The Development of a Wind Turbine System for Small Scale Applications

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This dissertation is submitted in satisfaction of the requirements for the

degree of Master of Science

in

Mechanical Engineering

at the

Galway-Mayo Institute of Technology

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Mr. Gerard O'Donnell, for the guidance he has given me throughout the period of this project. I would also like to thank to the various G.M.I.T staff, who have helped me in numerous occasions and without whose contribution this project would have not been possible. Last but not least I would like to thank Enterprise Ireland for financing this project, for the results achieved in themselves and also for the personal development that I have gained in the process.

Abstract

The purpose of the present project is to design a new wind turbine with a maximum power output ranging in between 6 and 8kW. The targeted retail price is €5000.

For achieving the project goals it was first intended to reverse engineer an existing wind turbine, the Proven WT6000, which fitted the project target from the technical point of view, it had a power rating of 6kW. Unfortunately, the price for this turbine is more than two times the one desired for the new turbine, and also the data that can be otained about it is very limited, firstly because some parts would have to be destroyed in the process and secondly because the manufacturer, for obvious reasons, would not disclose key data about the manufacturing of their product.

Mainly due to the very significant price difference, and encouraged by the various shortcomings of reverse engineering, it was decided that WT6000 will be kept as a technical benchmark, in terms of its stated performances, but a different approach was needed to the construction of the turbine.

To find out a new way of approaching the design, the first thing required was to accumulate extensive knowledge about wind turbines. That is why, the first step was to gather as much data as possible about their hystorical evolution, about the technology that they involve, and to put together the theoretical information that is absolutely necessary for designing the different parts. Only after this step was completed it was possible to make an informed decision over the general direction that should be taken.

In the second step, the new design was completed, aimed basically at meeting the output target, but at the same time employing the cheapest and simplest solutions, where possible. In the third stage the design was verified from the structural point of view. A price estimation was also performed, in an attept to form an overall image, and to see if the design approach has or not the capability of leading to a product offered on the market for €5000.

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Chapter 1 – Introduction

In the abstract it was stated what the project goal was and the general approach that would be taken.

In the following paragraphs the content of each chapter will be briefly described, the general layout attempting to follow the general direction already established.

Chapter 2 has the purpose of introducing the conecept of wind turbine, and thus a few relevant deffinitions will be given and also the hystorical evolution from very basic wind devices to wind mills and then to wind turbines will be presented. This presentation of the evolution could be of more help to the present project then it appears at the first sight, as it will help understanding better not only the old windmills, but the modern wind turbines too. As well, it offers the opportunity of browsing through a multitude of ideeas, some of which could still be of applied.

After assessing the historical aspect, in *Chapter 3* there will be presented the main components of a modern small wind turbine, highlighting the relevant characteristics and the main development issues.

The next step is to acknowledge the theoretical aspects involved in the design process of a wind turbine, all this information being gathered in *Chapter 4*.

Chapter 5 presents the Proven WT6000 wind turbine, which will be used as the technical comparison term for the turbine designed in this project. This presentation will help as well, not only because of the turbine itself, but it will also show how it interacts with its peripheral equipment, which can be generalised to all modern wind turbines in this size range.

Chapter 6 presents the solution that has been chosen for every component of the turbine, as well as the decision making process that led to it, thus including the complex aerodynamic calculations that determined the blade design and the generator calculations, to name just the two most important and complex components. Instructions for the building of the blades and the generator will also be given, firstly because they are especially designed for this wind turbine and they canonly work together, and secondly because their construction is not an obvious, straight forward process, like it is for the rest of the components.

The structural design verification of the newly designed parts is performed in *Chapter 7*. It has to be stated that the new design represents mainly a functional prototype, which will obviously undertake testing once it will be built, and most likely faults that cannot be forseen at this stage will occur. However, the structural verification will have to make sure that, at least theoretically, the prototype is safe to test.

Chapter 8 contains the estimation of the turbine's expected price, and an example of the turbine's payback period is also presented. The value is rather qualitative then quantitative because such calculations depend both on the particular site of the turbine, and on the final price of the product when it will be offered on the market.

Chapter 9 draws the conclusions and makes the recommendations for future development and applications.

Chapter 2- History of Windmills

2.1 Introduction

This chapter will present the historical evolution of the wind turbines.

A wind turbine is a device that transforms the kinetic energy of the moving air (wind) into mechanical usable energy. The way this is achieved, is that the wind causes a rotor to spin with a certain angular speed. The rotation is then transmitted to where it is needed by means of one or more shafts and possibly a gearbox [3].

In the past, the mechanical power delivered by the windmill was used directly for milling grain or pumping water. It is just in the past century that the windmills have been used to produce electricity [4].

Before moving on, it is desirable to state clearly what is the difference between a *windmill* and a *wind turbine.*

Modern technology has firmly established that a *wind turbine* is the prime mover of a wind machine capable of being harnessed for a number of different applications, none of which are concerned with the milling of grains or other substances, together with other various elements required for a complete power plant: mechanical transmission, nacelle, tower, load, control gear and so forth. [5]

The wind turbine could also be described as a wind energy conversion system (WECS), or, if used as an electrical power supply, as a wind turbine generator (WTG). [5]

The term *windmill* is generally used for referring to the older wind systems, especially for the multi blade water pumping wind machine (also known as the American farm windmill), and for the European four-sales wind machine (also known as the Dutch windmill). [6]

From the point of view of the rotation axis orientation, there are two types of wind turbines: *vertical axis wind turbines* (VAWT) and *horizontal axis wind turbines* (HAWT). This type of nomenclature is nowadays used throughout the whole wind turbine literature, and it obviously refers to the position of the main shaft. [5]

a – Horizontal Axis Wind Turbine **b - Vertical Axis Wind Turbine**

Fig. 2.1

An old terminology was naming the turbine by the plane containing the trajectory of a point chosen arbitrary on a blade. It is obvious that the trajectory is a circle that is contained in a vertical plane for a horizontal axis turbine and in a horizontal plane for a vertical axis turbine. According to that terminology, a HAWT is a *vertical windmill* and a VAWT is a *horizontal windmill* [5]. Still the modern terms VAWT and HAWT are more precise, and they will be used in the present thesis.

From the point of view of the relative position of the tower, rotor and wind direction, there are two configurations of horizontal axis turbines: *upwind* and *downwind*. An upwind configuration is obtained when the wind meets first the rotor and then the tower. If it is the other way round, the turbine is of downwind type. The upwind turbines can be easily noticed because they use a tail vane for keeping the rotor into the wind, except for the cases when a motor is specially fitted to the turbine for fulfilling this function. The turbine featured in Fig.2.1a has a downwind configuration.

2.2. The invention of the windmill and the early evolution

It is quite difficult to establish when the windmill was invented, as the ancient manuscripts used to be copied by hand and they usually were suffering changes through this process. Sometimes they have been mistranslated and sometimes the people performing the job felt the need to bring their own improvements, so the truth has been definitely altered.

However, it seems that the first mentioning of a device using the power in the wind is in Heron's work "Pneumatica". [7]

Together with various ingenious apparatuses operating on the basis of air or water, it can be found the description of a device that pumps air into an organ and consequently a sound is produced when the wind is blowing [8]. Whether this was Heron's own idea or his work is just a collection of ideas circulating during that period it is still unclear. [7]

The first record of a windmill dates from 1000 years ago, in Persia. It was a vertical axis windmill, and records from China feature vertical axis machines as well. [3]

The first records of a horizontal axis windmill are from Europe, and they have been quite precisely located during the 11th century. The European turbines were featuring usually four sales, possible flat boards in the beginning, and the horizontal primary shaft was driving a vertical one, which in turn was driving the grinding stones. [5]

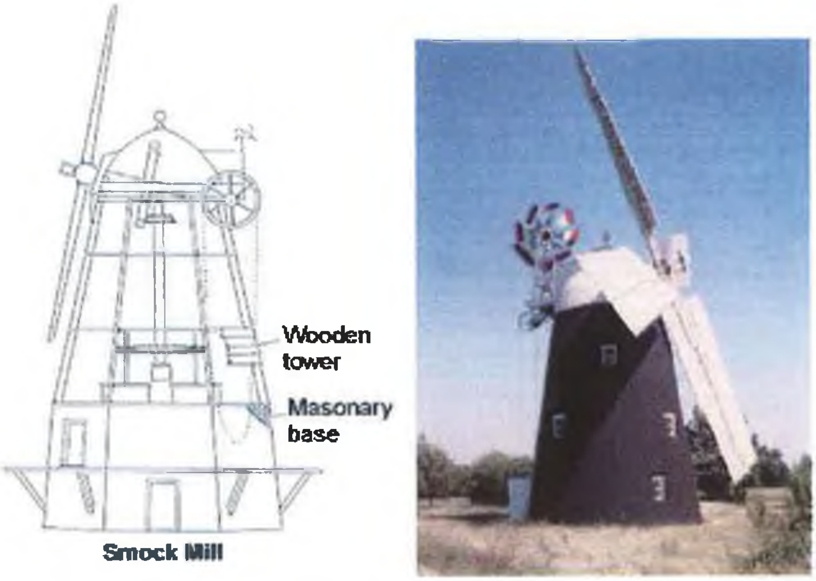
There are two main designs that have spread around Europe.

The simpler one is the *post-mill*. It features a mill that has the whole body mounted on a central post, enabling the machine to be turned into the wind. For the actual turning, the movable part of the structure had a long handler attached, and obviously a human was required to do the positioning. [3]

a **b** **c**

Fig 2.2 Different versions of the post-mill design.

The *tower-mill* design invention was driven by the need to build bigger windmills. With the increase in size, the design in which the whole structure had to be rotated was no longer viable.



well.

a **b**

Fig 2.3 Sketch and picture of a tower mill.

The tower mill consists of a tall building, on the top of which there is a rotating small structure. This top structure accommodates the primary shaft, and the driving gear fixed on it. Outside there are the sales, attached to the main shaft.

The tower mills made of timber were covered with clapboarding in England and often painted white, so that they came to be called *smock mills*, due to their supposed likeliness to the rural smock. [9]

2.3. Improvements of the early windmills

One of the most important improvements has been in the *sails* area. The flat board of the early blades had been replaced with a wooden lattice structure on which the sailcloth was fixed. This had brought the advantage that the cloth could shape itself in the wind, and was obviously adopting the most efficient shape. This shape resembles the modern airfoil one, and it brought a step forward in the overall efficiency of the mill.

Another advantage of using sailcloth was that the surface presented to the wind could be modified according to the wind speed, by modifying surface of the lattice structure covered by the cloth. At the beginning this was achieved by bringing the rotor to a rest and working manually on the sail. Later, ingenious mechanical devices had been used to achieve that automatically. [5]

What was characteristic for that times, was that all the improvements, especially on the blades shape, were achieved purely on experimental basis.

A very good example is that the sails were given a twist from root to tip, which is correct if one is aware of concepts like *relative velocity* and *angle of attack,* but it is amazing how somebody can achieve that result without applying the mathematical process that leads to it. Even more surprising is that some sails had the tips pitched at a negative angle to the plane of rotation, which might be in some cases theoretically correct, but it looks wrong if you are not aware of the modern aerodynamic calculus that is performed nowadays for any wind turbine blades. [10]

The explanation is rather simple, if first the relative wind concept is introduced. The wind "seen" by the blades is not the actual wind; it is a resultant of the real wind combined with the rotational movement of the blade. While the wind speed is constant throughout the span of the blade, the rotational component varies from zero at the rotor axis to its maximum at the blade tip.

Consequently, the blade relative wind speed and the direction vary with the distance to the hub. That is why, for maintaining a constant angle of attack for maximising the performance, the pitch of the blade varies from root to tip, such as at the root the pitch is at its greatest, decreasing towards the tip. This yields for the possibility of a small negative pitch angle to be required in some special cases.

The last major step in the history of the windmill was the *American windmill*. It was not necessarily a step forward compared to the European windmills, considering the latter were closer to the low-solidity modern aerodynamic concepts of a modern wind turbine than was the American windmill. However, the purpose was different, and it had been well served.

Whereas the main use of the Dutch windmill was to mill grains, the purpose of the American windmill was to pump water. For this, a high starting torque is required, as it starts directly under load. [6]

The way to achieve this high torque is to cover with blades as much as possible of the total swept area. However, a rotor that captures all the wind but it does not allow it to pass through produces no torque. The basic explanation lays in the fact that if the air is not circulating through the rotor, fresh air carrying kinetic energy is not allowed in, and thus no power is produced. [11]

Fig. 2.4 American windmills

These mills have what is called a *high solidity rotor,* i.e. a high ratio of blade area to the total area swept by the rotor.

Daniel Halladay is credited with the invention of the first commercially successful windmill, in 1854. It was intended as a small unit for pumping water. The output was around one horsepower (0.736kW), based on a rotor diameter of 5m and a wind speed of 7m/s, which was enough to meet its purpose. [12]

When moving from standstill, this type of rotor is very efficient, as it uses almost all the wind available to rotate it, but once it is spinning, every blade is running in the slip stream of the previous one, resulting in a great loss of efficiency.

However, the mill is not supposed to work at high rotational speeds, because the primary shaft drives a crankshaft that moves the reciprocating piston of the water pump. In a crack-rod mechanism the inertial forces increase with the square of the angular speed, and thus driving it too fast could just destroy the mechanism.

2.4 The transition from windmills to wind turbines

The transition to wind turbines began when windmill technology started to be used for producing electricity.

In Europe, the first who built a wind turbine generating electricity was *Poul LaCour*, in *1891*. His turbine featured the classic Danish design, with four twisted, rectangular blades. It was producing DC electricity [12]. Two of LaCours's concepts can be seen in Fig.2.6b.

In the USA, it was *Charles F. Brush* who built his version of the windmill generating electricity, in *1888*. The design used was the high solidity one from the American windmill. Due to the very slow speed of the blades, it had to feature a high step-up transmission system (50:1), by two belt-and-pulley sets in tandem, producing a final speed of 500rpm, at which the DC generator was rotating [13]. See also Fig. 2.5.

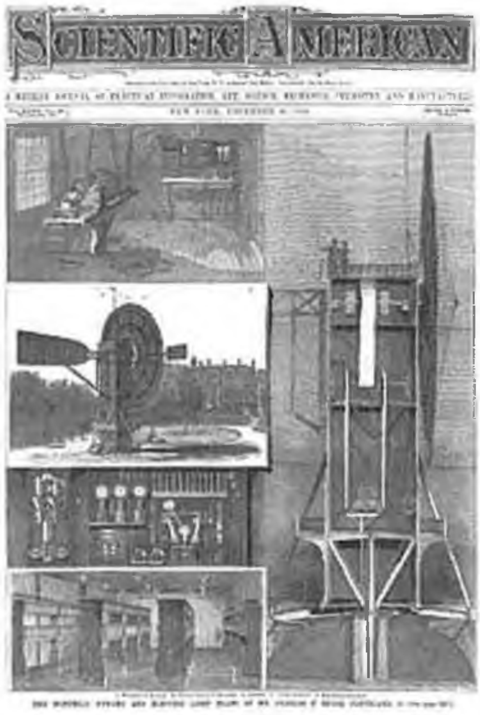


Fig. 2.5 Interior view of the Brush windmill

However, LaCour's wind turbine was better suited to electricity generation, as it yielded a higher efficiency and a higher speed of the primary shaft.

a - Brush's post mill design **b - Two of Poul LaCours's concepts**

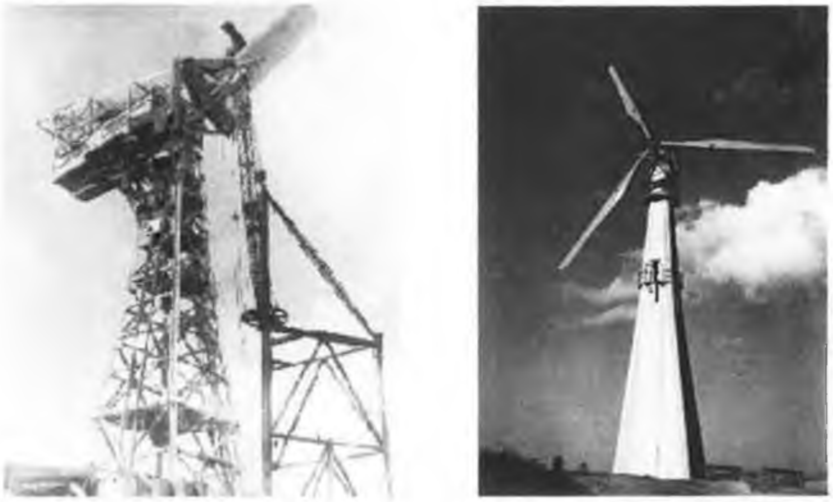
Fig. 2.6 Windmill design applied for electricity generation

The development of the aviation industry yielded great developments and knowledge gained in the propeller construction field.

This experience could be immediately applied to wind turbines, and the first ones to benefit from the advancing knowledge of aerodynamics were the F.L Smidth turbine in Denmark and the Smith-Putnam in the USA, both of them starting their service in 1941.

