gambit the possible airfoils. I have got draw them with the help of this generator available on internet:

http://www.ppart.de/aerodynamics/profiles/NACA4.html
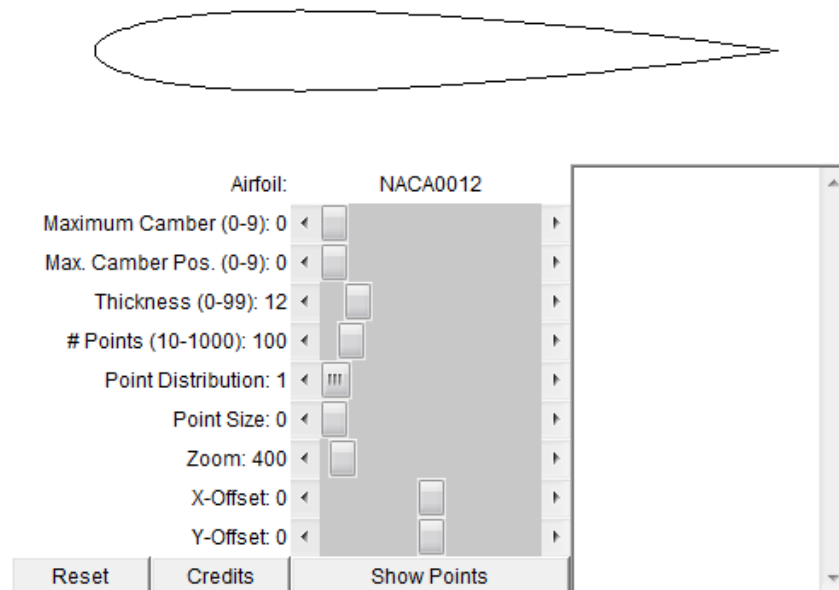
Figure 4.1.

Generator of coordinates

This generator gives you the coordinates of the NACAs that you need. How the Figure 4.1. shows you have to indicate the main characteristics of your NACA and choose the number of points that you need to draw your airfoil. To my project I have considered to generate 60 points for each airfoil. The next step is copy the coordinates in one text file and then import it in Gambit to create the airfoil.

To analyze the NACAs and choose the most appropriate of them I have drawn in 2D three Giromill wind turbines, one for each NACA, formatted for three airfoils separated 120º each one. This position of the airfoils in the turbine is because previous studies say this position reduces the vibrations of the wind turbine. The ratio of these 2D turbines is 2 meters.

The study requires draw one wind tunnel to indicate the direction of the wind flow, I have considered appropriated, to this case, draw one square tunnel whose sides are 12 meters each one. The two circles have been drawn to allow the rotation of the mesh. The littlest one has 1.5 meters of ratio and the other circle´s ratio is 2.5 meters. In the next figure I show the sketch in meters:
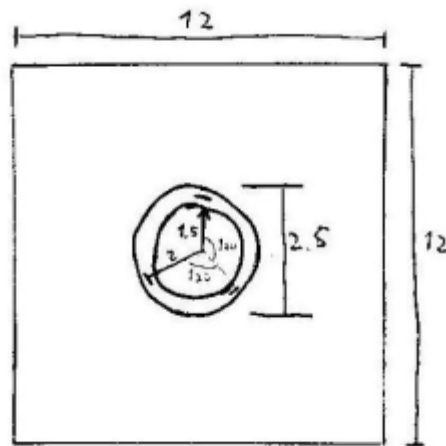
Figure 4.2.
Sketch of one 2D model

First of all, I have set the different points to guide the edges of the models. Then I have created the faces with these edges.

When all faces are drawn it is necessary do some operations which will allow the correct working of the model. In this model it is necessary, firstly, split the square with the biggest circle and then create other similar circle. The next step is to subtract of this circle the airfoils. And the last step is split the biggest circle with the smallest and then create other circle similar to the small one. Finally there are three faces: wind tunnel (the square without the biggest circle), the rotational ring and the central circle.

In the picture below we can see an example of how was designed the models.
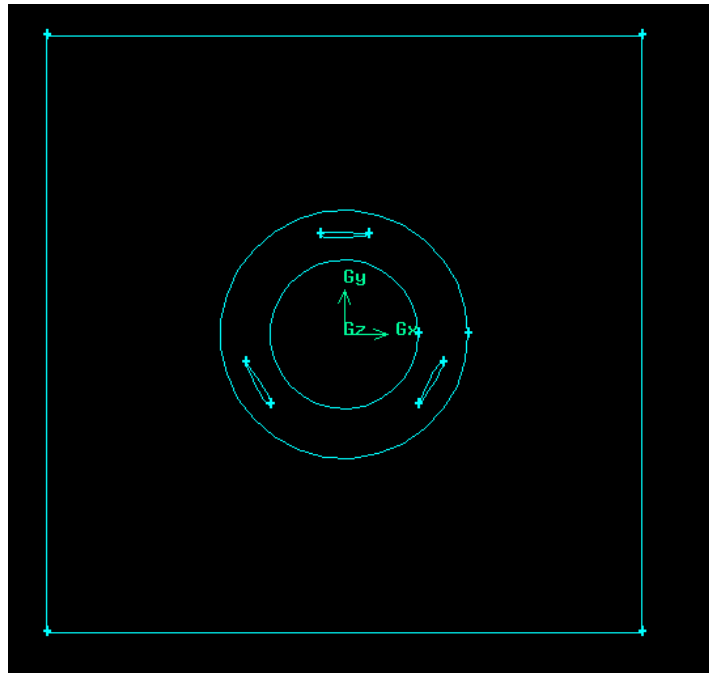
Figure 4.3.

2D model drawn in Gambit

The process is very similar designing the prototypes in 3D. First of all, I have set the different points to guide the edges of the blades, connecting these edges I have created the faces which will form the volumes of each blade. Then I have created the brick and the cylinders. When these volumes have been created it is necessary do some operations which will allow the correct working of the prototypes. In these models it is necessary, firstly, split the brick with the biggest cylinder and then create other similar cylinder. And the last step is to subtract of this cylinder the blades and the central axis. Finally there are two volumes: wind tunnel (the brick without the biggest cylinder) and the rotational part (the biggest cylinder without the blades and the central axis).
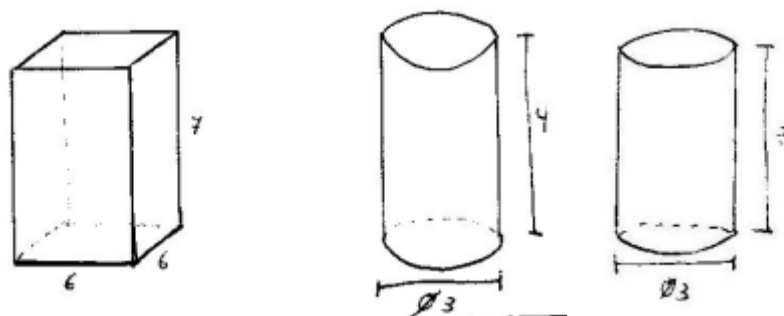
Figure 4.4.

Sketches of tunnels of the prototypes

In the picture below we can see the design of one of my prototypes in Gambit.
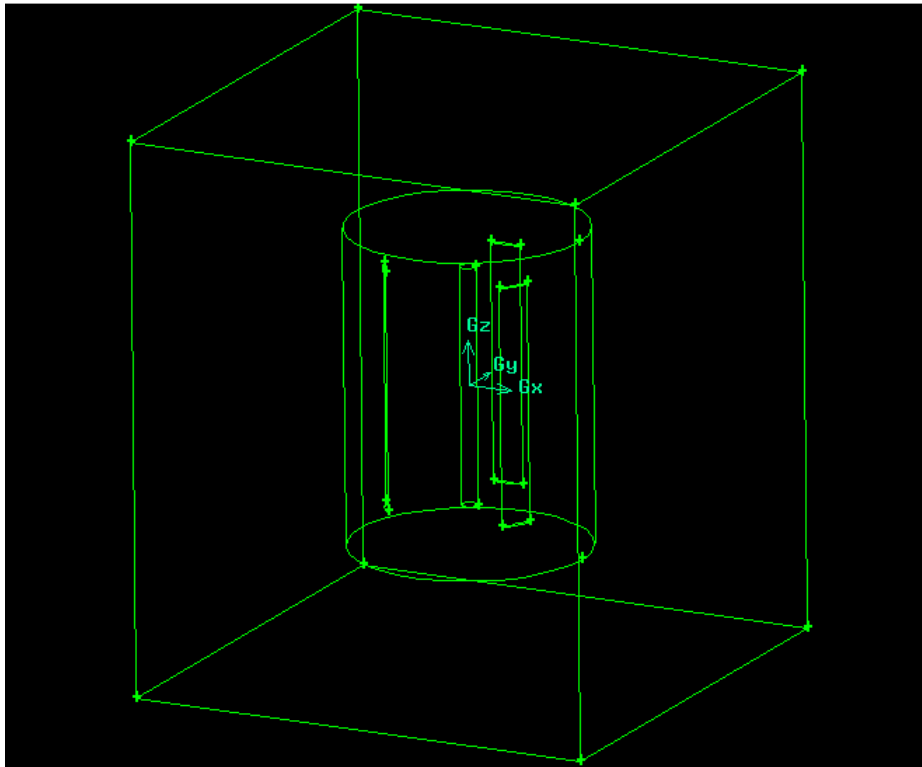
Figure 4.5.

Prototype drawn in Gambit

4.2.2. Mesh

Once the 2D models and 3D prototypes are already built, is time to mesh them. This process is different between the 2D models and the 3D prototypes.