The Danish design was based on an upwind 3-bladed rotor with stall regulation, operating at slow speed. Putnam's design was based on a downwind 2-bladed rotor, with variable pitch regulation. Both of them featured modem airfoils for their blades. [14]

Smith-Putnam turbine, rated at 1.25MW, was the world's first megawatt scale wind turbine, and it operated with excellent power production until 1945 when it was discovered it had been under designed in the blade hinge area, and the project had to be stopped because of the lack of funds. [15]



a - 1.25MW Smith Putnam Turbine; b - F.L. Smidth's Danish, 3-bladed design

Fig. 2.6

2.5 Early Small Wind Turbine Generators

The first wind electrical generator started to be built in the 1920's and 1930's in both Europe and the USA [16]. At the beginning they were simply using modified propellers, driving direct current generators, thus benefiting from the fast advancing aviation technology, like their bigger counterparts described before.

Their power output was ranging from 1 to 3kW, and the main purpose for which they have been built and used, was to supply the small electricity need that farms had back then: battery charging for a few light bulbs and radios. [17]

Both American and European models had 3-bladed high-speed rotor design in common. There have also been some 2-bladed models, they were not very popular, because they were experiencing strong vibrations due to the changes in gyroscopic inertia about the tower axis each time the blades passed from a vertical to horizontal position. These vibrations were only present during the changes in the wind direction. [16]

However, 2-bladed rotors are slightly more efficient than 3-bladed ones, because they create less turbulence, and they are also cheaper and lighter, so these were enough reasons for trying to find a solution to the vibrations problem.

When the blades are vertical, their moment of inertia about the tower axis is reduced, and thus they oppose low resistance to the rotation about this axis, a movement that occurs while the turbine is positioning into the wind. When the blades are horizontal, this moment is much greater, consequently opposing stronger to the turbine rotation. Considering that the rotor is spinning while the turbine is turning into the wind, it means that while is doing that the turbine is subjected to cycles of low and high resistance to its movement, which is causing the vibrations.

The solution came from Germany, from Professor Ulrich Hutter. His design approach aimed to reduce bearing and structural failures by "shedding" aerodynamic loads, rather than "withstanding" them, as did the Danish approach. One of the most innovative load-shedding design features was the use of a bearing at the rotor hub that allowed the rotor to "teeter" in response to wind gusts and vertical wind shear. Hutter's advanced designs achieved over 4000 hours of operation before the experiments were ended in 1968. [17]

The solution of the teetered hub is absolutely necessary to the 2-bladed rotors, and is very efficient in dampening the vibrations characteristic to this design. All the modern 2-bladed turbines feature this solution. The teetered hub allows the blades to maintain their plane of rotation during the fraction of time when they are into the horizontal position while the rest of the structure is still allowed to turn. Consequently, the moment when the blades change the plane of rotation is postponed until their moment of inertia is lower.

Unfortunately, the more complicated the design, the more expensive it is to put into practice, and consequently the less likely to find it on a small wind system, as in this case it represents a much higher percentage from the overall cost compared to the case of a megawatt scale turbine.

In the USA, the small wind turbines became rapidly popular with the farmers, as they were the only source for electricity in remote areas. Their use was extended to an entire array of direct-current motor-driven appliances, including refrigerators, freezers, washing machines, and power tools. But the more appliances were powered by the early wind generators, the more their intermittent operation became a problem. [17]

The continuous increase in the demand for a reliable and constant supply for electrical energy, as well as the extension of the national grids in the rural areas, has produced the decline of the small wind generators. [5]

This trend continued after World War II until the 1970's oil crisis has brought back the problem of alternative energy, for a short time though.

However, the increasing concerns about global warming, greenhouse effect and ultimately pollution, have revitalised in the 1980's the interest in wind turbines as an alternative source of energy.

Major research projects have been undertaken both in the USA and Denmark, concentrating on the development of large wind turbines. [18]

Small-scale turbines have not benefited of the same level of attention, and have remained until today to serve the same purpose for which they have been built in the first place 70 years ago: to power remote applications. They are also very popular with wind energy enthusiast. [6]

2.6 Recent Trends in the Small Wind Turbines Technology

Small systems are usually found in remote areas, often in conjunction with a diesel/electric generator and/or solar panels, feeding the resulting energy into a battery system, which in turn supplies a single user or a small grid.

It is the general convention that a small wind turbine is one that has less than 50kW rated output.

Within this category, there can be found micro systems, mid-range systems and mini systems, the following table summarising the main characteristics of these 3 sub-categories [19]:

Category	**Power (kW)**	**Rotor Diameter (m)**	**Max. Rotor speed (rpm)**	**Typical Uses**
Micro	1	3	700	Electric fences, yachts
Mid-Range	5	5	400	Remote houses
Mini	20+	10	200	Mini grids, remote communities

Looking at the rotor, there has to be stated that there are two types of forces resulting from the interaction between the airflow and the blades: drag and lift. Early windmills were relying on drag to produce their useful torque. Modern wind turbines are relying mainly on lift, although there is still some torque produced by the drag forces.

Consequently, the blades are shaped as aerodynamic airfoils, which have been developed at the beginning for the aviation industry, the theoretical aspects being treated in the next chapter. Usually, the rotor has three blades, as it is historically proven this is the best compromise between the efficiency and lightweight of a two-bladed rotor and the smoothness of torque delivery of a multi-bladed rotor.

Some of the modern wind turbines use a downwind rotor, the blades coning away from the tower, and thus the resistance the blades oppose to the airflow, creates the moment that rotates the top structure by the tower axis, making sure the rotor is perpendicular to the wind. This solution eliminates the need for a tail vane, but brings another disadvantages, which will be discussed in the next chapter.

The most of the research regarding small wind systems is concentrated on the aerodynamic profile of the blades, as the rest of the components are quite simple and their construction is straightforward. Besides the rotor, a small wind turbine has a shaft, a generator, bearings, a nacelle or a top structure to accommodate all these, a tower and its foundation, and a controller that manages the electrical load on the generator, to prevent it from stalling the rotor, or to control the rotor speed. A detailed description of the main components will be presented in the next chapter.

2.7 Conclusions

In this chapter there has been presented the historical evolution of the wind turbines in the last millennium, from their supposed invention to the beginning of the last century when they have first been used for electricity generation. There have also been stated the general recent trends. However, a detailed insight into the development issues of modern wind turbines can be found in the following chapter.

Chapter 3 – The Components of a Small Wind Turbine

3.1 Introduction

In this chapter the main components of a wind turbine will be described, outlining their relevant aspects and the different options that a turbine designer could chose from.

3.2 The Rotor

The rotor is the part of the machine that actually transforms the kinetic energy of the flowing air into the rotational movement of the blades.

Its design is extremely important, because, from the whole chain of processes necessary to obtain electrical energy from wind energy, at its level it takes place the highest loss of efficiency.

As it will be shown in the next chapter, any rotor, no matter how efficient, cannot transform more that 60% of the energy contained in the air that crosses the surface swept by the rotor. This is because for transforming 100% of the kinetic energy in the air, the air should be stopped, and in reality the air has to be left with enough energy to be able to leave the rotor, as otherwise no fresh air could come in, and no power would be produced.

This percentage is called the power coefficient, and the symbol is c. For an efficient turbine, like the megawatt scale Danish turbines, the power coefficient c can be as high as 0.47, which might not seem a high figure, but it actually represents almost 80% of the maximum that can be transformed.

Modern rotors are relying on the lift that blades are producing when moving through the air. This lift is actually the useful force that is pushing the blade forward and is creating a momentum at the shaft level.

The blade, in its movement, produces useful torque that is transmitted to the shaft, but it only does that after it has overcome the resistance from the air flowing around the blade. The resistance from the air is actually a force that tends to slow the blade, and is called drag.

Therefore an efficient blade has to have high lift and low drag coefficients.

From the number of blades point of view, there are two types of turbines: multi bladed and 2 or 3 bladed.

The main characteristic of the multi bladed turbine (starting from approximately 20 - 30 blades) is that it produces high starting torque in relatively slow winds. That is why its main use was to drive mechanically a piston pump in a well for lifting the water to the ground level. Although it has been widely used, this type of rotor has low efficiency compared to modern turbines, and can only transform about 10-15% of the energy in the wind. The explanation is on one side that multi bladed rotors don't use the modern aerodynamic aerofoil design, and even if they were, the blade solidity is too high, slowing the air too much, and by that loosing efficiency.

Modern wind turbines have 2 or 3 blades. The low solidity rotor is allowing much higher efficiencies, it can operate at higher rotational speeds, and thus it is better suited to drive an electrical generator.

The main problem with a turbine that has two blades is that when one of the blades is vertically up, thus facing the highest wind, the other is vertically down, in front of the tower, thus crossing an area where the wind speed is much lower. This difference in the pressures acting on the two blades is creating a moment at the hub level, every time a blade is passing near the tower. As it has been shown earlier, the solution is to allow the whole rotor to teeter, thus the vibrations are not transmitted to the rest of the structure.

The problem does not exist with 3-bladed rotors because its moment of inertia has a far lower variation throughput one revolution, and consequently they are preferred to the two bladed ones. However, the decision between two and three blades is not very straight forward, considering that a 2 bladed rotor has the advantage of saving the cost and the weight of one blade.

Still, 3 bladed rotors are largely used because of the simplicity of their design and the smoothness with which they deliver the torque, compared to the 2 bladed rotors.

The rotor can be placed upwind or downwind of the tower.

The upwind rotors need a tail vane to keep them facing the wind. Quite obviously, if there is any change in the wind direction, it will blow sideways on the tail vane, which in turn will rotate the whole top structure around the tower axis until the wind is parallel to the vane again.

Downwind rotors do not need a tail vane; their blades are mounted in such a way that they do not sweep the surface of a circle, but one of a cone pointing to the tower, acting more ore less like a tale vane and keeping the rotor in the wind. Although they are saving the cost of the tail vane there are greater disadvantages. They are running upwind occasionally, in light winds. Being not very stable, they can also rotate a few times around the tower until they find the wind.

Probably the most important disadvantage is that the tower disrupts the airflow, creating a shadow through which blades are passing every revolution, high fatigue loads being induced, and also loss of performance.

Upwind turbines experience the same phenomenon, though to a much lesser degree, because the tower creates turbulence upstream, but far less than it does downstream.

Any modern blade has the shape of an airfoil in its cross section.

An airfoil is a shape characteristic to plane wings, and it has the purpose of keeping the plane into the air, meaning that this kind of shape creates a force that opposes the plane weight, in order to keep the plain in the air at a certain altitude. The main challenge is for the airfoil to achieve that without increasing too much the aerodynamic resistance that the airplane meets when it is moving.

The way an airfoil works is that, by its shape, is forcing the airflow above the wing to move faster than the one beneath it. The Bernoulli law states that the total pressure has to be constant, meaning that the sum between the static and dynamic pressure has to remain the same. By increasing the speed, thus the dynamic pressure, the static one decreases by the same amount. Consequently, the static pressure above the wing is lower than beneath the wing, resulting a force that is acting upwards and perpendicular to the direction of the airflow.

This force is called lift, and when used in the wind turbine blades, is creating the power that spins the electrical generator.

Lift depends on the parameters describing the airfoil shape, the size of the blade, the relative air speed and the angle of attack. Every airfoil has in imaginary straight line that runs from the leading edge to its trailing edge. This line is called the *chord* of the airfoil. The angle between the chord direction and the relative airfoil direction is called the *angle of attack*. More explanations and details are given in Chapter 4.

Modern wind turbines have twisted blades, which maintain the same angle of attack throughout the whole span, but have the disadvantage of being more difficult to fabricate. Smaller machines, for which minimising costs is more important than for larger ones, feature sometimes cheaper blades with constant pitch, being built in such a way that they optimise the outer third of the blade, where the most of the torque is produced.

Another aspect to be taken into account when blades are discussed is the material from which they are made.

Obviously one of the most popular materials is wood, as it is readily available, it has been all the time, and it is very easy to work with. It is also a comparatively cheap material, it has good strength and very good fatigue life, which of utmost importance for a wind turbine blade.

Modern wind turbines are using on a large-scale basis wooden blades, building them either from single planks or wood laminates. This kind of blades need a special coating to protect them from the weather, and sometimes the leading edge is covered with fibreglass tape as it is exposed to erosion from the wind and the particles it carries.

Laminated wood has become more popular, because its strength can be controlled by varying the type of wood used, the direction of the grains, and the resin, the result being a blade stronger than a single plank.

Another material that has been used for blades is steel. The technologies for making steel solids, no matter what shape or size have been greatly improved in the last century, and its strength has been widely experienced upon and thus it is very well understood. Steel blades that can withstand a certain load have been used, with no structural problem. The main problem with steel is that is heavy, which means the rest of the supporting structure has to be stronger and heavier, leading to increased costs.

Aluminium is the other metal that has been used. It is strong for its weight, and is used throughout the aviation industry with great success, but unfortunately its relatively low fatigue life prevented it from being successful for wind turbines use.

Fibreglass has become a very popular material: it is relatively inexpensive, strong, and it has good fatigue characteristics. There is also yielding a variety of manufacturing processes. One of them is pultrusion, in which the cloth is pulled through a vat of raisin and then through a die, the finite product being characterised by a prismatic shape.

If the use of a twisted more efficient blade is desired, the technology is to place layer after layer of fibreglass cloth in half shell moulds of the blade. As every layer is added, it is coated with the polyester or epoxy raisin. When the shells are complete they are glued together for forming the complete blade.

3.3 The Hub

The blades are attached to the hub to form the rotor. The hub transmits the turning force from the blades to the shaft. There are three important aspects of the hub:

- How the blades are attached
- Whether the pitch is fixed or not
- Whether the attachment is flexible or not.

The blades can be attached to the hub in two ways: cantilevered or with struts and stays.

The most famous turbine to use guy cables for securing the blades was the Gedser turbine, named after the location in Denmark were it had been erected. It is shown in fig 3.1.

The struts increase the drag on the rotor, but they greatly reduce the load due to the bending moment at the blade root. Consequently, the blade spar, the main structural support of the blade, and its attachment to the hub do not have to be as massive as on a cantilevered blade.

The main problem with this kind of design is that the turbine can occasionally be caught downwind, and it is then highly exposed to failure, because it can only take over the load in one direction. For this reason all the modern turbines use the safer and visually better cantilevered blades.

Fig 3.1 The Gedser Turbine

In order to maximise the turbine performance over a broader range of wind speeds, some turbines feature pitch-changing blades. Changing the pitch can help to increase the starting torque, and also to protect the turbine in high winds, by decreasing the power delivered to the generator.

If the rotor has to start from standstill, the blades angle of attack is so high that the blades are stalled (lift is very low because of the airflow separation from the low pressure surface). For starting, the pitch has to be increased, thus decreasing the angle of attack, and then decreased gradually until the machine has reached the operational speed. Blades can be turned back at the high pitch position for minimising power and thrust on the tower, if the wind is becoming too high.

Most of small turbines, because of the design simplicity, feature fixed pitch blades and the pitch is a compromise between an acceptable starting torque and good performance at rated speed.

Usually the blades are rigidly attached to the hub, mainly because of the simplicity as well.

Some designs allow the blades to flap a few degrees back and forth for decreasing the fatigue stress due to gusty winds and the load cycles that a blade withstand during one revolution.

However, hinging the blades may reduce the stress in them, but has a negative effect on power output because is reducing the swept area of the rotor, and the blades may strike the tower, in the case of an upwind machine.

3.4 The Transmission

From the hub, the rotational movement is transmitted to a shaft, and from the shaft it has to be transmitted to the generator.

The simplest way is to drive the generator directly with the rotor, both of them spinning at the same speed. The disadvantage is that the speed of the rotor is low, 200-400rpm for a small wind turbine, and it lowers even more as the size of the turbine increases. For producing alternative current at 50Hz, a two-pole generator has to rotate with 3000rpm, a four-pole generator with 1500rpm and a six pole one with 1000rpm. It becomes obvious that if one wants to drive the generator directly with the rotor, a special multi-pole generator has to be used.

In a small wind turbine, it is not absolutely necessary to produce the current at 50Hz, because normally these systems are charging batteries, so the AC current has to be rectified to DC anyway. However, a special low speed generator is required, and this is the only disadvantage, that it has to be designed and manufactured specially for a particular turbine, thus increasing the cost.

On the other hand, a direct driven generator saves the cost and the weight of a step-up gearbox, and also slightly improves the efficiency, proving itself an overall better solution, almost all the modern small wind turbines featuring this type of design, like the Bergey and the Proven turbines.

As the turbine size increases, the rotor speed lowers, and for medium and large turbines it becomes more effective to use a conventional generator coupled to a gearbox, especially that turbines in this size are used to supply current to the national grids, and consequently they are imposed the frequency, which is 50Hz (in Europe).

3.5 The Generator

The generator is the place where the actual transformation from mechanical energy to electrical energy takes place.

When a conductor is moving through a magnetic filed, inside the conductor electricity is generated, being proportional to the intensity of the magnetic field, the length of the conductor and the speed with which this is "cutting" the magnetic field lines. An increase in any of these or in all of them will lead to an increase in the electrical power generated in the conductor.

In an electrical circuit, power is the product of current and voltage: $P = U \times I$, where U is measured in volts (V), I is the current and is measured in amperes (A), and P is the power, measured in watts (W).

In its simplest form, an electrical generator is a coil spinning in a magnetic field. An electrical generator has thus an armature and a field.

The armature is the coil of wire inside which the output voltage is generated and through which current flows to the load. The field is the place where the magnetic field is generated. Power can be obtained by either spinning the armature inside the field or the field inside the armature. The moving part is called rotor and the fixed part is the stator.

The generators can produce either direct current or alternating current, depending on how they are built.

In a DC generator, power is drawn off the rotor, which is the armature, and thus the whole current supplied by the generator has to pass through the brushes connecting the spinning coil to the wires leading to the electrical load. This produces a high wear rate in the brushes, which have to be replaced after a certain period of service.
In an AC generator, the current is generated into the stator windings, the rotor producing the magnetic field that spins inside the armature. The magnetic field can be produced by either coils through which direct current is passed, or by permanent magnets. In this type of generator, through the electrical connection between the rotor and the stator it is passing only the current for magnetising the rotor, the actual electrical load being drawn off the stator. This is significantly minimising the wear of the rotor electrical connection. Even more, if the field is generated by permanent magnets, this connection is totally eliminated, and thus it is recommended for low maintenance applications, like small wind turbines.

DC generators are no longer used in wind turbines, because, as it has been stated above, it is an easier and more elegant solution to produce AC and then convert it to DC, if that is required.

Usually AC generators, produce 3-phase current, meaning that for optimising the space usage within the generator, the coils are disposed around the stator in such a way that 3 alternating currents are produced, each of them having a phase that is behind the next one with one third of a cycle, or $\frac{2\pi}{3}$.

Induction generators, or asynchronous generators, produce AC as well, the difference being that the rotor is not excited by DC current, but by the three phases that produce a spinning magnetic field, which in turn creates current in the rotor. In the rotor, the current can flow however is induced by the magnetic field, as the conductors are all short circuited together.

The principle at the base is that there has to be a difference between the rotor speed and the magnetic field speed, produced by the armature, which is called the synchronous speed. That is why it is called asynchronous generator. If the rotor is spinning slower than the synchronous speed, the rotor is accelerated towards that speed, and power is consumed. If the rotor has exactly the synchronous speed, there is no electricity induced in it, and no power is either consumed or produced.

If power is applied to the rotor, tending to accelerate it away from the synchronous speed, current and magnetic field will be induced into it, in such a way that the interaction between the two magnetic fields, the one from the rotor and the one from the stator, will oppose to the rotor movement and it will tend to slow it down, and power will be produced in the armature, under the shape of 3-phase alternating current, identical to the one that excites the stator windings.

This type of generator has the advantage of having a comparatively simple construction, it is consequently very reliable, and it also can supply electricity into the national grids, the working principle guarantying that the supply fits exactly the grid requirements.

However, it cannot be used in a small wind turbine, as there is often no grid connection in the places where they are used, and even if it is, supplying to the grid is not the purpose of machines in this size.

For a small wind turbine, the simplest is to use a permanent magnet generator, and it will just produce energy every time there is enough wind.

If instead of permanent magnets electromagnets are used, there is a need for a DC supply to excite the rotor. Although a more complex controller is required, it provides the possibility of controlling the output by adjusting the current passing through the rotor coils.

Synchronous generators can operate at variable speed, which can optimise the performance, considering that the rotor speed can adjust to the wind speed, working at the highest possible efficiency for every wind speed. The output current will vary both in the overall power and in the frequency. This is the way small wind turbines operate.

Asynchronous generators operate at fixed speed, usually 2-5% above the synchronous grid speed, the output power varying with the torque applied to the generator shaft through the transmission, from the primary shaft connected to the hub.

Asynchronous generators are only practical to use with grid interconnected wind turbines, which are medium or large, and they also feature step-up gearboxes to be able to spin the generator slightly above 1500rpm (in the case of a 4-pole generator), the speed required for producing the grid 50Hz frequency.

Despite their simplicity, induction generators are not suitable for small wind turbines, one reason being that due to their low productivity, small wind turbines are not practical to deliver their power into a national grid, and it is extremely complicated to make this kind of generator work without the grid connection. The second reason is that normally a transmission system is required, and small turbine manufacturers avoid using one, as it increases the weight and the cost of the machine.

3.6 The Turbine Controls

Besides the mechanical parts that are strictly connected to the actual conversion process from the kinetic energy of the air to the electrical energy delivered by the generator, a wind machine has to feature parts that are insuring this process takes place properly.

The controls have a few different functions:

- The first is to ensure that the rotor is presenting all its available swept area to the wind, or that the wind direction is perpendicular to the plan of rotation, thus maximising the energy transferred to the generator.
- The second is to make sure that the electrical load put on the generator does not stall the blades, or otherwise that the power request fits exactly the turbine output for a certain wind speed.
- The third, and the most important for the structural integrity of the machine, is the protection in high winds.

Small wind turbines use the forces in the wind itself to orientate into the wind. For that, they have a tail vane that aligns itself and the rest of the top structure parallel to the wind direction. This is an upwind configuration.

In the case of a downwind configuration there is no tail vane, and the blades are mounted in such a way that the sweep a conical surface, this cone pointing at the tower and into the wind. The disadvantage is that the tower is covering partially the blade swept surface, which is producing a drop in the efficiency and is also increasing the fatigue load of the blades.

Both these configurations imply that the top structure is mounted on a bearing that allows it to swing freely around the tower axis, its position depending only on the wind direction.

Larger turbines are much heavier, and thus they cannot rely on the wind force to move them around the tower. Attached on the turbine casing there is a wind vane, measuring continuously the wind speed and direction. This information is fed into the computer that manages all the functions of the machine, which in turn, with the help of an electrical motor, positions the turbine in accordance with the information received.

The reason for which this system is not used on small machines is that it would increase the overall cost by a very important percentage. Large wind turbines are expensive and complicated machines anyway, and the computer control ensures that expensive equipment is working properly, justifying its price. Such a system could not find its place in a small wind turbine, where, as it has been stated before, things have to be kept as simple as possible. The simpler, the more reliable it is, and this is very important, especially for a small machine that receives significantly less maintenance and observation than a large one.

The common use for small wind turbines is to charge batteries. The variable AC delivered from the generator is converted to DC, which can then be charged into the batteries. The DC can also be used to heat an electrical resistance, like the electrical heater in a room or an immersion heater for a house's hot water tank. A controller has to be used to make sure that load is only applied when the turbine can deliver the requested power.

The modern turbines, because they are optimised for working at high rotational speeds, have a low starting torque, and thus if load is applied before the rotor has reached to a certain speed, it will just slow it down, eventually stopping it, or otherwise it will not even let it start.

The controller has also the function of connecting different loads to the turbine, for example switching between battery charging and house heating.

As the wind speed increases, the turbine will deliver more power, and will eventually reach the rated power of the generator. If no measures are taken, the generator will overheat, and then obviously will melt or burn the windings inside.

Even worse, if there is wind and no load applied, the rotor will speed up freely until the centrifugal forces will break the blades.

That is why it is necessary to fit every wind machine with means of controlling the power in high winds, i.e. to limit the power when the wind goes over a pre-established limit.

One of the simplest ways is to turn the turbine out of the wind, decreasing the area intercepted by the wind. This is also decreasing the thrust produced on the tower.

This method is called furling, and is easy to use with tail vane machines. The vain is normally parallel to the rotation axis of the blades. If the vane is set to a certain angle to this axis, the turbine will accordingly turn out of the wind, partially or completely. That is horizontal furling.

Some small machines use vertical furling, which means that the rotor is tilted skyward, with exactly the same effect of reducing the area intercepted by the wind.

This can be easily achieved by mounting the whole top structure on a hinge in such a way that the thrust on the blades creates an overturning moment in the hinge. Once this moment becomes greater than the one created by either springs or counterweights, the rotor turns upwards, consequently reducing the power output. This method is only practical with very small turbines, up to 2m in diameter, as the weights and the forces involved are reduced.

A method used by downwind turbines is to hinge the blades to the hub, enabling them to bend backwards in high winds, coning away from the tower and thus reducing the swept area. This method cannot be used on upwind machines as the blades could strike against the tower.

Reducing the aerodynamic efficiency of the blades is another method of protecting the turbine from destruction in high winds.

Some rotors feature blades that can change the pitch. In high winds the pitch is increased, the blades turn with their leading edge into the wind, reducing the angle of attack, thus reducing the torque delivered to the generator. That is called pitch control.

If the wind speed increases but the rotor is kept at a constant speed, the angle of attack of the relative wind to the blades will increase, thus increasing the power output. However, that is true only up to an angle of attack of around 13° [20]. If the angle of attack increases beyond that limit, the air flowing over the low-pressure face of the blade will separate from this surface, producing simultaneously a drop in the blade lift and an increase in the drag, and the blade becomes stalled. Consequently the blade efficiency will decrease dramatically, protecting the generator from being exposed to harmful loads.

The way this works is that if the rotor is applied sufficient load to prevent it from going over a certain speed, the power output will automatically decrease once the wind speed reaches the limit for which the turbine was designed. This is termed as stall control.

Pitch control and stall control can be combined, meaning that instead of turning the blades in the direction of reducing their angle of attack, they are turned in the opposite direction, causing them to stall. The advantage of stalling the blades is that the transition to a lower torque output is smoother, the disadvantage being that it increases the thrust on the tower.

Another method of limiting the power is to spoil the aerodynamic efficiency of the outer part of the blade, which is producing the most of the torque. Aerodynamic brakes have been used, but they had the disadvantage of reducing the efficiency even when they were not deployed, during normal operation.

Pitching the blade tips achieved the same type of control in high winds, without spoiling the efficiency below the critical wind speed.

When the wind speeds are extremely high, any wind turbine has to be stopped completely until the wind speed decreases to a level that yields safe operation.

Bringing the turbine to a halt is achieved through mechanical brakes, unless there is the possibility to turn the turbine completely out of the wind, in which case it will just stop by itself. A mechanical brake usually consists of a brake disk and brake pads, being applied automatically or manually, depending on the size of the turbine. Large turbines have their brakes hydraulically driven and are applied automatically by the computer controlling the whole operation of the machine.
On a simple small turbine the brakes can be applied manually from a lever mounted at the base of the tower.

However, safety measures have to be included into the design to prevent it from self destruction in high winds, considering that most of the time the machine is left unattended thus the designer cannot rely on the fact that if the turbine over speeds there will be somebody to stop it manually.

3.7 The Tower

The tower is what keeps the turbine up in the air stream. Consequently it can have as big an influence over the turbine performance as the design of the blades.

The main problem to take into account is that buildings, trees and other obstacles around the place where the turbine is erected create turbulence, and if the wind reaching the rotor is turbulent it causes an important drop in performance and it also induces greater fatigue loads than usual, so it has a double negative effect.

That is why, a wind turbine has to be placed far enough and high enough for minimising the interference of the surrounding buildings or other elements causing a turbulent airflow.

Beside the height requirements, a tower has to meet the structural requirements, in that it has to be able to withstand the loads. There are two loads on the tower:

- The weight of the turbine and
- The thrust from the wind.

The tower has to be able to take the axial load represented by the weight of the top structure, without buckling.

When the wind is blowing, a thrust force is exerted both on the rotor as well as over the whole height of the tower. When the rotor diameter is reduced, the thrust on the tower represents an important part of the overturning force trying to bring down the tower and the top structure on it. As the rotor diameter increases, the tower thrust becomes insignificant when compared to the force exerted on the blades.

Normally towers should be chosen in such a way to be able to withstand winds of up to 50 to 60m/s.

When calculating the thrust in extreme conditions, the regulation system that the turbine has must be taken into account.

Pitch controlled machines turn their blades with the leading edge towards the wind, thus reducing the surface that the blades present to the wind, and consequently greatly reducing the thrust.

The thrust is also greatly reduced if the turbine is furled out of the wind, being almost eliminated as a serious source of concern in extreme conditions.

However, stall regulated machines have to withstand much greater loads during high winds, and special attention must to be given to the tower and how it is connected to the ground.

There are mainly two types of towers:

- Free standing towers
- Guyed towers.

Freestanding towers can take the both loads by themselves, being usually bolted into a strong concrete foundation.

Guyed towers take the axial load from the turbine weight and rely on the guy cables to take over the thrust from the wind.

Guyed towers are much lighter and consequently cheaper than freestanding ones, but require a larger available area around the turbine for bolting the cables to the ground. The cables are hazards for people who have to pass that area, and they are also exposed to failure in the cable itself or in its ground connection. However, a careful decision over the size of the cables and the system used for fixing them into the ground can overcome these last two problems.

There are two types of freestanding towers:

- Lattice or truss towers
- Tubular or pole towers

For the same strength, the lattice towers are marginally less expensive than poles [6]. They are also easier to climb, if servicing is required.

Climbing the tower is only necessary if it is rigidly bolted to the foundation. Some towers, both pole and truss type, are hinged to a plate which in turn is bolted to the ground. In this case the tower together with the turbine on the top can be lowered and the maintenance on service operations can be completed at the ground level, which is definitely desirable as it considerably decreases risks.

Another aspect to be taken into account when talking about towers, both freestanding and guyed, is the impact they have over the landscape. It seems that for people closer to the turbine a pole is visually more pleasing than a truss tower. However, observed from a distance of 2-3km or more, a truss tower blends much better with the scenery than a solid pole. [21]

Having to withstand all the loads by themselves freestanding towers are more massive ands consequently have more visual impact over the surroundings than guyed ones.

Guyed towers are a popular choice for small wind turbines because they are offering the required strength at a lower price. Like the freestanding towers, they can be of either tubular or truss type, lattice ones offering a higher strength for the same weight and price. [6]

There is one more structural factor that has to be accounted for: the pairing of the resonance frequency of the tower with the vibration frequency of the top structure. Even if the tower is strong enough to withstand the weight and thrust loads, if the turbine and the tower happen to oscillate in harmony their movement will gradually amplify leading to abnormal displacements and strains within the structure, which in turn will eventually cause a failure.

In the end, as a conclusion, it can be stated that there are a few factors influencing the tower choice: the desired height, the loads that have to be withstood, the space available, the budget and the impact over the landscape.

3.8 Conclusions

In this chapter the main parts of a wind turbine have been presented, highlighting the main aspects for each component in an attempt to facilitate the understanding of what each part does, how it interacts with the rest of the system and how it influences the overall efficiency. This has also revealed what are the main areas on which the development efforts should be concentrated, representing key elements for the efficiency of the turbine.

Chapter 4 – Theoretical Aspects Involved by Wind Turbine Design

4.1 Introduction

This chapter has the purpose of putting together the fundamental theoretical aspects and the mathematical calculations that lay at the basis of the design of wind turbines.

First, a method for estimating the power output based on the rotor diameter and the wind speed will be presented and explained. Afterwards there will be given some details for understanding the shape of the blades and the parameters defining it, and based on these parameters, it will be presented another method for the power output calculation, whose results reflect better the complexity of the real performance.

4.2 The Energy in the Wind

It has to be clarified from the beginning that the air passing through a certain area over a period of time carries a certain amount of energy. The ratio of the energy to the period of time is the power of the air crossing the area.

The energy contained in the airflow is given by the movement itself, which is why it is called kinetic energy. This energy depends on both the mass and the speed of the air: $E = \frac{1}{2} m V^2$.

The mass of the air is the air density by its volume, thus: $E = \frac{1}{2} \rho v V^2$, but the volume of the air crossing a section over a period of time is the area of the section multiplied by the speed of the air. It becomes then easier to work with the power instead of the energy, and thus, the power becomes: $W = \frac{1}{2}\rho A V^3$.

The energy of the air crossing the area A, having the speed V over a period t of time is simply the power multiplied by the time: $E = \frac{1}{2}\rho A V^3 t$.

The unit for energy is joule and for power is watt, the relationship being that one watt is a joule of energy delivered over a period of one second: $1W = 1\frac{J}{s}$.

It is obvious that the energy in the air crossing the area swept by a wind turbine rotor cannot be entirely transformed into mechanical energy and then electrical energy. The energy converted at the rotor level is equal to the change in kinetic energy of the air passing through the rotor.

Fig. 4.1 Ideal airflow through a wind turbine rotor

Figure 3.1 shows an ideal air stream enclosing the rotor. It can be seen that the cross area of the stream increases as the air is slowed down by the rotor because the mass flow rate has to remain constant:

$m = \rho A_0 V_0 = \rho A_1 V_1 = \rho A_2 V_2$

This is based on the generally known assumption that the air travelling at subsonic speeds behaves like an incompressible fluid.