During this stage, first of all the edges will be meshed followed by the faces. First I have meshed the edges and then the faces of the simulation to get more accurate near the airfoils. The more accurate the mesh would be the better results I would get later. The mesh applied in the edges depends on the edge where is applied:

- In the edges of de square the mesh type is Successive Ratio with ratio 1 and interval size 0.1.

- In the edges of the two circles the mesh type is Successive Ratio with ratio 1 and interval size 0.07.

- In the edges of the airfoils the mesh type is Successive Ratio with ratio 1 and interval size 0.01.

The size of the cells in the faces depends on each design, but the elements are in all of them Tri and the type Pave. This is a very important key for analyzing the model because as the design is going to be iterated as a k-epsilon viscous model. The look of the mesh of one model is shown below:

Figure 4.6.
2D model meshed in Gambit

Like in the 2D models, the more accurate the mesh would be the better results I would get later to mesh the prototypes in 3D I have meshed the volumes directly:

- In the tunnel the elements of the mesh are Tet/Hybrid and its type is TGrid with interval size 0.2.

- In the rotational part the elements of the mesh are Tet/Hybrid and its type is TGrid with interval size 0.1.

This is a very important key for analyzing the model because as the design is going to be iterated as a k-epsilon viscous model. The look of the mesh of one model is shown below:
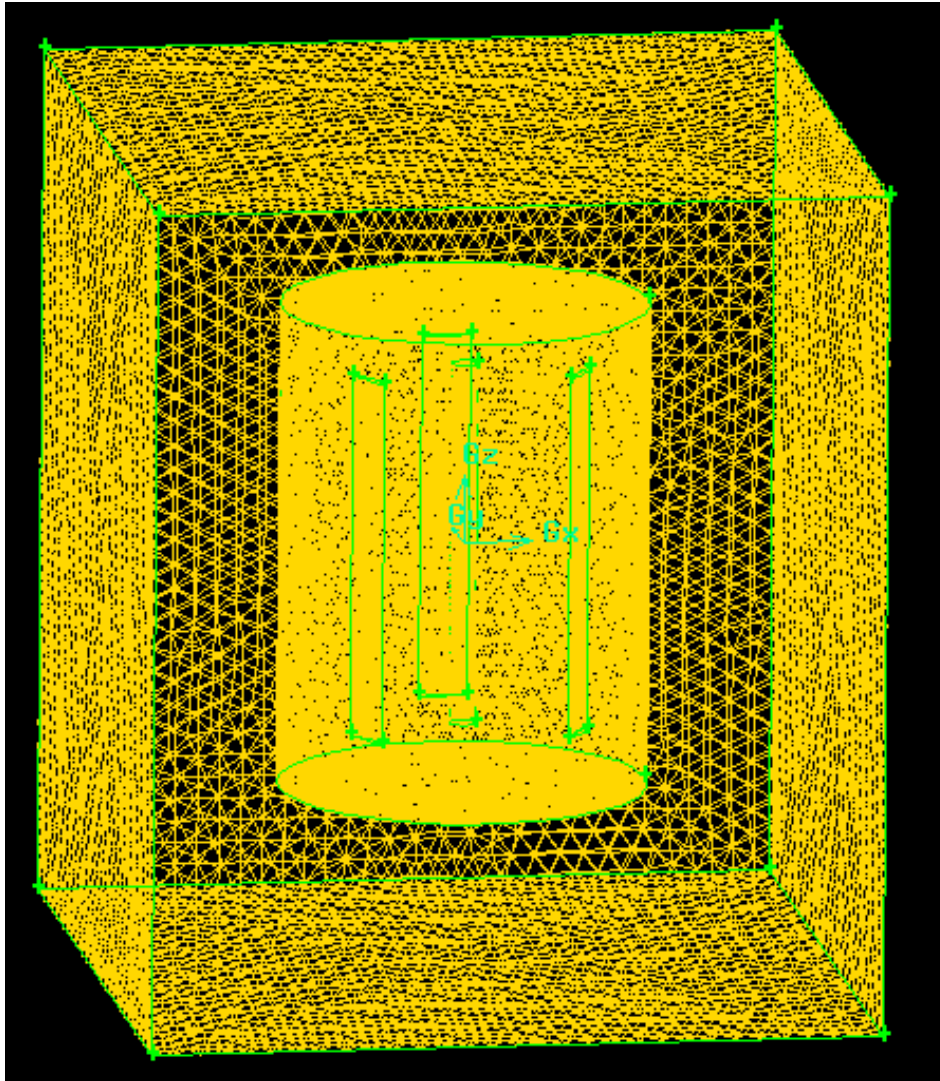
Figure 4.7.
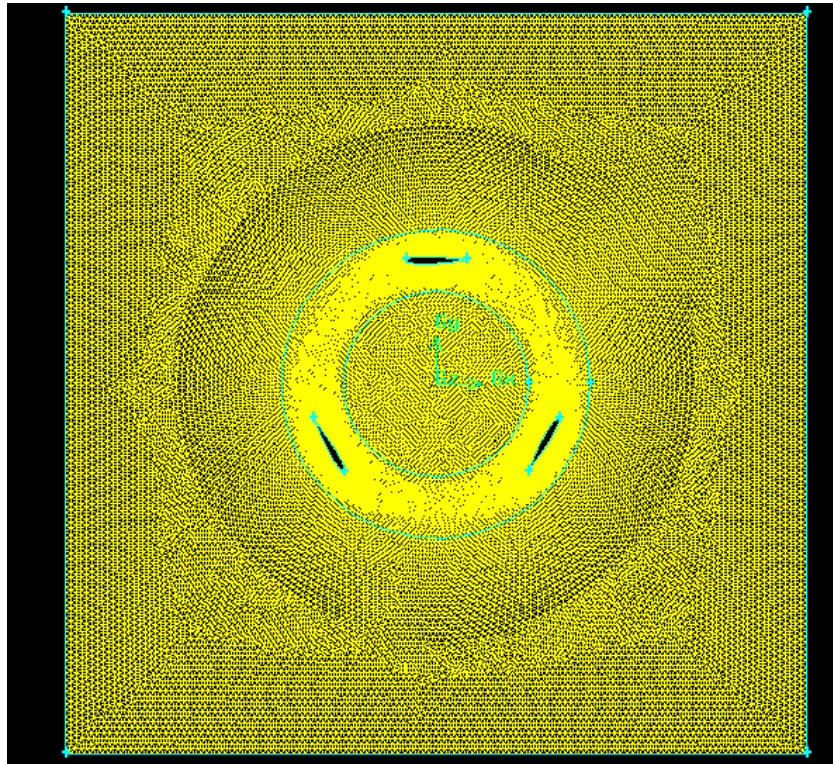
Prototype meshed in Gambit

4.2.3. Boundary conditions

The last stage in Gambit, before to export to Fluent, is to establish the boundary conditions of each edge and the continuum conditions of each face in Gambit in the 2D models:

- <u>Boundary conditions:</u>

    - top and bottom: WALL

    - inlet: VELOCITY_INLET

    - outlet: PRESSURE_OUTLET

    - blades: WALL

    - Circles (a, b, c, d): INTERFACE

- <u>Continuum conditions:</u>
    - airflow: FLUID
    - rotar: FLUID

In the design of the prototypes in 3D the last stage in Gambit, before to export to Fluent, is to establish the boundary conditions of each face and the continuum conditions of each volume :

- <u>Boundary conditions:</u>

    - blades: WALL

    - inlet: VELOCITY_INLET

    -outlet: PRESSURE_OUTLET

    - caras: WALL

    Cylinder (a, b, c, d, e, f): INTERFACE

- <u>Continuum conditions:</u>
    - fuera: FLUID
    - rotar: FLUID

When the mesh, the boundary conditions and the continuum conditions are established the last step in Gambit is export the mesh to can open it in Fluent.

4.3. Analysis in Fluent

After the mesh has been exported to Fluent, it is time to set the last parameters before running the design.

First of all it is necessary Grid all the interfaces defined in Gambit and then the grid has to be checked and scaled in order to make sure the mesh was well built in 2D models and prototypes in 3D both.
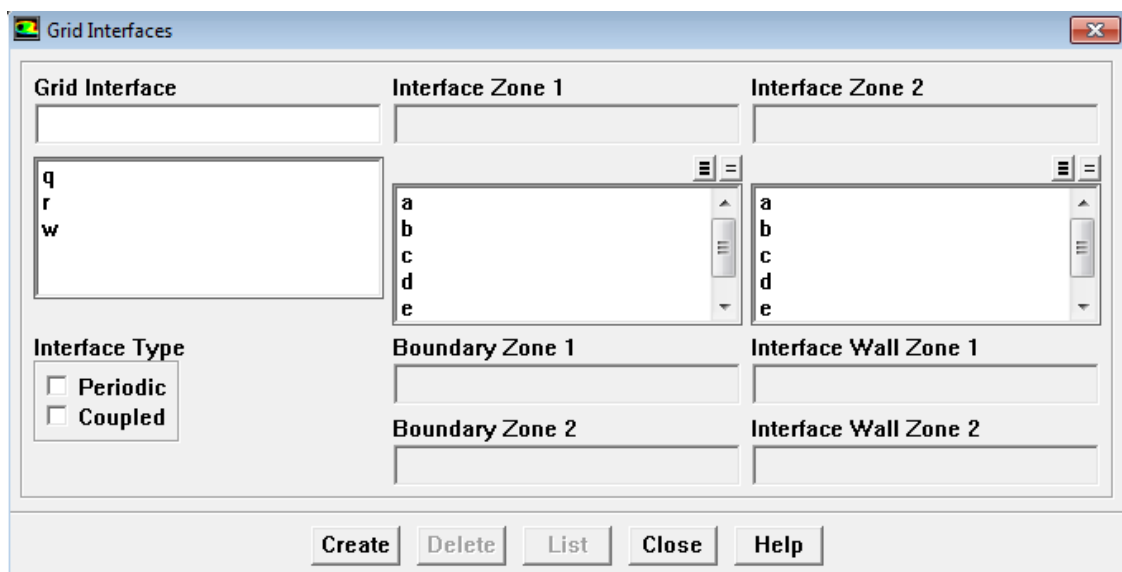
Figure 4.8.

Grid interfaces in Fluent

Later, the model has to be defined. These are a 2D and 3D, respectively, steady analysis as we can see in the picture below. And the viscous model has to be changed to k-epsilon.
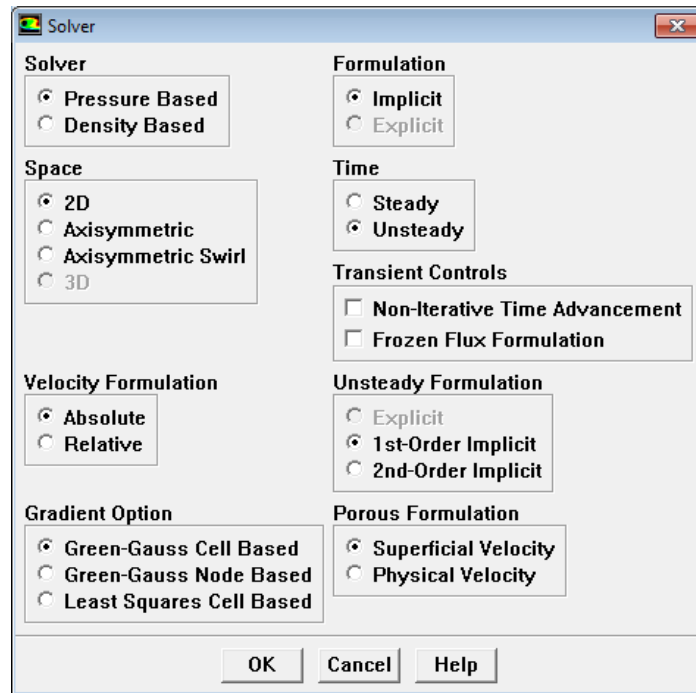
Figure 4.9.

Setting solver parameters in 2D

The next step is set the operation conditions where the gravity is not taken in account and the operating pressure is 101325 Pa. And the boundary conditions are set, obviously these parameters changes from one design to another.

It is important in the process of analysis of the three 2D models I have to take into account that in the reference values in the gap area I take the diameter of the rotor instead of the area and in the gap length I take the ratio of the rotor. We can see, in the below figure, the table of the reference values which I have used in the analysis of the three 2D models. This table is the same in the three analysis because the three have the same diameter and the same velocity inlet:

Figure 4.10.

Report > Reference values

Before running the analysis the model has to be initialized from the boundary condition inlet. The wanted results in Fluent are draw coefficient, lift coefficient and moment coefficient. To know these coefficients it is necessary print, plot and write them in Fluent how I show in the below figure:

Figure 4.11.

Solve > Monitors > Force

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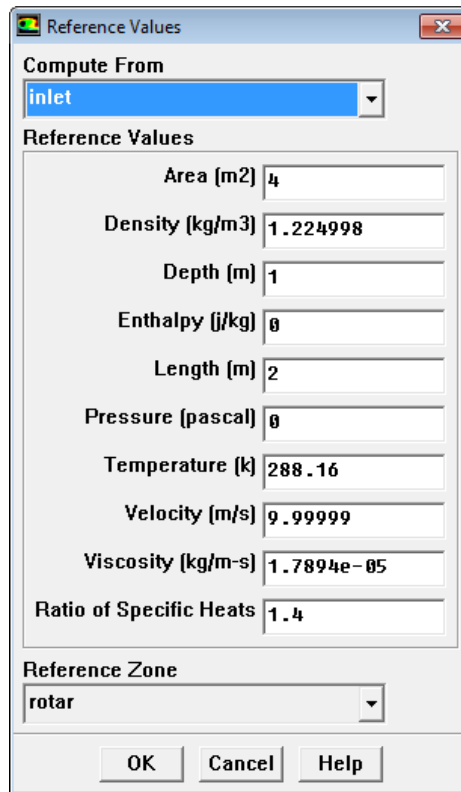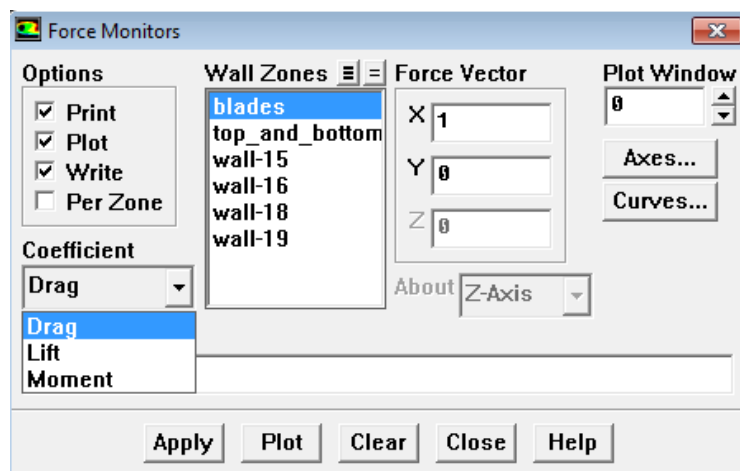With this operation text files are created by Fluent one for each coefficient which represent the evolution of the coefficients in the iterations. Then I have opened in Excel these text files to analyze the results obtained.

And finally the design is ready to iterate.

Once the iterations are done its time to get the results, from the menu display there are several options of obtain different graphs. The static pressure, velocity and other useful graphs can be obtained from this menu.

4.4. Final design in SolidWorks

4.4.1. Introduction

SolidWorks is a Parasolid-based solid modeler, and utilizes a parametric feature-based approach to create models and assemblies.

Parameters refer to constraints whose values determine the shape or geometry of the model or assembly. Parameters can be either numeric parameters, such as line lengths or circle diameters, or geometric parameters, such as tangent, parallel, concentric, horizontal or vertical, etc. Numeric parameters can be associated with each other through the use of relations, which allow them to capture design intent.

Design intent is how the creator of the part wants it to respond to changes and updates. For example, you would want the hole at the top of a beverage can to stay at the top surface, regardless of the height or size of the can. SolidWorks allows you to specify that the hole is a feature on the top surface, and will then honor your design intent no matter what the height you later gave to the can.

Features refer to the building blocks of the part. They are the shapes and operations that construct the part. Shape-based features typically begin with a 2D or 3D sketch of shapes such as bosses, holes, slots, etc. This shape is then extruded or cut to add or remove material from the part. Operation-based features are not sketch-based, and include features such as fillets, chamfers, shells, applying draft to the faces of a part, etc.

Building a model in SolidWorks usually starts with a 2D sketch (although 3D sketches are available for power users). The sketch consists of geometry such as points, lines, arcs, conics (except the hyperbola), and splines. Dimensions are added to the sketch to define the size and location of the geometry. Relations are used to define attributes such as tangency, parallelism, perpendicularity, and concentricity. The parametric nature of SolidWorks means that the dimensions and relations drive the geometry, not the other way around. The dimensions in the sketch can be controlled independently, or by relationships to other parameters inside or outside of the sketch.

In an assembly, the analog to sketch relations are mates. Just as sketch relations define conditions such as tangency, parallelism, and concentricity with respect to sketch geometry, assembly mates define equivalent relations with respect to the individual parts or components, allowing the easy construction of assemblies. SolidWorks also includes additional advanced mating features such as gear and cam follower mates, which allow modeled gear assemblies to accurately reproduce the rotational movement of an actual gear train.

Finally, drawings can be created either from parts or assemblies. Views are automatically generated from the solid model, and notes, dimensions and tolerances can then be easily added to the drawing as needed. The drawing module includes most paper sizes and standards (ANSI, ISO, DIN, GOST, JIS, BSI and SAC).

4.4.2. Design

The final design will be carried out in SolidWorks thanks to geometries can be exported and imported between Gambit and SolidWorks exporting and importing IGES geometries.

After study the results obtained in the analysis carried out with CFD I have designed in SolidWorks the final rotor. How we can see in the below figure the rotor is formed for three blades which are joined to the vertical axis for two aluminum circular sticks each one.
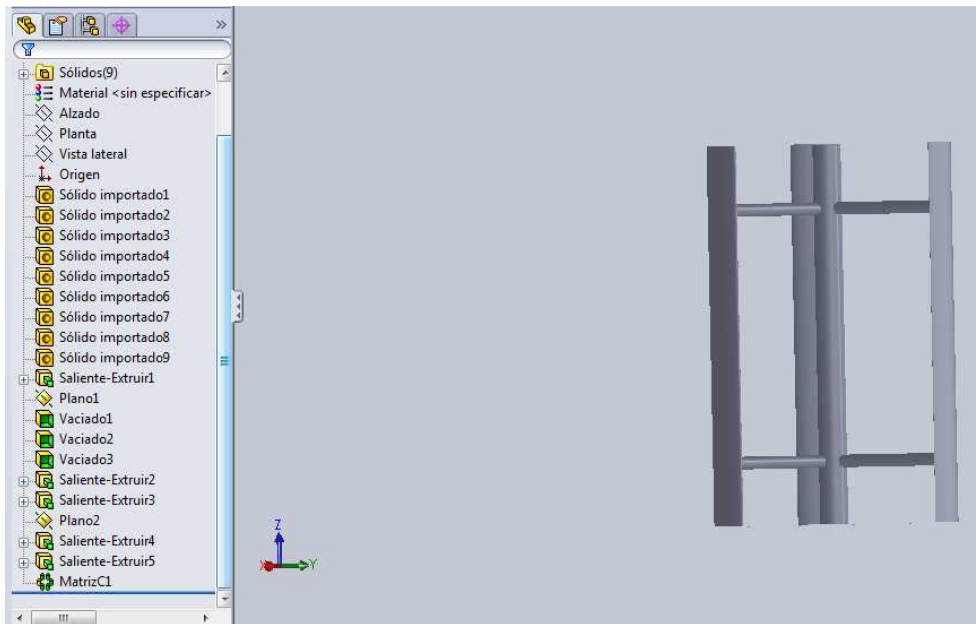
Figure 4.12.