The theory that is going to be detailed next is called the *Actuator Disk Theory* and it has been developed by Glauert for aircraft propellers and a few years later by Betz for wind turbines. It relies on simulating the rotor with a disk equalling its swept area and which can extract energy from the stream. [22][23]

The force on the rotor disc is given by the rate of change of momentum:

$F = m(V_0 - V_2)$

The power extracted by the rotor is represented by the rate of change of kinetic energy:

$W = \frac{1}{2} m\left(V_0^2 - V_2^2\right)$

The power can also be expressed as the product between the force and the speed at the rotor plane:

$W = FV_1$

Considering that: $W = \frac{1}{2} m\left(V_0^2 - V_2^2\right) = \frac{1}{2} m(V_0 - V_2)(V_0 + V_2) = \frac{1}{2} F(V_0 + V_2)$, it becomes clear that:

$V_1 = \frac{1}{2}(V_0 + V_2)$

If a factor, *b*, is used for expressing how much the rotor is slowing the air, $b = \frac{V_2}{V_0}$, then the expression for the power can be transformed:

$W = \frac{1}{2} m\left(V_0^2 - V_2^2\right) = \frac{1}{2} \rho A_1 \frac{1}{2}(V_0 + V_2) V_0^2\left(1 - b^2\right) \Rightarrow W = \frac{1}{4} \rho A_1 V_0^3 (1 + b)\left(1 - b^2\right)$

The coefficient of performance is defined as the fraction of energy extracted by the rotor from the total available energy, which is the energy that would have passed through the rotor swept area if the turbine was not there.

$C_p = \frac{W}{W_1}$, where $W_1 = \frac{1}{2}\rho A_1 V_0^3$, and thus C_p can be expressed as:

$$C_p = \frac{1}{2}(1+b)(1-b^2)$$

Differentiating C_p with respect to b reveals that C_p reaches its maximum when $b = \frac{1}{3}$,

therefore, $(C_p)_{\max} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left[1-\left(\frac{1}{3}\right)^2\right] = \frac{16}{27}$.

It results that the maximum power coefficient is 16/27 or approximately 59.2%. That means that even the most efficient wind turbine will not transform more than 59% of the available wind. However, modern wind turbines, that are considered very efficient, operate at values of C_p of around 0.47.

The coefficient of performance allows for a first-glance, gross estimation of a turbine power output, if the wind speed and the rotor diameter are known: $W = C_p \times \frac{1}{2}\rho A_1 V_0^3$.

There also has to be noticed that the turbine power output varies with the cube of the wind speed, which means that if the wind blows with half the speed for which the turbine was rated, the power output at that speed is eight times lower than the rated value. [20]

4.3 The Aerodynamic Profiles for the Blades

The profile of a wind turbine blade, as well as any aerodynamic profile, has the purpose of doing its work, like keeping the plane in the air or creating a useful torque for generating electricity, without loosing energy through friction with the air.

These profiles are called airfoils, and any object featuring this shape has the property that when it is moving, due to the pressures in the surrounding air, a force acts on it in a direction perpendicular to the direction of travel.

At the base of this phenomenon leys the Bernoulli law, that describes the behaviour of a fluid under different conditions of flow and height:

$$P+\frac{1}{2}\rho v^2+\rho g z=[CONSTANT]$$

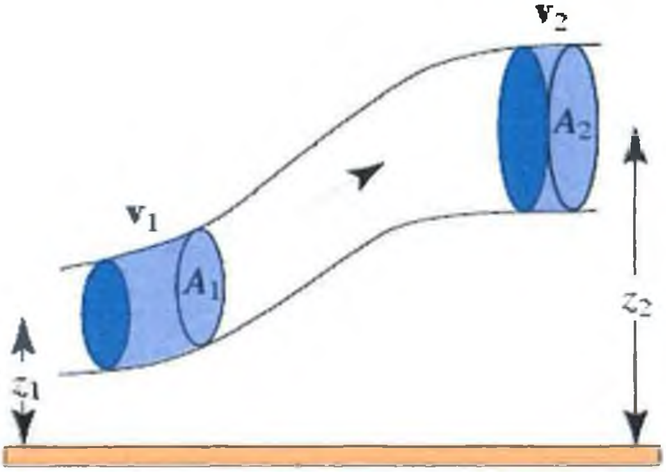


Fig. 4.2 Illustration of Bernoulli's law

The figure above shows an ideal stream flow, in which the static pressure (*P*) varies because of the change in altitude (z_1 to z_2), as well as because of the change in speed (V_1 to V_2).

The conclusion is that if a fluid is flowing around an object, and the shape of the object is in such a way that it forces the fluid to flow faster on one side of it, that side will experience a lower static pressure, taking into account that the height changes are negligible.

Considering that a difference in pressures appears, a force will be created that tends to push the object towards the side on which the lower pressure acts.

This is exactly how the airfoil shaped plane wings work. The pressure above the wing is lower than beneath it, so the force is acting in the upward direction on it, counteracting the weight of the plane, and thus keeping it into the air.

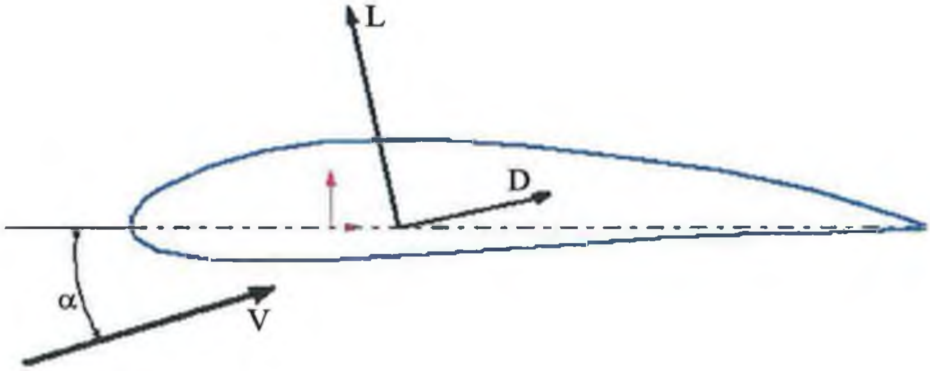


Fig.4.3 Lift and drag forces acting on an airfoil shape

The figure above shows a typical airfoil shape. The dotted line represents the chord of the profile and it runs from the leading to the trailing edge. The chord is the primary element of an airfoil shape, considering that all the parameters defining the shape are given in percentages of the chord length.

The air is flowing around this shape creating the lift L and the drag D forces, the direction of the drag being parallel to the direction of the incoming air with the speed V, and the direction of the lift being perpendicular to it.

It can be noticed that the air speed is not parallel to the chord direction, and the angle between them, α, is called the angle of attack. It can also be noticed that the shape is not symmetrical, which is exactly for making the air above travel faster and consequently create the lift. The asymmetry of the profile is given by its camber, a profile with zero camber being symmetrical.

If the camber is zero, the profile creates no lift if the angle of attack is zero as well, but it creates lift for positive angles of attack. A cambered profile produces lift even if $\alpha = 0$, and its lift increases with α, up to around 13°. After that value, the lift begins to decrease and the drag to increase dramatically, and the profile becomes stalled. This happens because the stream separates from the upper surface creating vortices that have the effect of slowing the air in the immediate vicinity of the surface, consequently reducing the lift effect. The turbulent flow around the shape also increases drag.

At the beginning of the century, the continuously developing aviation industry produced an increasing need for studying this airfoil shapes and how can they be improved.

In the USA, in 1915 was established an organisation that was called "National Advisory Committee for Aeronautics" (NACA), which had the purpose of conducting research in the field and foster any developments in this area. [24]

NACA has undergone a huge amount of wind tunnel testing for developing series of standardised shapes that would greatly help the design of the wings. It is obvious that the main goal when designing an airfoil is to produce as much lift as possible, keeping the drag to a minimum, i.e. to achieve the highest possible lift to drag ratio.

The main parameters that define a NACA profile are the length of the chord, the maximum thickness of the airfoil, the maximum camber, the distance from the leading edge where the maximum camber occurs, and the radius of the leading edge.

Mentioning some examples of NACA profiles explains how the designation of the 4 digits work:

NACA 0012 - Four-digit airfoil
First two digits indicate no camber.
Last two digits indicate max $\frac{thickness}{chord} = 12\%$

NACA 6415
The thickness represents 15% of the chord length.
The 64 camber means that the profile has 6% camber, at 40% of the chord.

Every NACA profile has a chord and a mean line, the latter being equally distanced from the upper and lower side of the airfoil. The mean line has the same ends with the chord but in between them the mean line is curved away from the chord, which is a straight line. In the example above, 6% camber means that the maximum distance between the mean line and the chord is 6% of the chord length, and this occurs at a distance from the leading edge equal to 40% of the chord length. It is obvious that in a symmetrical profile, the mean line and the chord coincide.

There are numerous possible combinations between thickness, camber and the other shape parameters, that is why the four-digit series have been followed by 5 and 6 digit series which contain a slightly more complex information about the profile and provide a better opportunity of matching the profile with the particular requirements of a specific application.

Besides its shape, an airfoil is characterised by the forces that are acting upon it: lift and drag. From the data collected during the wind tunnel tests, charts have been put together for every airfoil and the next page shows an example of such charts, displaying the variation of lift and drag coefficients with the angle of attack.

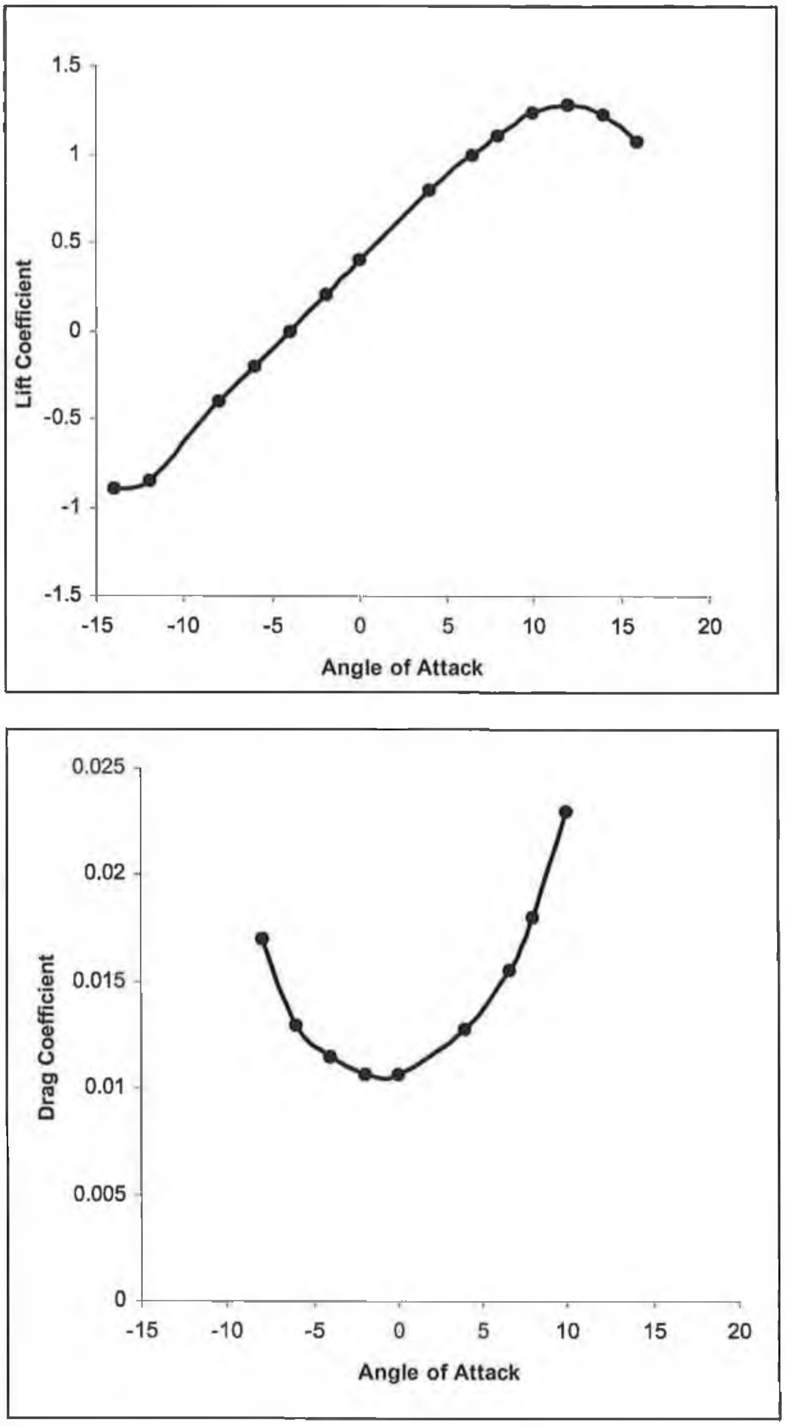


Fig 4.4 The variations of lift and drag coefficients with respect to the angle of incidence

The figure above shows the values for the lift and drag coefficients for the NACA 4415 airfoil, which will be used later in this project for defining the shape of the blades.

These coefficients serve in calculating the lift force and the drag one acting upon a certain airfoil shaped body, like the wing of an airplane or the blade of a wind turbine, when the angle of attack and the relative air velocity are known.

It has to be mentioned that besides lift and drag an airfoil generates a twisting moment that tends to reduce the angle of attack, which is why it is called the pitching moment. This moment is resisted by the section where the wing or blade is fixed, and it does not play any role in the aerodynamic calculations.

For a certain angle of attack, α, the expressions for lift and drag are:

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

Where ρ is the air density (~1.226 kg/m^3, at standard conditions: 288 K, 760 mm Hg), V is the relative air velocity and A is the plan area, which, in case of a constant section wing, is the length of the wing multiplied by the chord of the profile.

There also has to be mentioned that the lift and drag coefficients, C_L and C_D, depend on the turbulence degree of the flow, which is expressed by the Reynolds number:

$$\mathrm{Re} = \frac{velocity \times length \times density}{vis\cos ity} = \frac{Vc\rho}{\mu} = \frac{Vc}{\nu}, \ \nu = \frac{\rho}{\mu}.$$

Where V is the relative wind speed, c is the chord length and μ is the air viscosity. Re can be interpreted as the ratio of the inertial to the viscous forces in the fluid, which means that the lower the Re, the lower is the turbulence. For air, at standard sea level conditions, Re = $69000Vc$, where V is in m/s and c is in m. [25]

For obtaining an accurate result when computing the output of a wind turbine it is necessary of calculating the appropriate Re and use the corresponding aerodynamic coefficients.

4.4 Blade Element Theory

This is a simple method for calculating the aerodynamic forces acting on the blades of a wind turbine.

The main problem with a wind turbine blade is that the conditions vary from root to tip, i.e. the relative wind speed and direction change considerably. The solution of this theory is to divide the blade into radial sections (elements) that can be considered separately as working in homogenous external conditions, and thus the flow around each element can be determined. It is assumed that the flow over a particular element can be treated independently of the adjacent ones.

Using the aerodynamic coefficients the forces on each element are determined, and by summarising them the total load on the blades is obtained.

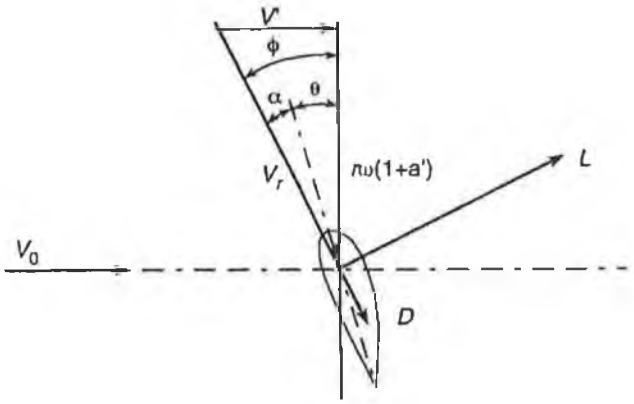


Fig. 4.5 Representation of the forces and air speed relative to a blade element

The relative wind at the rotor V_r varies with the radius r and is the resultant of an axial component $V' = V_0(1 - a)$ and a rotational component $r\omega(1 + a')$, where a is the axial interference factor, a' is the tangential interference factor used for expressing the induced swirl velocity $w = \omega r a'$ at the rotor disk, and ω is the angular speed of the rotor.

Knowing the direction and the speed of the airflow relative to each blade element, the lift and drag generated by that element can be calculated by using the aerodynamic coefficients for the particular airfoil.

The projection of the forces on the axial direction gives the thrust force on the rotor and the projection on the plan of rotation gives the driving force.