Final design

To get the final design in SolidWorks the first step is import the geometry from Gambit. Here there is one problem because in Gambit the decimal numbers are indicated with the symbol ¨.¨ and in SolidWorks the decimal numbers are indicated with the symbol ¨,¨. So I have to import in Gambit the geometry, apply it the scale 0.001 and export it again before import the geometry in SolidWorks.

The imported geometry in SolidWorks consists in the three vertical straight blades. To create the central vertical axis I have drawn one ring of 30 mm of thickness and 200 mm of exterior diameter and then I have extruded it 3 meters.

The next step has been, creating the plane 1 in the top faces of the three blades and the central vertical axis, empty the three blades given them their thickness. After it, I have closed the top faces of the three blades and the central vertical axis. To close the bottom face of the central vertical axis it has been necessary create the plane 2.

The last step in the final design of the vertical axis wind turbine is to create the horizontal circular sticks. The way to get them it is, drawing in one of the blades two rings with 100 mm of exterior diameter and 10 mm of thickness. They are separated for 2 meters and situated symmetrically. The sticks of the other blades have been created by one matrix. Below I add two figures which show the interior details of the rotor:
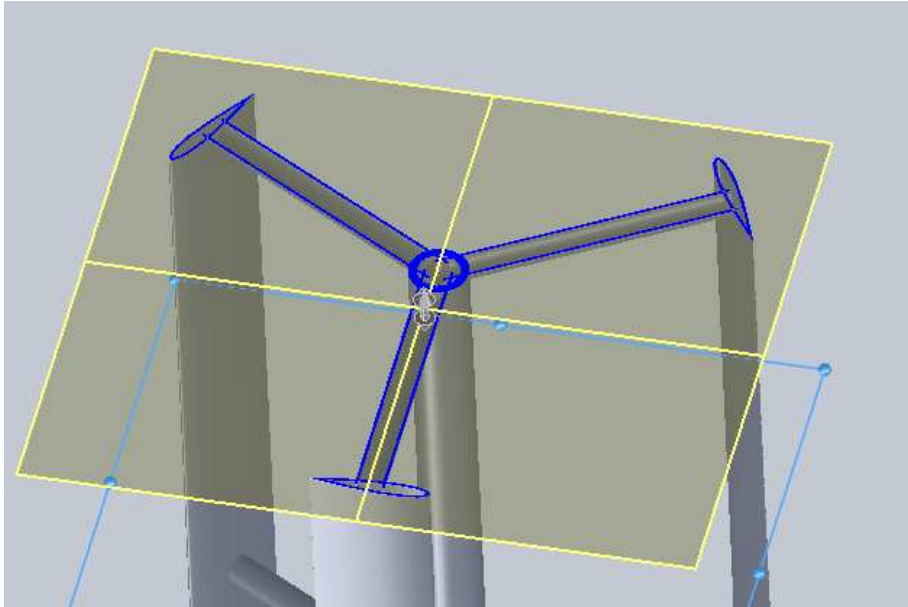
Figure 4.13.

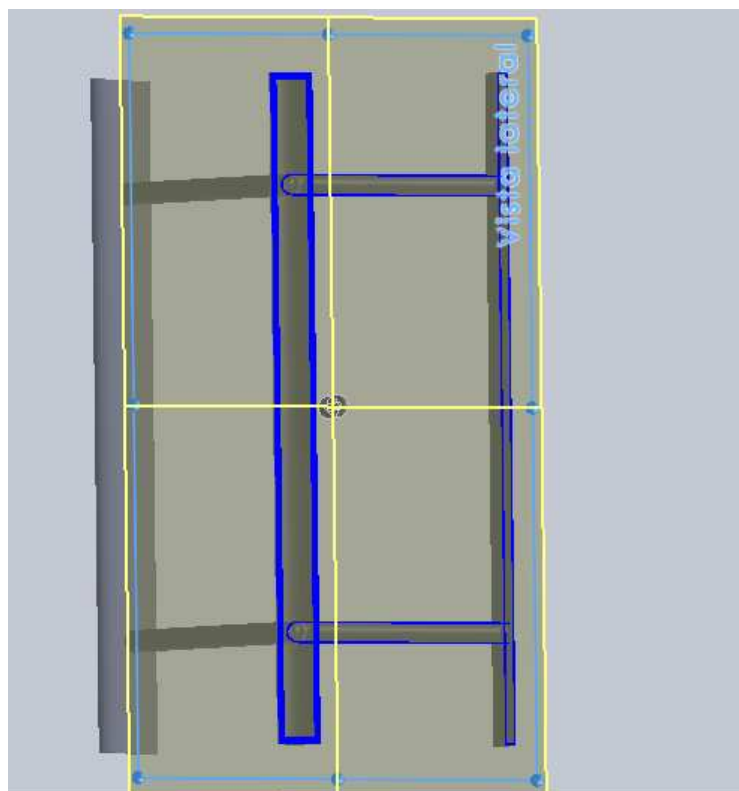**Detail SolidWorks horizontal**

Figure 4.14.

Detail SolidWorks vertical

It is important say the thickness of the parts of the rotor are not final because I have not done the appropriate study of efforts.

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5. RESULTS AND DISCUSSION

5.1. CFD

In order to develop this project I have done the calculations with CFD, which is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. The fundamental basis of any CFD problem is the Navier-Stokes equations, which define any single-phase fluid flow. These equations can be simplified by removing terms describing viscosity to yield the Euler equations. This software gives you the power to simulate flows, heat and mass transfer, moving bodies, etc, through computer modeling.

The CFD began in the 60's in the aerospace industry, and nowadays has become into a vital tool for many industries for the prediction of fluid flow. It has been expanded significantly to different industrial applications and industrial processes involving heat transfer, chemical reactions, two-phase flow, phase changes and mass transfer, among others.

In order to obtain an approximate solution numerically, a discretization method have to be used to approximate the differential equations by a system of algebraic equations, which can later be solved with the help of a computer. The approximations are applied to small domains in time and/or space. The accuracy of numerical solutions depends on the quality of the discretizations used as much as the accuracy of experimental data depends on the quality of the tools used.

It is important to bear in mind that numerical results are always approximate because there are reasons for differences between computed results and reality like:

- ➢ The differential equations might contain approximations or idealizations.
- ➢ The approximations made in the discretization process.
- ➢ Iterative methods are used in solving the discretizated equations. So, unless they are run for a very long time, the exact solution of the discretizated equations is not produced.

Discretization errors can be reduced by using more accurate interpolation or approximations or by applying the approximations to smaller regions, but this usually increases the time and cost of obtaining the solution.

Compromise is needed in solving the discretized equations. Direct solvers, which obtain accurate solutions, are not very used because they are too expensive. Otherwise iterative methods are more common but the errors produced by stopping the iteration process too soon need to be taken into account.

5.1.1. Fluent

Fluent is a package of simulation computational fluid dynamics (CFD) and the most used in the world, with a background of more than 25 years of development carried out by Fluent Inc. who are certified under the international standards of ISO 9001 and TickIT.

The structure of Fluent allows you to incorporate a lot of models for different physical and chemical processes. Not only can you perform simulations of laminar or turbulent flow, Newtonian or non-Newtonian, compressible or incompressible, single phase or multiphase, but also processes of heat transfer by radiation, conduction and convection of course, as well as melting processes and chemical reactions such as burning of gases, liquids and solid fuels.

The general capabilities of Fluent simulation are:

- 3D simulations, 2D map, 2D axisymmetric, 2D axisymmetric with swirl.

- Unstructured meshes (triangles and quadrilaterals in 2D, tetrahedra, prisms and pyramids in 3D)

- Simulations of steady or unsteady flow.

- Any speed system (subsonic, transonic, supersonic and hypersonic).

- Laminar flows, turbulent, non-viscous.

- Newtonian and non Newtonian flows.

- Wide variety of turbulence models, including k-epsilon, k-omega, RSM, DES, and LES.

- Heat transfer, including natural convection, forced or mixed; solid conjugate heat transfer / fluid, including solar radiation.

- Mixing and reaction of chemical species, including models of homogeneous and heterogeneous combustion reaction models / deposition on surfaces.

- Models multiphase and free surface, including heat transfer and chemical reactions.

- Lagrangian trajectory calculations for the dispersed phase (particles, drops, bubbles), including models for sprays and thin films.

- Models of phase change for solidification and casting applications, cavitation model and model of wet steam.

- Medium permeability porous non-isotropic, inertial resistance, heat conduction in solids, and option to calculate interstitial velocity.

- Models for fans, radiators and heat exchangers.

- Dynamic mesh capability for modeling flow around moving objects during the simulation.

- Inertial reference frames (stationary) or non-inertial (rotating or accelerating).

- Multiple frames of reference and sliding mesh options.

- Mixed model planes for rotor-stator interactions.

- Collection of tools for aeroacoustic models.

- Volumetric source terms for mass, momentum, heat and chemical species.

- Database of material properties.

- Dynamic coupling (two-way) with GT-Power and WAVE.

- Additional modules for fuel cells, magnet hydrodynamics and fiber continuum model.

- Extensive customization capability via user-defined functions (c programming).

5.1.2. Gambit

Gambit is Fluent's software for geometry and mesh generation. The interface for geometry creation and meshing brings together most of Fluent's preprocessing technologies in one environment. Advanced tools for journals can conveniently edit and repeat the session for the construction of parametric studies.

Gambit combines CAD interoperability, geometry cleanup tools CAD, decomposition and meshing tools that result in one of the easiest ways of preprocessing, fast and direct CAD to mesh quality.

Gambit can import geometry from any CAD / CAE, Parasolid formats, ACIS, STEP or IGES. Additional modules are also available to integrate CATIA V4, Pro / E. The tolerance and repair capabilities provide geometries automatically connected during the import process.

5.2. Choice of the most appropriate airfoil

5.2.1. Analysis in Fluent

The NACAs used in the 2D models which I have analyzed are: NACA 0012, NACA 0015 and NACA 0020. In the analysis of these models the operating conditions of them are:

- Operating pressure: 101325 Pa

- Velocity inlet: 10 m/s

- Rotational speed: -10 rad/s

The rotational velocity is negative due to direction of rotation of the airfoils.

The results of the moment coefficients of each model obtained iterating in Fluent are the pictures shown below:
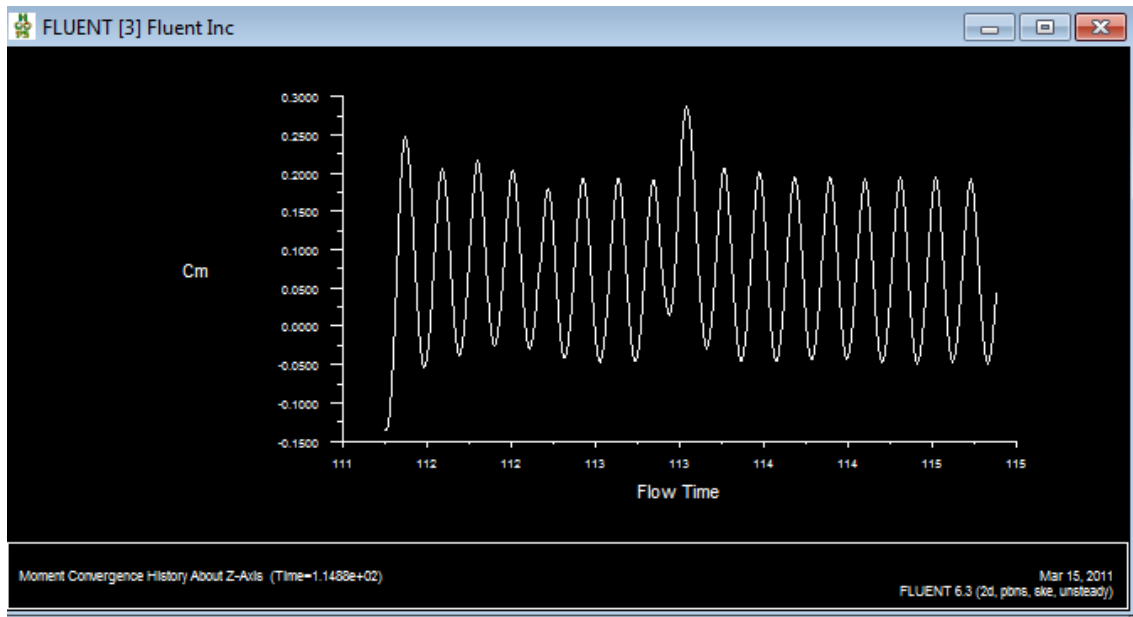
Figure 5.1.
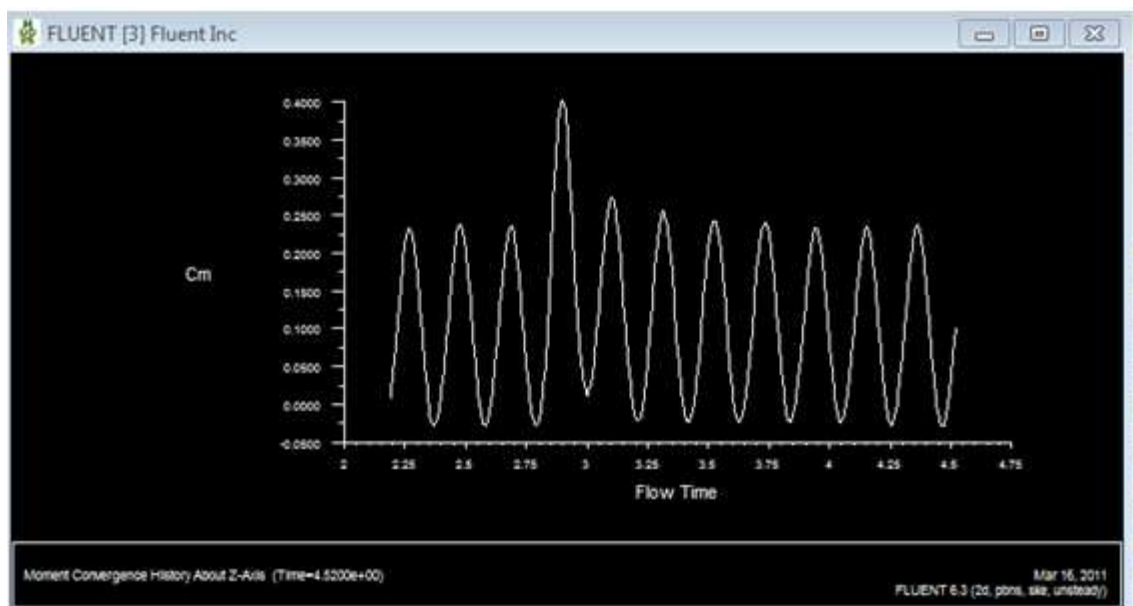
Moment coefficient of NACA 0012

Figure 5.2.
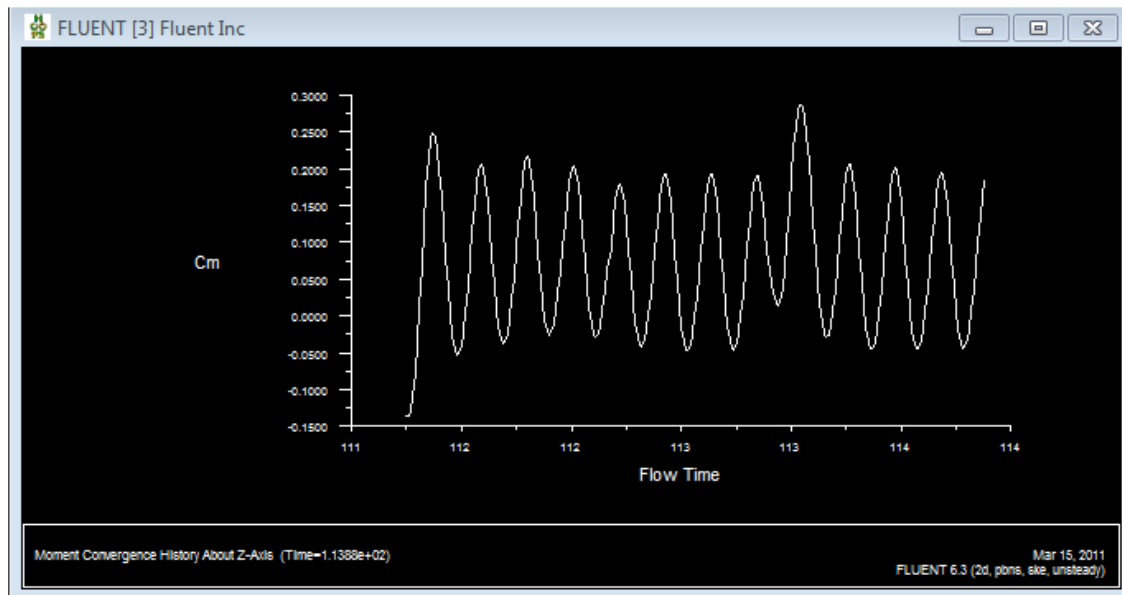
Moment coefficient of NACA 0015

Figure 5.3.

Moment coefficient of NACA 0020

These graphs are oscillating due to rotation of the blades. Each maximum and minimum appears when the airfoils are in the same position that other airfoil.

5.2.2. Results in Excel

To can analyze the results obtained in Fluent is necessary open the text files created by Fluent in Excel.