Considering that the rotor has B blades and than the local chord is c, the expressions for the net torque, power and thrust the following:

$$dQ = \frac{1}{2}\rho V_r^2 r(C_L \sin\Phi - C_D \cos\Phi)Bcdr$$

$$dW = \frac{1}{2}\rho V_r^2 \omega r(C_L \sin\Phi - C_D \cos\Phi)Bcdr$$

$$dT = \frac{1}{2}\rho V_r^2 (C_L \cos\Phi + C_D \sin\Phi)Bcdr$$

The local element thrust is given by the axial momentum loss:

$$dT = \rho V_0(1-a)(2\pi r dr)2(aV_0)$$

The torque produced by a certain element is given the rate of change of angular momentum:

$$dQ = \rho V_0 r(1-a)(2\pi r dr)2(a'\omega r)$$

Combining the two ways of expressing the thrust and the torque dT and dQ, the following equations are obtained:

$$\frac{a}{1-a} = \frac{\sigma R}{8r}\left(\frac{C_L \cos\Phi + C_D \sin\Phi}{\sin^2\Phi}\right) \tag{4.1}$$

$$\frac{a'}{1+a} = \frac{\sigma R}{8r}\left(\frac{C_L \sin\Phi - C_D \cos\Phi}{\sin\Phi\cos\Phi}\right) \tag{4.2}$$

$$\tan\Phi = \frac{V_0(1-a)}{\omega r(1+a')} = \frac{R}{rX}\left(\frac{1-a}{1+a'}\right) \tag{4.3}$$

Where $\sigma = \frac{Bc}{\pi R}$ is the blade solidity ratio (ratio of the blade area to the rotor swept area) and $X = \frac{\omega R}{V_0}$ is the tip speed ratio (the ratio of the blade tip speed to the wind speed).

The lift and drag coefficients depend on the angle of attack $\alpha = \Phi - \theta$ and can be found from tables or charts if a standard airfoil is used. Equations (4.1), (4.2) and (4.3) have to be solved iteratively for the given pitch angle θ, assuming that convergence will be obtained, leading to the final values for a and a'. The procedure is to guess the first values for a and a' and calculate Φ from equation (4.3). With this value for Φ and the values for C_L and C_D resulting from $\alpha = \Phi - \theta$, the coefficients a and a' can be calculated from equations (4.1) and (4.2) and then with the new values the whole process must be repeated until convergence is achieved.

The same procedure is performed for elements at different radial positions along the blade and the overall power and thrust of the rotor can be found by summing up the values obtained for each blade element:

$$W = \omega \sum_{i=1}^{i=n} dQ$$

$$T = \sum_{i=1}^{i=n} dT$$

The iterative procedure described above has been applied in this project for designing the shape of the blades, and thus it was slightly less complicated because as a designer you know exactly the desired angle of attack of the blade, and therefore the two aerodynamic coefficients need not be updated at every step, it is just the final pitch angle θ that is resulting from the final value for Φ and the desired value for α.

4.5 Vibrations and Fatigue issues

It has to be stated from the beginning that it is a difficult undertaking to develop a mathematical model on the basis of which the loads can be predicted and their effects calculated, considering that the processes involved are very complex and unpredictable to a certain degree, as they all depend on when and how hard the wind is blowing.

The complexity and unpredictability occur mainly during he transient phases, i.e. when the wind speed varies and/or when the turbine is aligning itself with the wind.

However, the main load variation is due to the cyclical loads on the blades.
If a steady wind speed is considered, during one cycle a blade has to withstand the following loads:

- Compression and tension alternatively due to its own weight.
- Tension due to the centrifugal forces.
- Variable wind thrust.

It is obvious that rotating in a vertical plane, one blade passes two extreme positions vertically upwards and vertically downwards from its axis of rotation, its weight direction pointing alternatively inside and outside the blade, generating the compression tension load cycle.

If m is the mass of the blade, ω is the angular speed of the rotor and R is the mean length of the blade, there is a centrifugal constant force that puts the blade under tension, then the force F "felt" by the blade in the section where is connected to the hub can be expressed as: $F = m\omega^2 R$.

The wind thrust on the blade varies as well, having the extreme values in the two vertical positions of the blade. Due to the vertical wind speed variation, on the upper part of its trajectory the blade is exposed to higher wind speeds than on the lower part.

The wind speed at the ground level is zero, due to the friction between the air and the ground surface. The wind speed increases with height most rapidly near the ground and less rapidly at greater heights. At around 2km above the ground the change in wind speed becomes zero.

There have been developed a few functions to describe the variation of the wind speed with the altitude, one of the most common being the power exponent function:

$$V(z) = V_r \left(\frac{z}{z_r} \right)^{\alpha}$$

Where z is the height above ground level, V_r is the wind speed at the reference height z_r above ground level, $V(z)$ is the wind speed at height z, and α is an exponent that depends on the roughness of the terrain.

A typical value for α could be 0.1. If it is considered a turbine with a hub height of 10m and a rotor diameter of 6m, then the tip of the blade is exposed alternatively to the corresponding winds at 7m and 13m above the ground. Thus, if the wind speed at 13m is 15m/s, then at 7m the wind speed is $15\left(\frac{7}{13}\right)^{0.1}$ =14.1m/s. It results a difference of almost 1m/s between the top and the lower part of the rotor, which has its effect on the load on the blade.

Actually the load variation due to the variations in air velocity is much greater than that, because the tower creates turbulence both upwind and downwind of itself, decreasing the wind speed even more in the area where the blades pass close to the tower.

As it can be seen, the blades are exposed to fatigue failure, and the variable loads on the blades are partially transmitted to the rest of the structure as well.

A computer simulation is required for a good estimation of the machine behaviour under these conditions, but such a simulation can only be accurate for the cyclic loads, which are a certainty. Each load that can be induced by sudden changes in wind speed and direction can be analysed separately, but the combinations that can happen in reality are numerous and anyway an accurate simulation cannot be achieved because of the random character of the wind. Statistics and previous experience can help, but no matter how accurate they may seem, the safety factor is the only secure solution for the unpredictable weather that can put the turbine under extreme strains. [5]

However, there are only two ways of failure in a wind turbine: due to a sudden overloading of the material or due to fatigue. Depending on the design of the machine and the means of control in high winds only one of these two will determine the design. For example, an upwind machine, stall controlled, due to its design, will have to withstand even the highest winds, but it is less exposed to fatigue than a downwind machine, that is why it is likely that designing it to withstand a very high wind will automatically make it strong enough to cope with the fatigue exposure as well.

That is why, considering the worst-case scenario is an efficient way of building a reliable wind turbine, especially for the small scale ones where the use of a slightly greater safety factor can lead to a very solid and durable design.

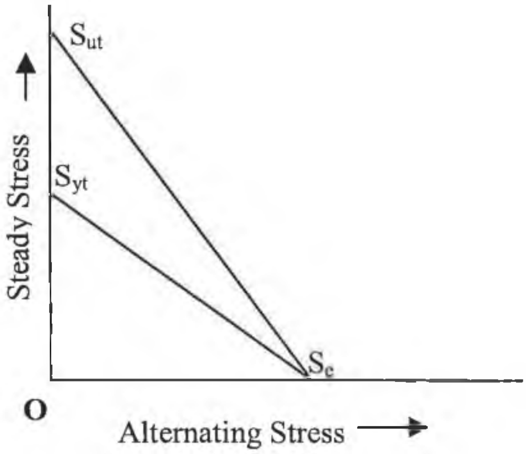


Fig. 4.6 The combined effect of steady and alternating stresses

Generally a fatigue-producing load has an alternating part and a steady one. Depending on which is greater the total stress can alternate equally above and below zero, or it can have greater values on either side of zero, with the extreme situations when the total stress has the same sign throughout the whole cycle. [32]

A certain material is characterised from the strength point of view by its capacity of coping with a steady stress and with an alternating one. In the chart above, for a certain material, U is the maximum steady stress that the material can take without breaking, and F is the maximum alternating stress for which the material can operate without failing.

Considering that a real life load is a combination of the two, it could be asserted that any load corresponding to a point under the U-F line is acceptable. However, if a load has a corresponding point very close to this line and also close to the vertical steady stress line, that is not acceptable because although the material will not brake, it is too close to its limit.

That is why, Soderberg suggested the S_{yt} -S_e line as a reference for deciding whether a load is acceptable or not.

Normally, any design should include a safety factor, and the relationship between the stresses and the safety factor should verify the following equation:

$$\frac{\sigma_{steady}}{S_y} + \frac{\sigma_{alt}}{S_e} = \frac{1}{SF}$$

Where, $\sigma_{\max}$ is the allowable maximum stress, S_e is the stress corresponding to the fatigue limit, and *SF* is the safety factor.

It has to be stated clearly that the fatigue limit depends on the number of cycles of alternating load the material has to withstand. It is obvious that the fatigue limit will be higher for a material that has to take throughout its designed life 100,000 cycles compared to the fatigue limit for a material that has to withstand 1,000,000 cycles without breaking.

With a few exceptions when the knowledge about the life of a product and the loads it will take is extremely precise, normally a designer should make sure the fatigue failure would never occur. It has been found by long experience that if a piece can outlive 10^6 cycles of stress reversals, it can stand these reversals indefinitely. [25]

Considering that a wind turbine blade undertakes approximately 10^9 cycles over a 30 year period, it becomes clear why it is so fatigue-sensitive, and why a piece that is virtually indestructible through fatigue could still fail in the typical conditions of a wind turbine.

4.6 Steady loads and basic formulas

As it has been stated earlier, the other aspect of the possible failure modes is for the maximum yield stress to be exceeded.

A wind turbine has to withstand a variety of type of loads: bending in the tower and the blades, torsion in the shaft and tension and compression in the blades.

The maximum allowable stress produced by a bending moment in the critical cross section is:

$$\sigma_{bending} = \frac{1}{SF} \times \frac{M \times y_{\max}}{I}$$

Where M (Nmm) is the bending moment in that cross section, I (mm^4) is the cross section moment of inertia, and y_{max} (mm) is the distance from the neutral axis of the cross section to the furthest fibre of the section, that being the place where the maximum stress σ (MPa) is produced.

The stress produced by an axial loading, i.e. compression or tension, only depends on the area of the cross section and the force being applied:

$$\sigma_{axial} = \frac{F}{A}$$

Where the force F is usually given in N and the area A in mm^2. Obviously, the value has to be corrected with the safety factor for obtaining the admissible value.

Another basic but important formula is the one than gives the maximum shearing stress in a shaft of circular section that is transmitting a certain torque T:

$$\tau_{\max} = \frac{TD}{2I_p}$$

Where I_p is the polar moment of inertia of the cross sectional area of the shaft, and D is the external diameter of the shaft. For a circular shaft, the polar moment of inertia is $I_p = \frac{1}{2}\pi R^4 = \frac{\pi D^4}{32}$. Considering that the interior of the shaft is responsible for only a small percentage of the transmitted torque, some shafts are hollow, their polar moment of inertia being: $I_p = \frac{\pi}{32}\left(D^4 - d^4\right)$, where D and d are the external, respectively the internal shaft diameter.

These formulas are basic for the strength of materials, they are simple and represent basic loadings, but they are very useful as any real loading is actually a combination of these simple and comprehensive loadings, and calculating each effect separately and then summing them up as vectors has as a result the effect of the complex loading.

4.7 Conclusions

This chapter has presented the main theoretical aspects involved in the design of a wind turbine rotor, form a very simple estimative method to a more complex theory. By treating the rotor blades as airfoils it was shown how standard airfoil theory can be applied for calculating the forces on the blades and thus the power produced by the rotor.

There have also been shown the main aspects of the airfoil shape and briefly explained how the change in shape can influence the performance.

All the information presented will be used in the specific calculations of the present project, realising the connection between theory and practice. The only exception is the structural considerations, which will not be directly applied, considering that the structural analysis will be performed on the 3D model with the aid of finite element analysis software.

Chapter 5-Proven WT6000 Presentation

5.1 Introduction

In this chapter the wind turbine that is going to be used as a technical benchmark, especially form the overall performance point of view, will be presented.

Considering that this is an already established market product, besides the turbine itself the manufacturer proposes different peripherals, which are normally part of a wind system. Although they are not the subject of the present project, a brief description of these accessories will be provided for facilitating the understanding of the wind turbine and the role that it is playing in a complete wind system ready to supply electricity.

5.2 The Turbine

The turbine is manufactured by Proven Engineering, in Scotland, and it features a three-bladed rotor, downwind from the tower.

It is designed to deliver the rated power, which is 6kW, in a wind of 12m/s. When the wind speed increases over the cut-in speed, which is 2.5m/s, the turbine starts delivering power. The cut-out speed is the one at which a turbine stops or it is being stopped out of safety reasons because the wind speed is too high. Proven WT 6000 does not have any cut-out speed because it is designed to modify passively the blade geometry when the wind speeds above 12m/s, and thus it keeps delivering energy even in the highest of winds.

The Rotor

The rotor has a diameter of 5.6m and it spins at 200rpm at rated power. The blades are made mainly from a combination of wood and epoxy except for their root, which is made of a combination of polyurethane and rubber.

The blades are hinged at the base, the rubber part at the root allowing them to bend backwards due to the wind thrust. At the front of the blade there is a spring that sets the force that opposes to this tendency. However, the spring is set in such a way that it allows the blade to flex backwards for wind speeds above 12m/s.

The hinge direction is not perpendicular to the blade axis, which means that when the blade bends backwards it is constrained to change the pitch as well, causing it to turn away from the wind.

During normal operation the angle between a blade and a vertical plane is 5°, as it can be observed in the *Appendix 1* drawing. The same angle can be as high as 45° during extremely high winds, in which case the rotor effective area is reduced by 50%.

It can be concluded that the output of the turbine is controlled in two ways in high winds:

- The first is by reducing the area that the rotor presents to the wind, by enabling the blades to bend away from the tower.
- The second is by increasing the pitch, thus slowing the rotor.

Figure 5.1 displays the top part of a wind turbine, which is delivered as one piece by all the manufacturers, because a certain blade design has to be paired with a generator that will allow for optimum performance and with a top structure, also called nacelle, that will cope with all the loads that can occur. In the 3d model featured in figure 4.1 it can be noticed from left to right the generator, the galvanised steel structure and the blades. In this drawing both the generator and the structure have transparent covers, but in reality they are black.

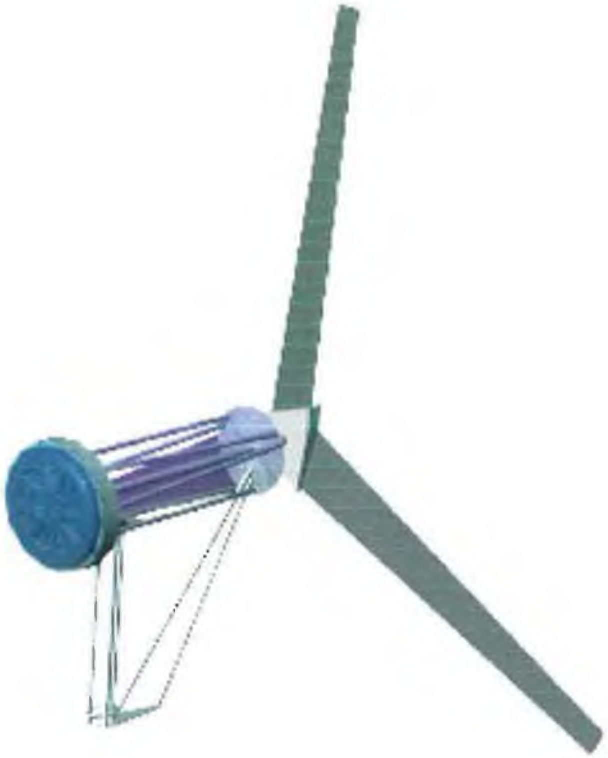


Fig. 5.1 3D model of the WT6000 top structure – the corresponding 2D drawing can be found in Appendix 1

The Generator

The generator produces 6000W at 200rpm, it has permanent magnets and it is directly driven by the rotor. To compensate for the lack of a step-up gearbox the generator has an increased diameter. This has the same end effect with a gearbox, i.e. it increases the relative speed between the magnets and the windings. The other shortcoming of a very slow generator is that the current produced has a very low frequency: if a two-pole generator produces 50Hz at 3000rpm, than the same generator it would only produce 3.5Hz at 200rpm. The solution is to increase the number of poles. However, increasing the diameter of the generator has the effect of producing more room fore placing more magnets, and so mounting a larger number of magnets is not a problem. It has to be mentioned that mounting more magnets has to be accompanied by placing more windings in the armature for collecting the current. Considering that most of the generators, including the one in the WT6000, produce 3-phase current, it can be stated, for a clearer image to develop, that a 2 pole generator has 3 windings around the rotor for producing 3 phases and a 4 pole one needs 6 windings but only half the rotational speed to produce the same frequency and 3 phases.

Depending on the application, at the same power output there are three options for the generator to produce the current at 48V, 120V or 240V. The coils producing these different voltages require the same amount of space, considering that a high voltage one has more windings but thinner wires, having to carry less current.

The use of permanent magnets removed the need for any electrical connection between the rotor and the stator, eliminating thus the parts that were the most exposed to wear.
The generator on the turbine purchased by G.M.I.T. was rated at 240V. If the desired use of the turbine is battery charging than the 48V generator is advisable because it does not require a transformer to bring down the voltage to the one that fits the batteries. The 240V generator is suited for heating, because in a resistor what matters ultimately is the overall power, the advantage of having a higher voltage being that it can be transmitted with fewer losses.