Once I have opened it in Excel I have done the graph shown below to know what NACA is better. In this graph I have represented only three oscillations because they represent one full circle of the rotor of the vertical axis wind turbine. Fluent gives you the values of the moment coefficient but I need know the values of the power coefficient of the 2D models so I have to apply the equation which relates the power coefficient with the moment coefficient of the rotor how I have explained before:

$$\lambda = \frac{wR}{U} \qquad\qquad [\mathbf{3.5.}]$$

Where w = 10 rad/s

R = 2 m

U = 10 m/s

So the tip speed ratio of these three 2D models is:

$$\lambda = \frac{wR}{U} = \frac{10 * 2}{10} = 2$$

The tip speed ratio of these three 2D models is 2, it means the velocity of the airfoils is double of the velocity of the wind. So I have to multiply all values of the moment coefficient by 2 to know the values of the power coefficient following the below equation:

$$Ct = \frac{Cp}{\lambda} \qquad\qquad [\mathbf{3.7.}]$$

After this, I have calculated the average value of each line to know exactly the value of the power coefficient of each 2D model. The result obtained for each 2D model is:

- NACA 0012: C_p = 0.037

- NACA 0015: C_p = 0.117

-NACA 0020: C_p = 0.079

Finally I have chosen the NACA 0015 to my final design because in my study these NACAs have a power coefficient upper than the others NACAs.
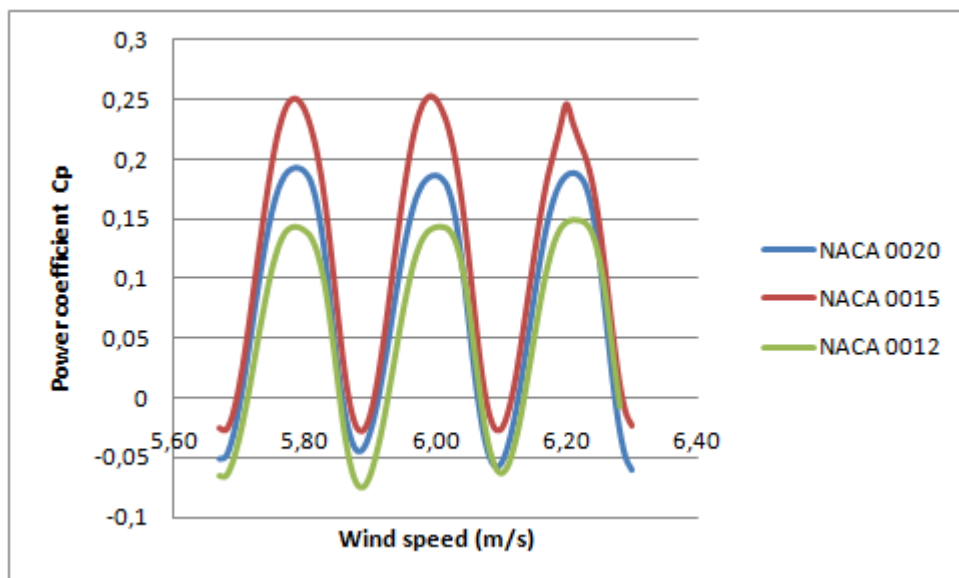

Figure 5.4.

Power coefficients of 2D models

5.3. Choice of the best prototype

5.3.1. Criteria on the prototypes

Effects of solidity on performance

Solidity is one of the main parameters dictating the rotational velocity at which the turbine reaches its maximum performance coefficient. Higher solidity usually dictates lower tip-speed ratio and lower efficiency. At low tip-speed ratios, the rotor blades do not interact as strongly with much of the air flow passing through the volume swept out by the proceeding blades, but at high tip-speed ratios, rotor blades begin to interact with the wakes strongly from upstream blades.

The equation to calculate the solidity of each prototype is the following:

$$S = \frac{N * c}{D} \qquad [5.1.]$$

Where S = solidity

　　　N = number of blades

　　　c = chord length (m)

　　　D = diameter (m)

For each one of the three prototypes the solidity will be:

$$S_1 = \frac{N * c}{D} = \frac{3 * 0.4}{2} = 0.6$$

$$S_2 = \frac{N * c}{D} = \frac{3 * 0.2}{2} = 0.3$$

$$S_3 = \frac{N * c}{D} = \frac{3 * 0.15}{1.5} = 0.3$$

Effects of swept area

The swept area of a Giromill wind turbine is given by the length of the blades multiplied for the rotor diameter:

$$A = L * D \qquad [5.2.]$$

Where A = swept area (m^2)

L = blades lenght (m)

D = diameter (m)

For each one of the three prototypes the swept area will be:

$$A_1 = L * D = 3 * 2 = 6\ m^2$$

$$A_2 = L * D = 2 * 2 = 4\ m^2$$

$$A_3 = L * D = 2 * 1.5 = 3\ m^2$$

Effects of chord length

The chord line is a straight line connecting the leading and trailing edges of the airfoil, at the ends of the mean camber line. And the chord is the length of the chord line and is the characteristic dimension of the airfoil section.
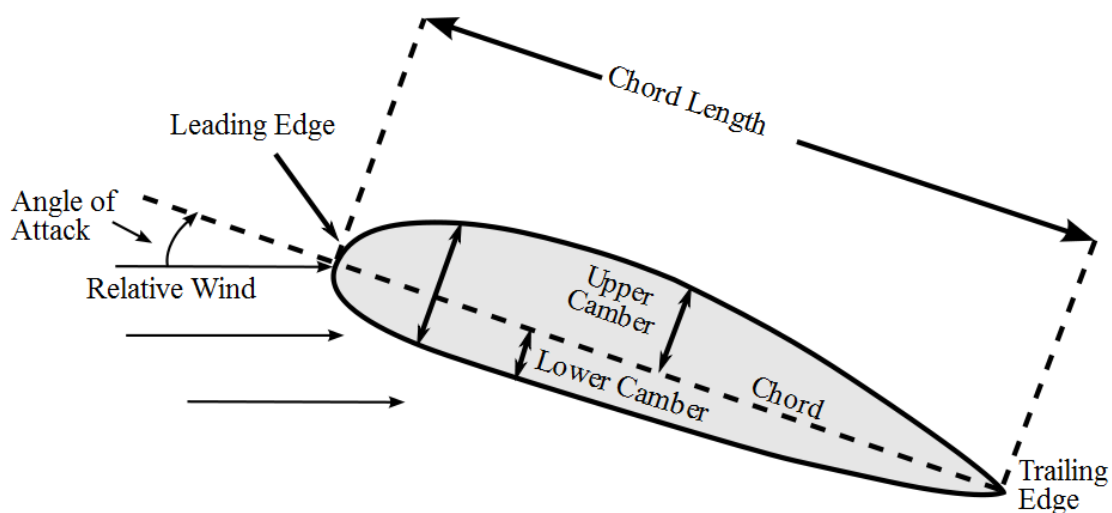

Figure 5.5.

Characteristics of airfoils

The chord lengths of the blades in each prototype are:

- Prototype 1: c = 0.4 m

- Prototype 2: c = 0.2 m

- Prototype 3: c = 0.15 m

5.3.2. Analysis in Fluent

The three prototypes have been analyzed in the same conditions of working to be compared and knowing the results obtained I have could chose the best prototype of them. These operating conditions are:

- Operating pressure: 101325 Pa

- Velocity inlet: 10 m/s

- Rotational speed: -12.5 rad/s

The rotational speed of the rotor is negative due to the direction of working of it, how I have explained when I was analyzing the 2D models.

To check the correct working of the rotor in the figure shown below we can see the direction of the movement of the wind and the direction of rotation of the blades, through pathlines option:
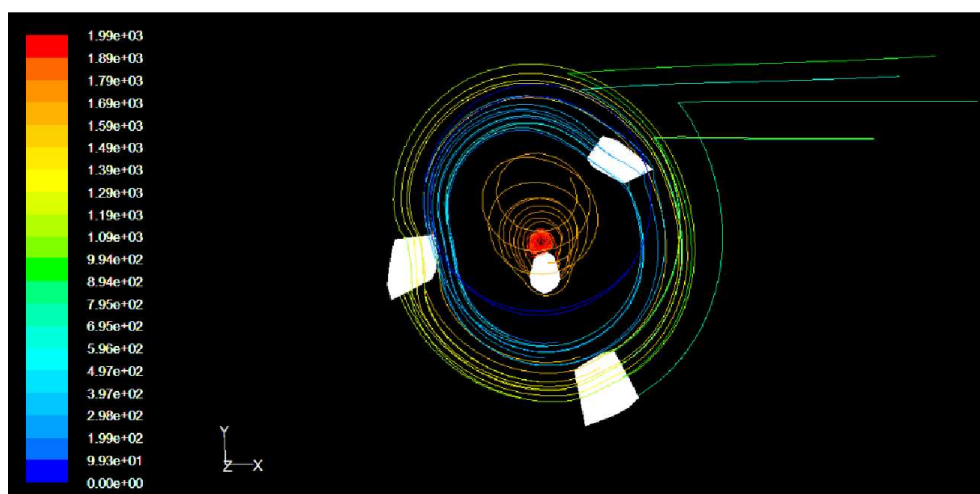

Figure 5.6.

Movement of the wind

After doing the iterations, in the following picture, the velocity vectors coloured by velocity magnitude (m/s) of the fluid close to the blades is shown:
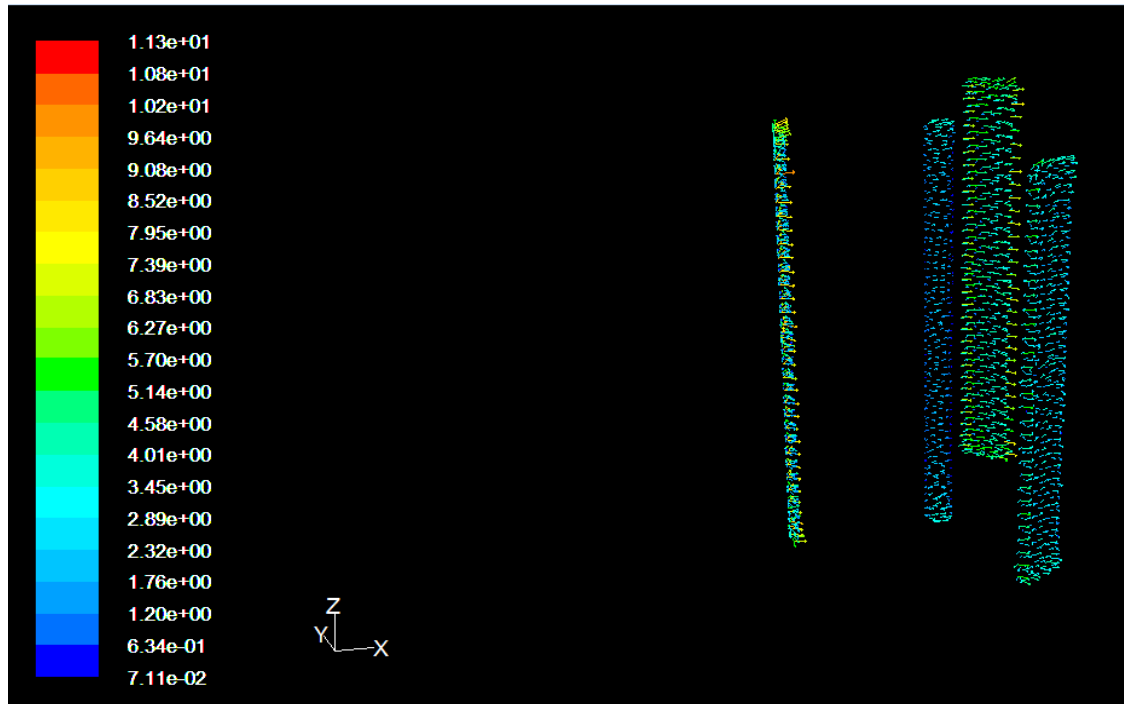
Figure 5.7

Velocity vectors coloured by velocity magnitude (m/s)

5.3.3. Results in Excel

To can analyze the results obtained in Fluent is necessary open the text files created by Fluent in Excel. The process of analysis is similar to the 2D models.

Once I have opened it in Excel I have done the graph shown below to know what prototype is better. Fluent gives you the values of the moment coefficient but I need know the values of the power coefficient of the three prototypes so I have to apply the equation which relates the power coefficient with the moment coefficient of the rotor how I have explained before:

$$\lambda = \frac{wR}{U} \qquad\qquad [3.5.]$$

Where w = 12.5 rad/s

$$R_1 = R_2 = 1 \text{ m}$$

$$R_3 = 0.75 \text{ m}$$

$$U = 10 \text{ m/s}$$

So the tip speed ratios of these three prototypes are:

$$\lambda_1 = \frac{w * R_1}{U} = \frac{12.5 * 1}{10} = 1.25$$

$$\lambda_2 = \frac{w * R_2}{U} = \frac{12.5 * 1}{10} = 1.25$$

$$\lambda_3 = \frac{w * R_3}{U} = \frac{12.5 * 0.75}{10} = 0.9375$$

So I have to multiply all values of the moment coefficient of each prototype by its tip speed ratio respectively to know the values of the power coefficient of each prototypes following the below equation like in the analysis of 2D models:

$$Ct = \frac{Cp}{\lambda} \qquad [3.7.]$$

After this, I have calculated in Excel the average value of each line to know exactly the value of the power coefficient of each prototype. The result obtained for each prototype is:

- Prototype 1: $C_p = 0.077$

- Prototype 2: $C_p = 0.047$

-Prototype 3: $C_p = 0.01$

Finally I have chosen the proportions of the prototype 1 to my final design because in my study this prototype has its power coefficient upper than the others two prototypes.

In this graph I have represented only three oscillations because they represent one full circle of the rotor of the vertical axis wind turbine like in the analysis of 2D models:
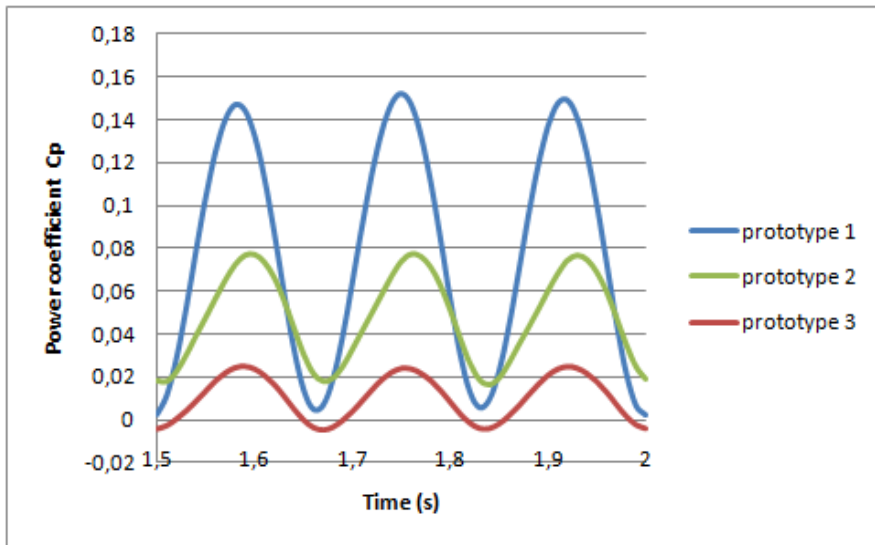
Figure 5.8.

Power coefficients of prototypes

In conclusion, I show the below figure which shows the characteristics of each prototype and its power coeffient (C_p):

Parameters	Prototype 1	Prototype 2	Prototype 3
Chord length (m)	0.4	0.2	0.15
Blades length (m)	3	3	2
Diameter (m)	2	2	1.5
Solidity	0.6	0.3	0.3
Cp	0.077	0.047	0.01

Figure 5.9.

Characteristics of prototypes

5.4. Analysis of T.S.R.

5.4.1. Introduction

Once determined the proportions of the final design of the rotor, the next step is determine the best T.S.R. of operation of the wind turbine. The letters T.S.R. are the acronym of Tip Speed Ratio (λ) which is the relationship between the velocity of blades and the velocity of wind, how I have explained before. We can see the power coefficient

of the rotor depends of its tip speed ratio. So to design the final rotor firstly it is necessary know what Tip Speed Ratio give to the rotor the largest power coefficient.

5.4.2. Analysis in Fluent

To know what T.S.R. is the best, I have carried out one study in which I have applied to the rotor one wind of 5 m/s and I have done rotate to the wind turbine with different rotational speeds in Fluent. So I have forced to the rotor to work with different Tip Speed Ratios. How we can see in the graph shown below, exactly I have studied the rotor working with five different Tip Speed Ratios: 0.5, 1, 1.5, 2 and 2.5. Being 101325Pa the operating pressure.

Knowing the wind velocity, the ratio of the rotor, and the Tip Speed Ratios which I want to analyze the wind turbine, it is necessary apply the equation of the Tip Speed Ratio (λ) to determinate the rotational velocity of the blades. So I have to realize the following calculations:

$$\lambda = \frac{wR}{U} = \frac{w*1}{5} = 0.5 \longrightarrow \quad w = 0.5*5 = 2.5 \text{ rad/s}$$

$$\lambda = \frac{wR}{U} = \frac{w*1}{5} = 1 \longrightarrow \quad w = 1*5 = 5 \text{ rad/s}$$

$$\lambda = \frac{wR}{U} = \frac{w*1}{5} = 1.5 \longrightarrow \quad w = 1.5*5 = 7.5 \text{ rad/s}$$

$$\lambda = \frac{wR}{U} = \frac{w*1}{5} = 2 \longrightarrow \quad w = 2*5 = 10 \text{ rad/s}$$

$$\lambda = \frac{wR}{U} = \frac{w*1}{5} = 2.5 \longrightarrow \quad w = 2.5*5 = 12.5 \text{ rad/s}$$

Fluent gives you the values of the moment coefficient but I need know the values of the power coefficient of the rotor, so I have to apply the equation which relates the power coefficient with the moment coefficient of the rotor how I have explained before:

$$Ct = \frac{Cp}{\lambda} \qquad\qquad\qquad [3.7.]$$

5.4.3. Analysis in Excel

To can analyze the results obtained in Fluent is necessary open the text files created by Fluent in Excel. After this, I have calculated in Excel the average value of each line to know exactly the value of the power coefficient of the rotor when it is working in each condition. This process is repeated each time that I have to do one analysis of the Fluent results .The result obtained for each conditions of work is shown in the below graph created in Excel where it is proved that the performance due to work of the rotor are when its Tip Speed Rotor is 2:
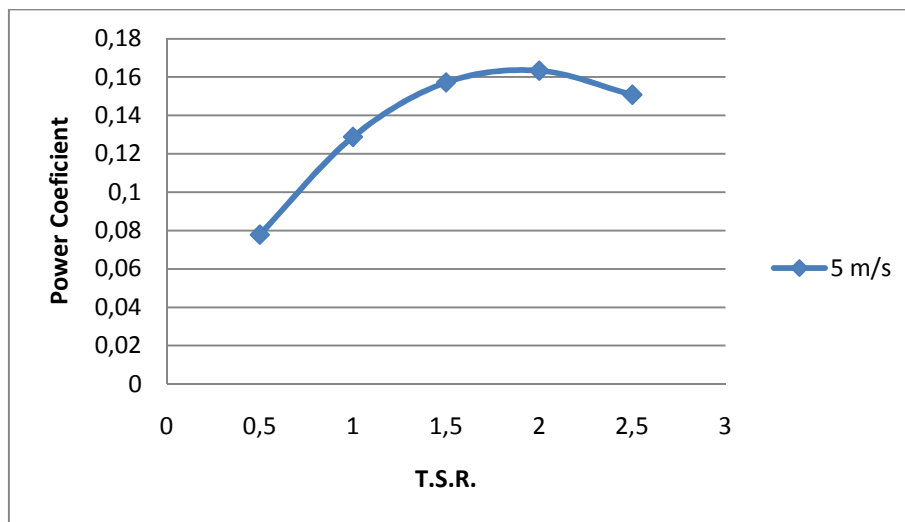
Figure 5.10.