The Nacelle

As it can be seen in figure 5.1 the nacelle is a structure made mainly from steel beams, 37mm in diameter welded on 10mm steel plates that keep the structure together. The whole assembly is galvanised for ensuring that rust does not appear throughout the turbine life.

Inside the nacelle it can be found the shaft that connects the rotor and the generator. It has 60mm in diameter and it transmits the 6kW power at the rated speed of 200rpm, which means that the torque transmitted is about 325Nm.

The shaft is kept into its position by two tapered roller bearings. It is obvious that tapered bearings are required because there are axial and radial loads on them and this is the best-suited bearing type to this kind of combined loads. Inside the nacelle there can also be found the slip-rings and the brushes, mounted coaxially with the tower that collect the three phases current supplied by the generator. This kind of electrical connection is required by the fact that the tower is fixed while the nacelle is free to rotate around it.

5.3 The Tower

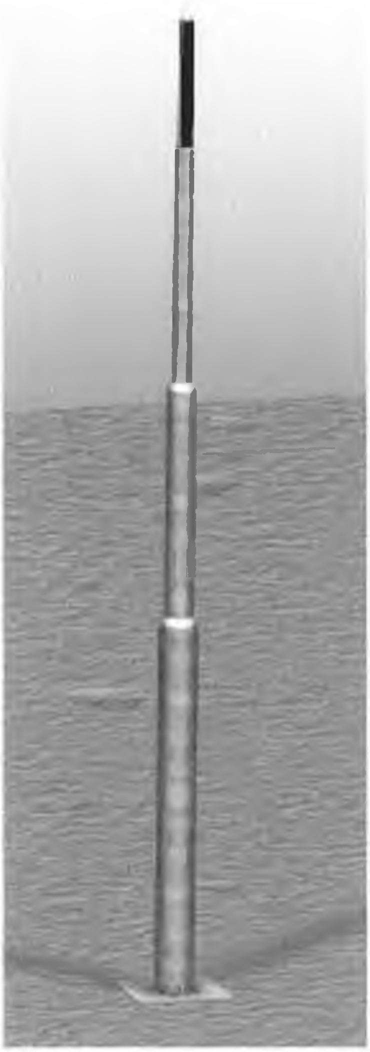


Fig. 5.2 Tower 3D model

The tower recommended by the manufacturer is 9m high and is made of three tubular sections, the external diameter at the base being 450mm and 200mm at the top.

In the figure 5.2 it can be noticed at the top of the tower a darker shaft, called the tower mount, which has the purpose of fitting exactly into the bearings of the top structure.
The turbine can be purchased without the tower offered by the manufacturer, but if that is the case, the tower mount should be purchased separately and fitted to the desired tower. However, another option is to fabricate the tower mount, considering that it has a basic shape.

Normally the tower is fitted with a hinged base plate that allows for the tower to be brought down and back up easily for maintenance operations. Half of the hinge is bolted to the concrete foundation and the other is welded to the tower. Gussets are also welded at the base for strengthening the joint.

If the decision is taken not to use the manufacturer tower, than the new supporting assembly, i.e. tower and tower-mount should be checked to see if they withstand the loads exerted by the turbine, which are mainly the turbine weight and the thrust created in the highest wind.
The weight of the top structure is 400kg, or approximately 4000N, and the thrust generated is 10000N.

A 2D drawing of the tower can be found in *Appendix 2.* In *Appendix 1* can be found a 2D drawing of the WT 6000 nacelle together with the blades and generator that are accomodated by it. The main purpose of these two appendixes is to create a general image about how the structure and the tower are built. They are not dimensioned in detail because they have not been designed within the present project.

5.4 The Peripheral Equipment

Typically the electrical power output of a wind turbine has a very variable character, following the distribution pattern of the wind speed over time. Even more, the output of a small wind turbine, which has variable speed, varies both in magnitude and frequency.

Obviously this kind of supply cannot be useful, and the purpose of the peripheral equipment is to transform the variable supply that is delivered directly from the turbine generator into a more reliable a constant source for the different appliances that can be found in a household.

Consequently, the turbine adjacent equipment has the following functions:

- To store the energy when it is supplied but not needed and to deliver it when it is required.
- To bring the supply within the necessary limits for enabling its use.
- To control the load on the turbine generator and balance the load with the possible output for a certain wind speed for preventing the turbine from stalling.

Usually the equipment that connects the turbine to the useful loads comprises of a controller and a bank of batteries.

Inside the controller the current is firstly converted from AC to DC for charging it into the batteries. Unless it is used for heating rooms or water tanks, the DC supply from the batteries has to be converted back into AC, this time at a constant 50Hz and 220V for suiting the AC appliances. The heaters, whether they are for rooms or for water, are basically electrical resistances and can be used with a DC supply. However, appliances like TV sets and computers can only work with a supply that resembles the one from the national grid for which they had been designed.

The controller has thus the basic task of connecting either the batteries or the house loads to the turbine.

5.5 Conclusions

In this chapter the Proven WT 6000 wind turbine has been presented together with the main parameters defining its performance.

There have been described the main parts of the turbine, i.e. the rotor, the generator, the nacelle and the tower, and the main characteristics of each of them have been established.

It has also been explained how the high winds protection works and how the turbine is controlled for making sure that it can always deliver its power and it does that in the most efficient way.

Chapter 6 - Solutions Chosen for the New Turbine

6.1 Introduction

Fig. 6.1 shows the new turbine and its main components. This chapter will present each of them in detail. Special attention will be given to the calculations that have determined the shape and size of the blades, considering that the rotor has the most important influence over the turbine performance and efficiency. There will also be described the generator and its typical calculations, and guidelines will be given for the construction of the blades, generator and nacelle.

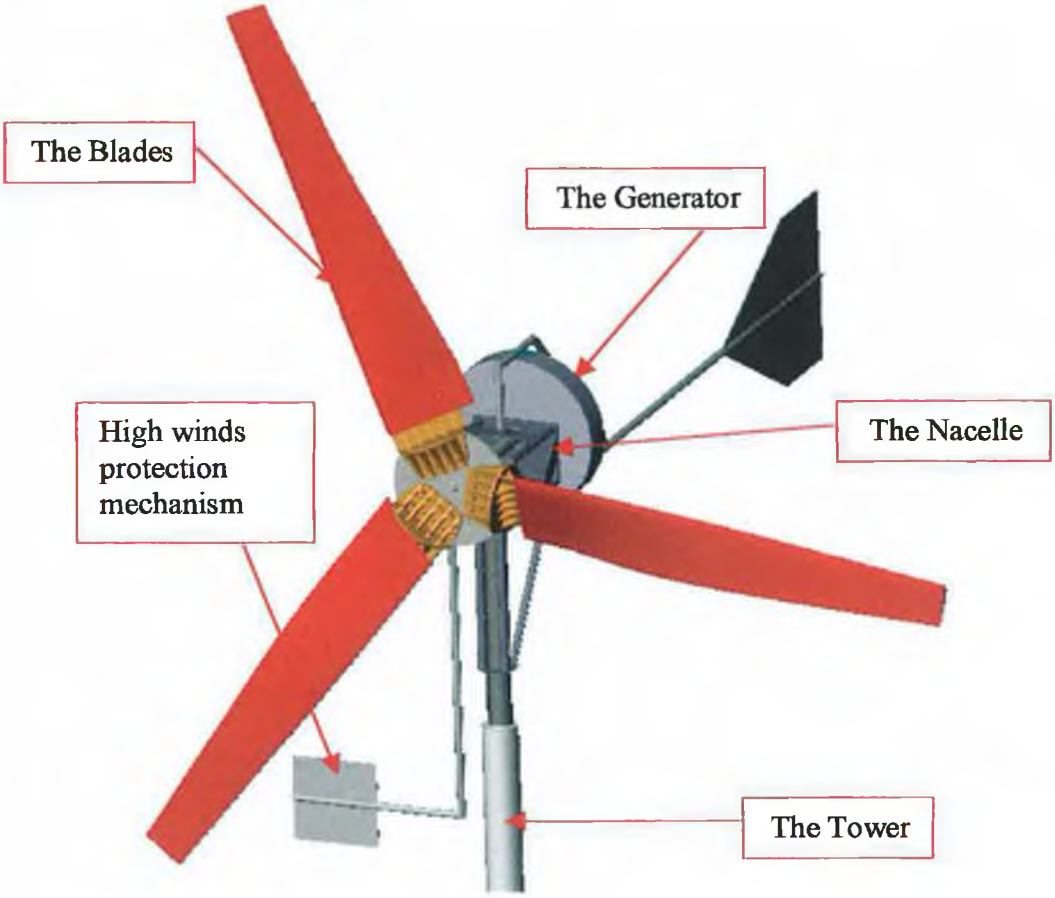


Fig. 6.1 The new design

6.2 The Rotor and the General Concept for the Turbine's Operation

The first option related to the rotor that has to be decided upon is whether it should be upwind or downwind. This decision also influences the design of the rest of the parts. As it has been stated earlier a downwind rotor saves the costs of a tail vane, but it will increase the blades price, considering that they have to be stronger. There are two reasons for which the blades need to be stronger:

- The first is that they are more exposed to fatigue loads, having to cross the tower shadow region every revolution.
- The second is that in a simple turbine there are no means to take the rotor out of the high winds, so the blades have to withstand even the most critical weather conditions without failing, compared to an upwind rotor that can be very easily furled out of the wind if the wind speed increases over a pre-established limit.

There are also other disadvantages of the downwind rotors:

- Besides inducing higher fatigue loads, the tower shadow also decreases the actual area that intercepts the wind, reducing thus the turbine efficiency.
- The blades are more expensive and more complex research is required to simulate how they cope with the loads that can occur.
- Downwind rotors can occasionally be caught upwind, which decreases their efficiency because the blades are not symmetrical and they are obviously designed for the wind flowing in the opposite direction.
- Finally, they are not as stable as the upwind rotors, which have a tail vane, and it is not abnormal for a downwind rotor to rotate several times around the tower in light winds until it finds the correct position.

The choice has been made for the upwind rotor that will consequently work in a less turbulent stream, which improves the efficiency. Considering that in the case of the present project there is not possible to use a complex and very accurate simulation software for predicting the turbine performance, the fact that the rotor works in a less

turbulent flow also allows the available power estimations, achieved through basic methods, to be closer to reality.
The other advantage is that using a tail vane for directing the rotor into the wind provides the possibility of furling the rotor horizontally by changing the relative position of the tail vane and the nacelle.

Most of the small wind turbine manufactures have chosen for their models the upwind configuration, with a furling tail vane as means of protection against high winds, proving that it is an overall better solution.

However, it has to be mentioned that downwind turbines have a more modern, better aspect, and thus they have less visual impact on the landscape, although that should not be a major problem with small wind turbines that are usually not higher than 15-20m.

6.2.1 The Over-Speed Control – Aerodynamic Stalling

Another important aspect of the blades that has to be discussed regards the means by which the output is controlled when the winds are higher than the speed for which the turbine is rated. The power limiting mechanism, in the present design, is provided by the blade shape itself, for wind speeds between rated level, 12m/s, and 100km/h, or 28m/s. Winds blowing faster than 100km/h can be considered abnormally high, and for that another protection mechanism has to be employed.

Considering that the power output varies with the cube of the wind speed, it is obvious that winds above rated speed can easily produce more power than the generator can cope with, which means that the rotor will speed up and possibly damage itself. The other possibility is that, noticing that there is more power available, the controller puts more load onto the generator to balance it, which will stop the blades from over-speeding, but will produce higher currents in the generator's windings, eventually burning them. That is why means have to be provided to keep the power output to a quasi-constant level once it has reached its maximum. Usually the maximum output is designed to be reached for wind speeds around 10-15m/s. When choosing the rated wind speed a compromise has to be achieved. It is not economical to design the turbine to reach is maximum in higher winds because firstly they have a very low rate of occurrence and secondly this would compromise the turbine efficiency in lighter winds which occur more often. It is not economical either to design the machine for extremely low winds, because, as it has been stated earlier, the output, varying with the cube of the wind speed, is very low, and thus improving the efficiency for the light winds would have almost no effect on the overall produced energy. The Proven WT 6000 is rated for 12m/s wind speed, and it has been decided to design the new turbine for the same wind speed.

There are a few different methods employed by the turbine manufacturers for limiting the power output in high winds, the most common being:

- Pitching the blades to reduce their efficiency.
- Stall control.
- Furling the rotor, horizontally or vertically, to reduce its effective area.
- Aerodynamic brakes, like blade tip brakes, flaps and ailerons.

These methods have all been detailed in the second chapter. Considering that the price of the machine has to be kept to a minimum, a design in which the blades or some parts of them are movable is not desirable because it is too complicated, and thus expensive.

Consequently, the solution chosen for the new turbine is the stall control.

The way the control system works is the following: once the wind speed reaches the 12m/s speed, the rotor will reach its rated 180rpm, and the blades are designed and pitched in such a way that their angle of attack is 13° for this combination of rotor and wind speeds.

The turbine controller will load the generator with the amount needed for maintaining the 180rpm speed. Once the wind starts blowing faster the blade angle of attack will increase over 13° because of the two relative wind speed components, only the axial component will increase, being the actual wind speed, the rotational component will remain constant as the rotor will maintain its speed due to the controller. The flux separation from the low-pressure surface of the blade will occur and the blade efficiency will decrease as it has been explained in the third chapter where the relevant airfoil theoretical aspects have been discussed.

6.2.2 High Wind Protection – Tail Furling

As it was stated erlier, for abnormally high winds (i.e more than 100km/h) the turbine has to be protected by turning it out of the wind, which is achieved by furling its tail.

The system designed is completely mechanical, and its operation relyes solely on th wind speed, and the energy that it contains.

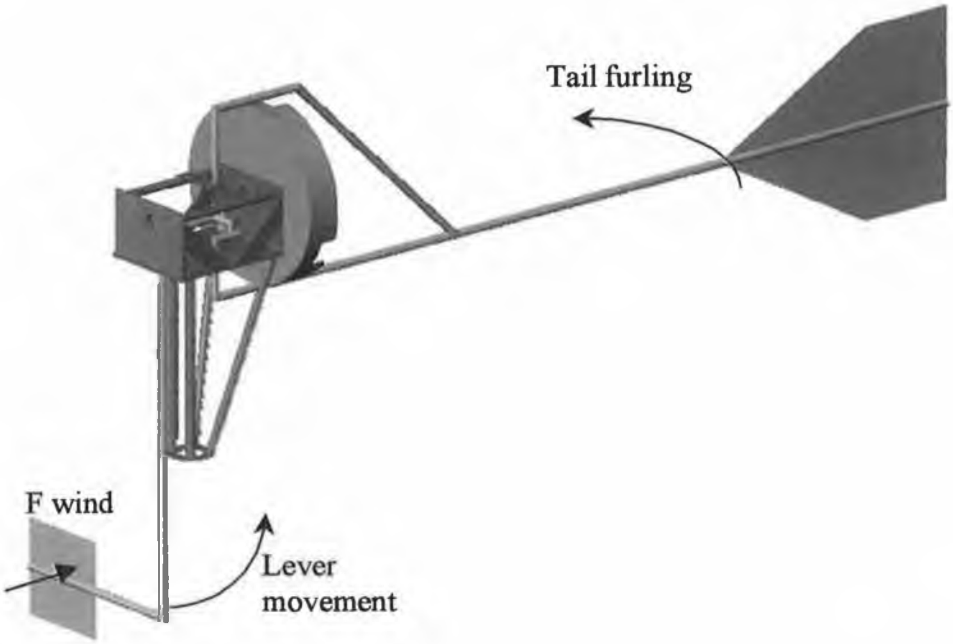


Fig. 6.2 The wind force causes the tail to furl

As it can be seen in fig. 6.2, the tail vane is not rigidly attached to the structure, it is hinged. During normal operation, the mechanism locks it into its position, forcing the whole structure to follow the alignement of the tail with the wind direction.
When the wind speed goes above 100km/h, the pressure acting on the surface of the plate will produce a high enough force (F wind, in the picture), that will be able to overcome the force of the spring inside the nacelle, and thus move the whole lever assembly in the direction from the picture. This has the effect of unlocking the tail from the structure and vice versa.

The force on the plate, not only turns the lever, but also produces a tendency for the whole structure to turn clockwise, when looked at from above. Normally this tendency is counter-acted by the tail, which has a much longer arm and a much larger vane area, which means that it is successful keeping the rotor orientated into the wind. When the tail becomes unlocked, the nacelle becomes free to follow the tendency produced by the small plate. The relative movement shown by the tail arrow in fig. 6.2 will occur, and both tail, and plate (and thus rotor), will orientate prallel to the wind direction.

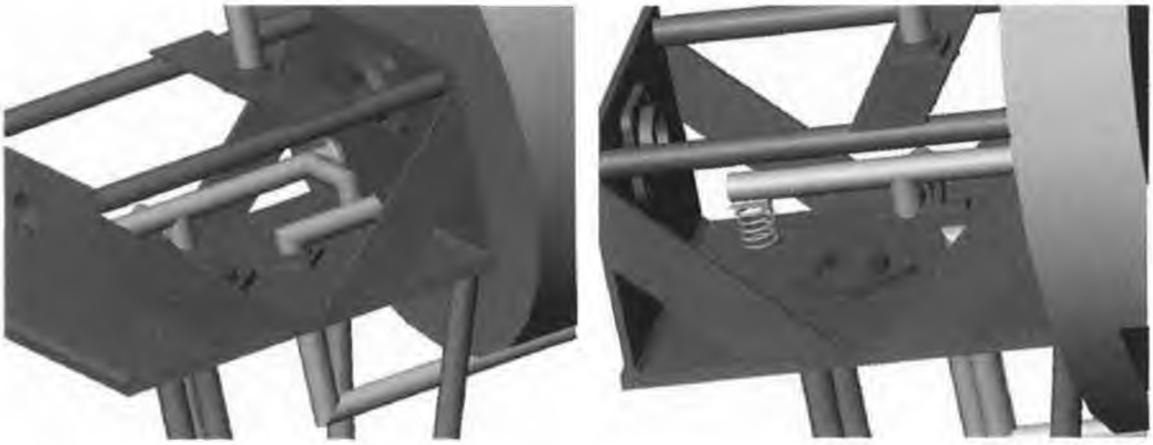


Fig. 6.3 Details of the furling mechanism inside the nacelle

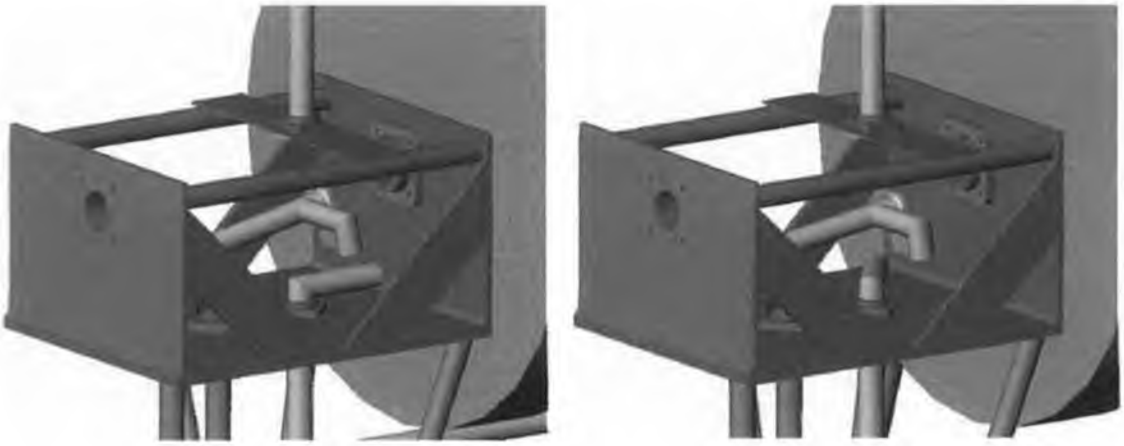


Fig. 6.4 Once released, the tail rotates relatively to the structure

The way of setting the mechanism is to balance the force of the spring with the force exerted by the wind on the plate, i.e with the plate area. Below there will be shown breifly the typical calculations. From Bernouli's law it can be deducted that the pressure on a surface placed in a streav of speed v given by: $P = \frac{1}{2}\rho v^2$, where ρ is the air density, in kg/m^3. The force should result from multiplying the pressure by the area of the plate, in the present case. However, to this calculation there is a correction factor to be applied, called drag coefficient. Every body placed in a fluid stream will be acted upod with a certain force, that is obviously proportional to the cross section of the body perpendicular to the flow, the squared flow speed, and other characteristics of the body shape, expressed through the drag coefficient, *CD*. As a conclusion, the force that acts upon the plate is: $F = \frac{1}{2} \times CD \times \rho \times v^2$.Knowing that the *CD* of a squared plade is approximately 1.17 [54], the area of the plate is 0.25m^2, and that the wind speed is 20m/s, it results that the force that acts on the plate is 75N. The wind speed reaching the plate is 20m because the plate is shaded by the blades in front of it. Considering that approximately 30% of the total wind energy is used by the rotor for producing power, and that the real wind speed should be 28m/s when the tail furls, it can be calculated that the air reaching the plate has a velocity of 20m/s. The force acting on the plate is amplified by the ratio of the levers with which act the plate force and the spring force. It results that the force oppsed by the spring should be 650N. If the spring force is lower than this, then the mechanism will deploy at a lower wind speed, and vice versa.

6.3 The Rotor Calculations

It is obvious that for the stall control to be efficient the aerodynamic calculations have to be performed for finding out exactly the pitch that is required for the blade to reach its limit of efficiency at the desired wind speed. However, there are many steps to follow up to that stage, and they are described in the next pages.

The first thing that has to be decided when designing the rotor is how much power does it have to deliver.

$$W = C_p \times \frac{1}{2} \rho A_1 V_0^3$$

Considering that some data is available from the Proven turbine, which has a rotor diameter of 5.6m and it delivers 6kW at 12m/s wind speed, a first estimation of the power output of the new turbine can be performed for a rotor diameter of 5.8m, slightly higher than the WT6000 figure, considering that the power rating has to be slightly higher as well (6-8kW range).

$$W = C_p \times \frac{1}{2} \times 1.226 \times \pi \times \frac{5.8^2}{4} \times 12^3 = C_p \times 27.987 kW$$

It is known about the power coefficient that, as explained by the Betz theory, it cannot be higher than 0.59. Values for the power coefficient range from 0.2 in the case of a wind device relying on drag to produce the power, to 0.45 for a modern wind turbine, relying on lift, a good example being the megawatt scale Danish turbines.

Considering that the new turbine relies on lift, it is more likely to get a power coefficient closer to 0.4 rather than 0.2, so a first approximation of the power coefficient of 0.3 should be covering.

$$W = 0.3 \times 27.987 = 8.4 kW$$

Taking into account that the target power rating is between 6 and 8kW, a first approximation for the power rating at 8.4kW can be considered satisfactory.

The next step is to calculate the actual forces of lift and drag that the blade is generating, following the blade element theory method, described in chapter three, and from their sum will result the torque and the thrust that the blades are producing.

The blade element theory calculates the output starting from the data about an existing rotor, which is typical for a verification method rather than a design one. However, the way to use it for the design phase is to decide the initial dimensions of the blade, verify the output, and then, if necessary, modify accordingly the parameters of the blade. The following three equations have to be repeated iteratively for each station along the blade length until *a* and *a'* converge towards their real values:

$$\frac{a}{1-a}=\frac{\sigma R}{8r}\left(\frac{C_L\cos\Phi+C_D\sin\Phi}{\sin^2\Phi}\right);\ \frac{a'}{1+a}=\frac{\sigma R}{8r}\left(\frac{C_L\sin\Phi-C_D\cos\Phi}{\sin\Phi\cos\Phi}\right);$$

$$\tan\Phi=\frac{V_0(1-a)}{\omega r(1+a')}=\frac{R}{rX}\left(\frac{1-a}{1+a'}\right)$$

As it was stated in chapter three, the values for the lift and drag coefficients C_L and C_D should be updated between iterations, because the changes of the Φ angle should modify the value of the angle of attack α, and consequently the lift and drag coefficients. In the present case, the variation of Φ changes the pitch angle θ, instead of the angle of attack α, because this is the design phase, and the pitch angle is not decided yet, but α is decided and it has a fixed value, enforced by the condition of the blade to become stalled at that combination of wind speed and rotor angular speed.

It has been decided that the blades will be shaped on the basis of the NACA 4415 airfoil, the designation meaning, like it has been explained in chapter three, that the airfoil has a thickness representing 15 percent of the chord length, the maximum camber is 4% of the chord length and the position of the maximum camber is at a distance from the leading edge equal to 40% of the chord length. The NACA 44xx series have been intensely used for wind turbine blades, and thus data about them is easily found. The most common are NACA 4412 and NACA 4415, and 4415 has been chosen because its higher thickness accounts for higher strength relative to the bending moment produced by the wind thrust, and it also increases slightly the lift coefficient, thus improving the performance. [31]

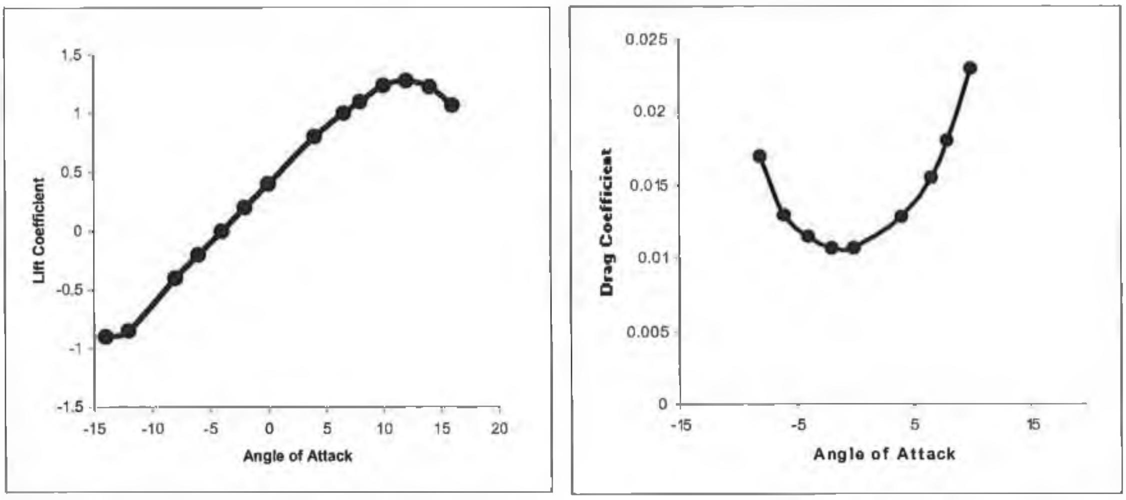


Fig. 6.5 Lift and drag coefficients for NACA 4415

The airfoil being decided, the lift and drag coefficients can now be found from tables, the charts above being taken from Abbott and Von Doenhoff - "Theory of Wing Sections – Including a Summary of Airfoil Data".The coefficients are given for a Reynolds number of 3.0×10^6.

Applying the formula for the Re number $\mathrm{Re} = \frac{velocity \times length \times density}{viscosity} = \frac{Vc\rho}{\mu} = \frac{Vc}{\nu}$, for a chord length of 0.5m and a relative wind speed of 50m/s, and considering that at sea level Re = $69000Vc$, it results that in the present case Re = 2.0×10^6. The lowest Re number for which information is given is 3.0×10^6, but the errors that occur because of that are negligible, firstly because the behaviour is similar for that range of values, and secondly because the blade element theory cannot be very accurate, making the errors due to inaccuracies in the lift and drag coefficients insignificant.

Looking at the momentum theory equations it can be noticed that there is more information required: the actual length of the profile chord, the wind speed and the blade rotational speed, that are both used for calculating the tip speed ratio. As it has been already explained, the tip speed ratio is the ratio of the tip speed to the wind speed:

$X = \frac{\omega R}{V_0}$. The chord length and consequently the profile thickness have to be larger at the root of the blade than at the tip, for improving the strength at the blade root where the maximum bending moment occurs. It has been decided to have a 0.5m chord at the root that decreases linearly to 0.25m at the tip.

The calculations have been performed for 12 stations along the blade length, starting at the tip, at 2.9m distance from the rotor axis of rotation and ending at the blade root, at 0.5m distance from the axis. The 0.5m at the blade root are not airfoil shaped and thus not producing any useful torque as that space is reserved for the blade connection to the hub.

At the blade tip, the analysis was performed on smaller slices, only 0.1m wide, and towards the root the distance between adjacent sections was increased to 0.25m because the most of the torque is generated by the outer third of the blade, so lower accuracy for the root will not influence the results significantly.
the solution was to input all the data and the equations manually into a Microsoft Excel chart and perform the iterations for each of the twelve sections.

The tables in *Appendix 3* show the iterations corresponding to each blade section used for the analysis.

The main purpose of these calculations was to find out the values of the two interference coefficients, *a* and *a'*, that are necessary for calculating the torque and the thrust that each of the sections considered is generating.

In each table can be noticed the last two columns on the right, containing the values for *a* and *a'*, and how their value converge from iteration to iteration towards the final value. Each iterative process has seven steps because it proved that so many are necessary for the changes between iterations to become insignificant.

These calculations also provide the information about the pitch angle of the blade, which can be found out by subtracting the desired angle of incidence α, from the angle resulting directly from the calculations, ϕ.

In the present case, it has been decided that the desired angle of incidence is 13°, because that is where the blade is stalled. However, for this profile, the stalling process begins at 10°, and between 10° and 13° the lift coefficient continues to increase, increasing with approximately 15%, before starting to drop when the angle of attack goes beyond 13°. It also has to be taken into account that from the moment of stalling, at 10°, the drag coefficient also begins to increase, maintaining the performance rather constant between 10° and 13°, after which the performance suddenly starts to drop.

It can be noticed that from a radius of 2.25m up to the tip, at 2.9m, the resulting ϕ angle varies from 12.3° to 10.3° respectively, so for obtaining an angle of attack of 13° it would be necessary for the pitch angle θ to vary from –0.7° to –2.7°. It might be remembered that in the second chapter the observation was made that some of the Dutch windmills had negative angles of attack at the tip of the sale, something that must have looked wrong in that age when no theory about aerodynamics had still been developed. One can only admire their experimental skills and the correctitude of their results, which can now be demonstrated mathematically. However, it has to be stated clearly that it is only the combination of rotor speed, blade length and desired stall control that lead to this special situation, and the present case is an exception, rather than the rule.

The result of the calculation indicates that the pitch should vary from 30.7° at the root to –2.7° at the tip. A blade conforming this kind of shape should perform very well at the speed for which it is designed, i.e. in this case 180rpm and 12m/s wind. The problem with small wind turbines is that they cannot be brought up to speed and they have to start by themselves. When the rotor is stationary and the wind starts to blow hard enough for the electricity generation to begin, the blades are deeply stalled, because the relative speed has only one component, the wind. Once the blades start to move the angle of attack decreases rapidly to its normal operating value.

When the blades are starting to rotate, it is only relying on drag-type forces to do that. If the blade has negative pitch at the tip, the tendency of the drag forces generated at the root of the blade to move it in the correct direction will be opposed the drag forces generated at the tip, which will try to rotate in the opposite direction. This explains why a blade having this shape will not start by itself, or, even worse, it might even start to rotate in the wrong direction.

That is the reason why the blades of the new turbine will feature 0° pitch from 2.25m radius to the tip radius, which will ensure that the rotor will start, and it will also yield for a 10.3° angle of attack at the tip, so the blade will still be stalled, only that it will be a gradual stall from a deeper one at the root to a lighter one at the tip. This is not necessarily dangerous, because once the wind speed will reach 15m/s the angle of attack will be 13° at the tip as well, and the performance will drop suddenly, especially if it is considered that the rest of the blade will be even in a deeper stall state.

The results of the calculations have been gathered in the following table, for calculating the overall torque and thrust the rotor is generating, the power being easily calculated afterwards by multiplying the torque by the angular velocity.

r	dr	ϕ	c	a	a'	ρ	Vo	ω	dT	dQ
2.80	0.10	10.20	0.25	0.29	0.011	1.226	12.0	18.5	127.90	57.16
2.70	0.10	10.50	0.26	0.30	0.012	1.226	12.0	18.5	125.79	53.54
2.60	0.10	10.80	0.27	0.30	0.013	1.226	12.0	18.5	121.13	51.25
2.50	0.10	11.20	0.28	0.31	0.014	1.226	12.0	18.5	118.64	47.38
2.25	0.25	12.34	0.31	0.31	0.018	1.226	12.0	18.5	266.93	109.49
2.00	0.25	14.37	0.34	0.27	0.021	1.226	12.0	18.5	218.63	98.10
1.75	0.25	16.51	0.36	0.26	0.027	1.226	12.0	18.5	186.74	83.69
1.50	0.25	19.34	0.39	0.25	0.036	1.226	12.0	18.5	155.99	70.23
1.25	0.25	23.13	0.42	0.23	0.049	1.226	12.0	18.5	122.78	57.34
1.00	0.25	28.24	0.45	0.20	0.072	1.226	12.0	18.5	88.74	45.01
0.75	0.25	35.08	0.47	0.19	0.117	1.226	12.0	18.5	64.02	30.34
0.50	0.25	43.69	0.50	0.18	0.236	1.226	12.0	18.5	40.93	18.65
								Total	**1638.23**	**722.19**

Table 6.1 The calculations for the total thrust and torque

The formulas used for calculating the torque and the thrust produced by each section have been discussed in chapter four:

$dT = \rho V_0(1-a)(2\pi r dr)2(aV_0)$ $dQ = \rho V_0 r(1-a)(2\pi r dr)2(a'\omega r)$

The total thrust generated at 12m/s wind speed and 180rpm is $T = \sum_{i=1}^{i=n} dT = 1640N$ and the torque produced is 722 Nm. It results that the power is: $W = \omega \sum_{i=1}^{i=n} dQ = 11.9kW$.