Power coefficient versus T.S.R.

In conclusion, the next analysis will be realized with the rotor working with Tip Speed Ratio 2.

5.5. Find out the power curve of the wind turbine

5.5.1. Introduction

Once the Tip Speed Ratio is known, how I explained before to this rotor the Tip Speed Ratio of work will be 2, it is time of find out the power curve of the wind turbine.

There are many ways to explain what is a power curve of a wind turbine:

- The power curve of a wind turbine is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds.

-Representation of the electric power produced by a wind turbine at different wind speeds.

- Power curve indicates the wind energy captured by a turbine

5.5.2. Analysis in Fluent

To find out the power curve of the wind turbine I have analyzed the behaviour of the wind turbine with different wind speeds, but maintaining constant and equal to 2 its Tip Speed Ratio in Fluent, so the rotational velocity of the wind turbine is different for each velocity following the equation which defines the Tip Speed Ratio:

$$\lambda = \frac{wR}{U}$$

[3.5.]

5.5.3. Analysis in Excel

Like in the others analysis, to can analyze the results obtained in Fluent is necessary open the text files created by Fluent in Excel. After this, I have calculated in Excel the average value of each power coefficient (Cp) line to know exactly the value of the power coefficient of the rotor when it is working in each condition. To define the power curve I have found out the generated power by the wind turbine with 11 different velocities.

How Fluent gives you the values of the moment coefficient but I need know the values of the power coefficient of the rotor, so I have to apply the equation which relates the power coefficient with the moment coefficient of the rotor how I have explained before:

$$Ct = \frac{Cp}{\lambda}$$

[3.7.]

Once I have known the value of the power coefficient (C_p) in each condition, I have had to calculate the generated power using this equation:

$$Cp = \frac{P}{\frac{1}{2}\rho U^3 A} \qquad [\mathbf{3.4.}]$$

Now I show in the below figure the characteristic power curve of the wind turbine, in which I show the power in Watts versus the wind speed in m/s. I have analyzed the power generated by the rotor between wind speeds of 3 to 15 m/s. The lowest power generated is 38.71 W with a wind speed of 3 m/s and the maximum power is 2715 W when the wind speed is 15 m/s. I have not analyzed upper wind speed because generally for this size of rotor the maximum revolutions are between 30 – 40 rad/s for safety.
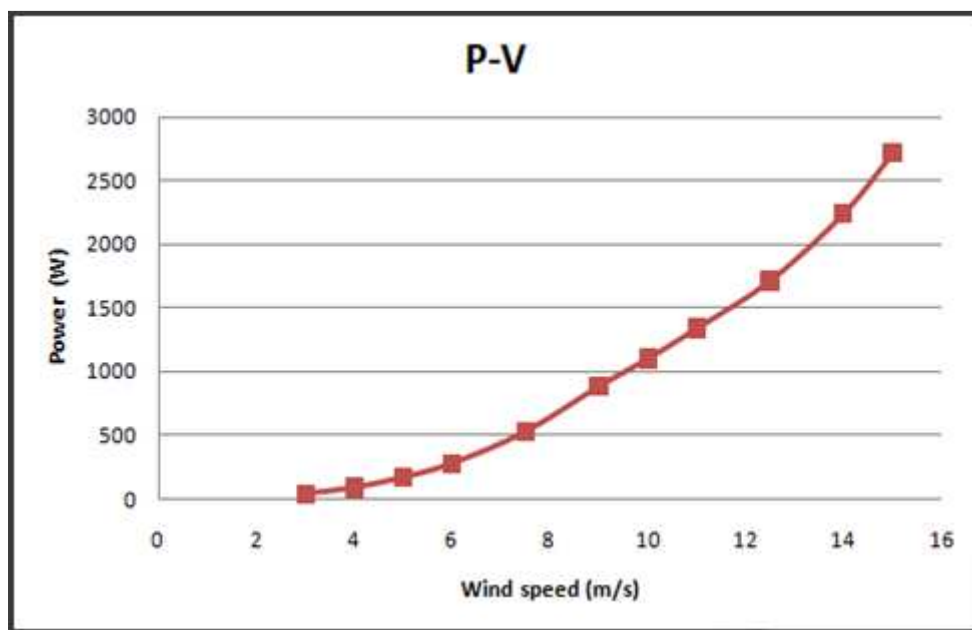

Figure 5.11.

Power curve

5.6. Comparisons between results in 2D and in 3D

Finally knowing the final design of the rotor I have compared its behavior in 3D and in 2D. This below graph shows how the power coefficients drop with upper wind speed in both cases. But the difference is that the power coefficient in 2D is upper than in 3D for all wind speeds. The main reason will be that the 2D CFD simulation does not include the effects of the tip vortices present on the 3D simulations.
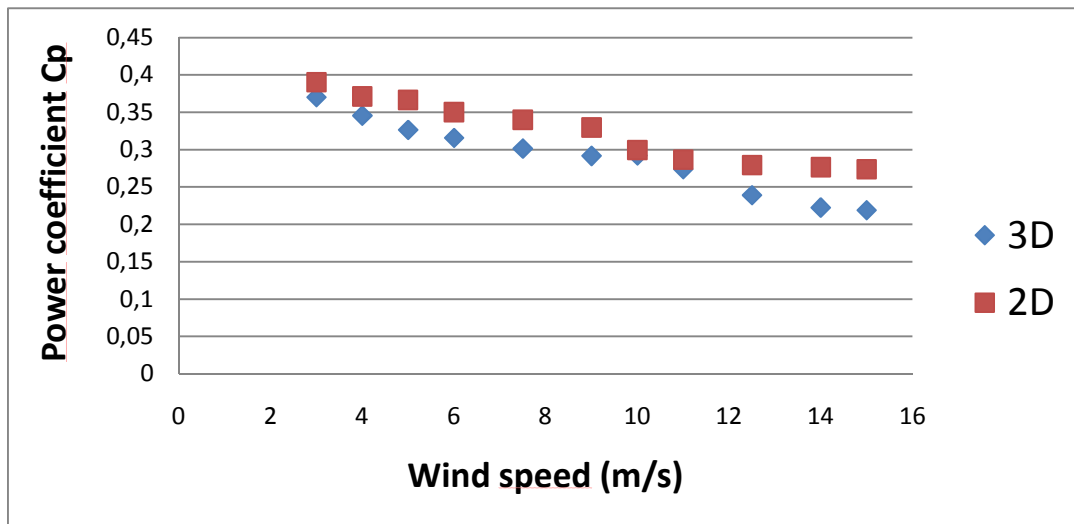
Figure 5.12.

Comparisons between 2D and 3D

6. CONCLUSIONS

This project has been carried out with lot of software problems that have slowed the analysis and it is more difficult to reach a complete conclusion without a great number of analyses. However, these problems have help to deepen in this part of the study that is the development of Giromill turbine.

To get the final design in SolidWorks the first step is import the geometry from Gambit. Here I have had one problem because in Gambit the decimal numbers are indicated with the symbol ¨.¨ and in SolidWorks the decimal numbers are indicated with the symbol ¨,¨. So I have to import in Gambit the geometry, apply it the scale 0.001 and export it again before import the geometry in SolidWorks. I have had this similar problem when I have done the analysis between Fluent and Excel.

The challenge when it comes to a wind turbine is to extract energy from the wind. According to physics, it is impossible for a windmill to exceed 59% efficiency when extracting kinetic power from the wind and converting it into mechanical power. The remaining 41% of the power must remain in the wind. Being the vertical axis wind turbines less efficient than the horizontal axis wind turbine.

In the analysis carried out in this project it has been demonstrated the power coefficient drops with high wind speed. This fact appears because the ability of the wind turbine is reduced with high wind speed, so the wind turbines are less efficient with these winds.

The power coefficient predicted by the two dimensional computational model is significantly higher than that of the experimental and the three-dimensional CFD model. The predictions show that the presence of the over tip vortices in the 3D simulations is responsible for producing the large difference in efficiency compared to the 2D predictions. The dynamic behaviour of the over tip vortex as a rotor blade rotates through each revolution is also explored in the paper.

7. RECOMMENDATIONS AND FUTURE LINES OF WORK

When you are building wind turbines should be taken into account the resistance, the dynamic behavior and fatigue properties of materials and of the whole. But in this project the rotor has been designed taking into account only the considered aerodynamic work.

Wind turbines are subject to fluctuating winds and, thus, fluctuating forces. This is particularly true in the case are located in a very turbulent wind climate. Components subject to repeated bending can develop cracks, which ultimately can cause failure of the component. Metal fatigue is a well known problem in many industries.

In the design of a wind turbine is very important to calculate in advance how the different components will vibrate, both individually and collectively. It is also important to calculate the forces involved in each bending and stretching of a component.

This is the subject of structural dynamics, where physicists have developed mathematical computer models that analyze the behavior of the entire wind turbine. These models are used by wind turbine manufacturers to design their machines safely.

The noise emission of wind turbines may have two different origins: mechanical noise and aerodynamic noise. Mechanical noise can result from the multiplier, in the transmission (axis) and in the wind turbine generator due to moving metal components or bumping against each other. Aerodynamic noise is due to when the wind hits different objects at a certain speed, usually starts beeping. Wind can also induce vibrations on surfaces, each of these surfaces gives its own sound.

Other step in the design of the wind turbine is to define the start velocity of rotation and the maximum rotation speed of the rotor.

So, new studies are necessaries to complete the final design of the wind turbine.

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