It can be noticed that the power resulted from the calculations is considerably higher than the first estimation.

Considering that the total power available from the wind crossing the area swept by the rotor is approximately 28kW, it results that the power coefficient is 0.42, considerably higher than the 0.3 coefficient on which the first estimation was based.

The Proven wind turbine covers a smaller area, and the total power from the wind is only 26kW, and its power rating is 6kW. It has to be remembered that the generator actually delivers 6kW, which means that the rotor should be able to deliver 7.5kW, considering that the generator is not 100% efficient. The required power estimation of 7.5kW relies on the fact that the efficiency of a synchronous generator can be as low as 80%. [5]

Based on the data above, it can be calculated that the power coefficient of the Proven WT6000 is 0.28, which compares to the 0.42 figure obtained for the new blades.

The explanation of this difference in efficiency is that firstly the new blades have been designed to operate at the highest angle of attack possible, which maximises the performance by maximising the lift coefficient. The reason for that was for the blades to be at the upper limit of performance at a certain wind speed, which leads to their immediate drop of performance when the wind speed is increasing over that limit.

The Proven turbine has a pitch angle of 5° at the tip of the blade while the new design blades have 0° pitch, which means that roughly there is a 5° difference in their angle of attack, which theoretically can account for approximately a 20% decrease of the lift coefficient. It also has to be taken into account that the new blades are twisted, optimising the performance for the whole blade, from root to tip, which could also produce a small difference on the overall efficiency. [20]

The new blades are using a thicker profile (15% of the chord compared to the 12% of the WT6000), which can account for a 2% increase of the lift coefficient. [30]

The conclusion is that there can be explained approximately 25% of the 50% difference between the coefficients of performance from the Proven wind turbine and the new turbine. However, 25% of the 50% difference cannot be explained, which means that they could be generated by the errors inherent to the blade element method that has been used for the power estimation. Consequently, it can be expected that the real performance of the newly designed rotor is about 25% lower than the estimated figure of 11.9kW, which leads to an estimation of the power output of approximately:

$(1-0.25)\times 11.9 = 8.9kW$

6.4 The Construction of the Blades

As it has been discussed in the third and fourth chapter, a blade that maintains a constant angle of attack from root to tip has a twisted shape that follows the direction of the relative speed to the blade, resulting from the combination of the wind speed and the rotational speed of the blade.

Fig. 6.6 Twisted blade

The picture above shows the blade that has been calculated to stall at 12m/s wind speed throughout its whole length. It can be noticed that the pitch at the root is higher than the one at the blade tip. There is the same NACA 4415 profile used from root to tip, but the chord length and consequently the profile thickness vary, being larger at the root for improving the blade strength, the root being obviously the place where the highest bending moment is experienced.

It can also be noticed, that besides the outer 2.3m of blade length, where the shape is determined from calculations and the angle of attack condition, at the base has been added a 250mm section, that has no pitch variation. That section has the purpose of attaching easier the blade to a metal part, that, in its turn, will be attached to the hub. The metalic balde root can be observed in fig 6.7.

Fig. 6.7 Positioning of the blade root within the blade

The material for the blades has been decided for Glass Reinforced Plastics (GRP) as it is a comparatively cheap material, it has excellent fatigue properties, and it copes well even with the more complicated shapes. The latter is an especially important property in the case of the present project, considering the twisted shape of the blades.

How to build a blade

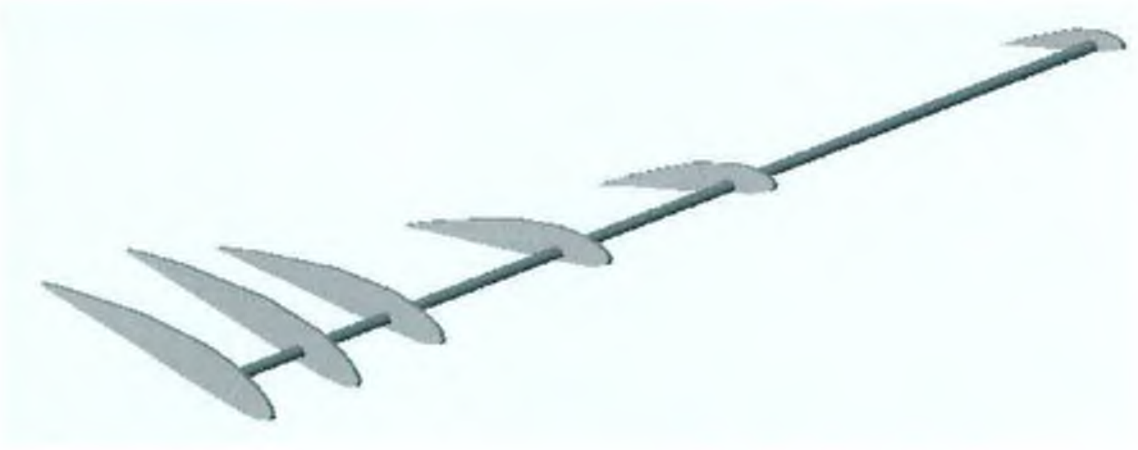


Fig 6.8 Blade skeleton

The first step to be taken is to build a skeleton like in figure 6.8. This skeleton will then be filled with a hardening paste, for example the one used for repairing the cars bodywork. After it hardens, the excess paste will be polished out until the object resembles exactly the final shape of the blade.

Appendix 3 presents the detailed calculations for each section of the blade, information that has to be used for finding out the pitch of every section of the skeleton.

Attention should be paid at the exact position of every section, because in the tables the radius *r* is the distance to the imaginary axis of rotation, not to the blade root. That is why it is indicated to take as a reference the distance to the blade's tip.

The exact shape of the sections can be found out easily, because it is a standard airfoil, NACA 4415. However, the following table can help understanding the procedure.

X	Y	R=0.5	
1	0	500,0	0,0
0,958	0,014	479,0	7,0
0,84	0,045	420,0	22,5
0,672	0,081	336,0	40,5
0,486	0,106	243,0	53,0
0,313	0,113	156,5	56,5
0,176	0,098	88,0	49,0
0,084	0,072	42,0	36,0
0,033	0,047	16,5	23,5
0,0094	0,027	4,7	13,5
0,0012	0,014	0,6	7,0
4,00E-04	0,006	0,2	3,0
0,00E+00	0	0,0	0,0

X	Y	R=0.5	
0	0	0	0
0,002	-0,005	1	-2,5
0,006	-0,012	3	-6
0,019	-0,022	9,5	-11
0,047	-0,032	23,5	-16
0,101	-0,04	50,5	-20
0,191	-0,041	95,5	-20,5
0,319	-0,036	159,5	-18
0,484	-0,028	242	-14
0,665	-0,017	332,5	-8,5
0,835	-0,0086	417,5	-4,3
0,956	-0,0033	478	-1,65
1	0	500	0

Table 6.2 Coordinates of a NACA 4415 section with a 500mm cord length

The coordinates of the points defining a NACA section are given as a certain percentage of the total cord length. For obtaining the real dimension, the values in the white columns have to be multiplied by the length of the cord, 500mm in the example. The table on the left gives the coordinates of the points defining the shape of the profile above the cord, and the one on the right the points below the cord, it can be noticed that Y values are negative.

The data obtained this way can be used to draw an MS Excel chart, like the one in figure 6.9.

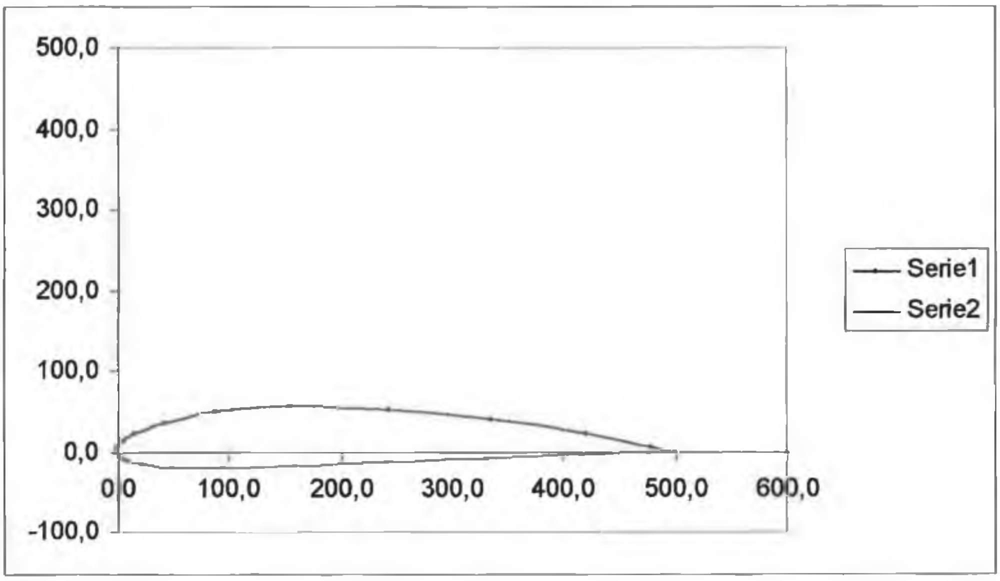


Fig. 6.9 NACA 4415 section

Once obtained, the profile can be scaled up or down to obtain the required cord length.

Over a 2300mm distance, the cord varies from 250mm at the tip to 500mm at the root. If *D* is the distance to the blade tip, and *c* is the local cord length, it can be easily shown that the relationship between them is:

$c = \frac{5}{46} \times D + 250$, where both c and D are in mm.

It has to be remebered that the blade contains an aditional 250mm section for hub fitting, which means that the last two sections of the skeleton towards the root are identical, i.e. both have a 500mm cord and the same pitch angle. The resulting overall length of the skeleton should be 2550mm. When fitting the different sections onto the skeleton's pole, it has to be taken into account that the axis of the pole should fall exactly on the cord line, at ¼ of cord length from the leading edge and obviously ¾ to the trailing edge.

Once the skeleton is ready, it is then a matter of time and skill to transform it into a replica of the blade.

The second step is to cast around the obtained pattern, the moulds. It is advisable to cover firstly the pattern with a special paint, to ensure the easy removement of the moulds afterwards.

The moulds, as the blade, are made of fibreglass, and this step of the fabrication mainly consists of covering the pattern with successive layers of epoxy resin and fibreglass cloth. The moulds should have at least 20mm thickness to insure their rigidity and durability.

After the fibreglass hardens, it has to be cut along the leading and the trailing edge of the pattern that is inside it, resulding two fibreglass half-moulds, like the ones in figure 6.10.

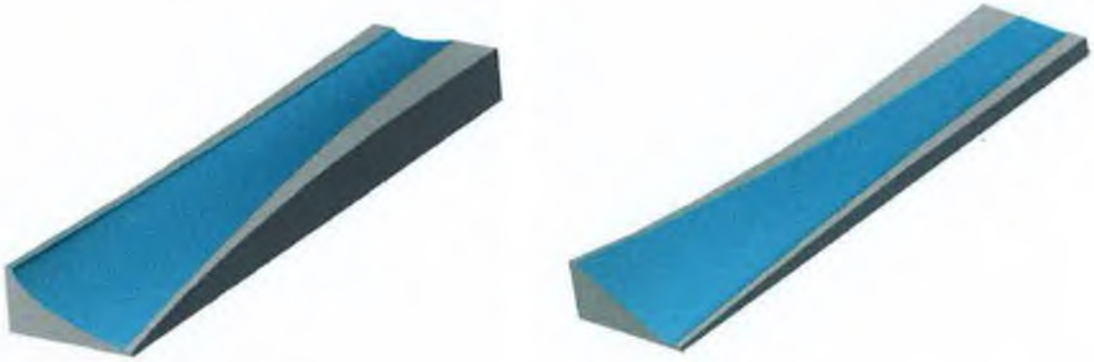


Fig 6.10

Considering that the inner faces of the moulds fit exactly the outer surface of the blade, at this stage the actual blade can be fabricated.

The third step consists of laying in these shapes layers of epoxy and fibreglass, until a thickness of 5mm is achieved. The moulds should be painted before this operation to prevent the GRP of the blade from sticking to the already hardened one of the mould.

After they harden, the two halves of the blades can be removed from the moulds and sticked together with epoxy resin. The moulds can be re-used to make another blade.

It may be remebered now that there are also the metal pieces that have to be attached to the blade. One way to achieve this is to place the metal roots in their position and then fill that part of the blade with resin. After hardening, there will be and intimate contact between the metal pice and the blade. Afterwards, holes can be drilled through the whole assembly and bolts passed through the holes. Considering that the bolts will be tightened on GRP, not metal, larger washers should be used. Four M12 bolts should be used. Actually, the only load that they take over is the one due to the centrifugal force, which can be as high as 9000N. This produces in the bolts a shear stress of 20MPa. However, it could also be taken into account that the tightening produces an extra tensile stress, which cannot be too high as it is limited by the GRP compressive strength, 140MPa. That level should not be reached, and neither should the 70MPa which is the tensile strength, so it is recommended that the stress produced in the blade material should be 30MPa. If the washer of the tensile strength has a diameted of 25mm, then the ratio between bolt cross sectional area and the one of the compressed material is 3. This means that the tension in the bolt is 90MPa. Due to the friction between materials, the shear stress will disappear, at least partially, but even if it does not do that, it will only increase the total stress with 2MPa. This concludes that the maximum stress that could occur is 92MPa, which ensures a safety factor of at least 3.8, depending on the bolt material characteristics. A detailed drawing of the blade can be found in *Appendix 4*. The detailed drawings of the root piece are in *Appendix 6*.

6.5 The Generator – General Description and Calculations

The primary decision that has to be taken when choosing the type of generator is whether it should be directly driven or through a gearbox.

Using an off-the-shelf generator presents the advantage of the lower price due to its mass production, but it cannot be directly driven because this type of generators are usually designed for working at 1500 or 3000rpm and the rotor shaft would just drive it at around 200rpm, which is too far from its operating range. Another disadvantage is that in this power range, of 6 to8 kW, the mass production generators have electro-magnets, which means that a small amount of electricity is required before electricity can be produced. Supposing that batteries are included in the wind system, there would not be difficult to excite the generator armature with current from the batteries, but a situation in which the batteries are empty could occur, in which case there would not be possible to produce electricity, even if there was enough wind.

General-purpose generators work well with large turbines inter-connected with the national grid. The grid current is connected to the armature, generating the synchronous speed, and thus applying torque to the generator shaft produces electricity, and even if the rotor speed does not vary with the wind speed, the amount of electricity increases with the wind speed due to the corresponding modifications in the torque produced by the blades. This also guarantees that the current produced matches exactly the frequency of the grid.

However, in a small wind turbine, the advantages of using a cheap generator are out weighted by the disadvantages of having to complicate the design:

- A special step-up gearbox has to be used, to match exactly the ratio between the generator and the rotor speed, consequently increasing the cost.
- Means have to be provided to excite the generator armature.
- The gearbox requires additional maintenance.
- Space has to be provided to fit the gearbox inside the nacelle.
- Typically the efficiency of this simple gearbox is about 98-99%, consequently producing a small loss of the turbine overall efficiency of about 1-2%.

The conclusion is that building a dedicated generator that works directly at the rotor speed is a better solution, and it is widely used by the small wind turbine manufacturers.

One of the main characteristics of a slow speed generator is that it has a much larger diameter that increases the relative speed between the magnetic field and the armature windings, thus compensating for the lack of a step-up gearbox. The other characteristic is that it has more poles than a general-purpose generator, which allows for producing an acceptable frequency. Whereas a generator spinning at 3000rpm needs only two poles to produce 50Hz, one that spins at 200rpm would require 30 poles for producing the same frequency. However, the frequency produced by a small wind machine does not need to meet a certain value for the frequency, and it could not do that anyway, considering that the rotor speed varies accordingly to the wind speed.

The generator used for the WT6000 turbine has a frequency of 25Hz, as mentioned in the previous chapter. It has been decided to use a similar one for the new turbine, being characterised by low speed (180rpm) and multi-pole, large diameter configuration. The 12 permanent magnets spinning at around 180rpm inside the armature, which has 18 coils, generate 3-phased alternating current at approximately 20Hz.

Considering that the power expected to be delivered by the rotor is 8.9kW, the generator should be rated at 10kW, to make sure that it has the capacity to load the rotor enough for maintaining its speed of 180rpm, which is necessary for keeping it stalled. However, once they are stalled, the blades performance decreases, and thus the full capacity of the generator could only be required for short periods of time.

Theoretical considerations and calculations

Faraday's induction law states that if a conductor is shaped such that it creates a loop, and the surface of the loop is crossed by a variating magnetic flux, a voltage, or an electro-motive force – e.m.f., will be generated in the conductor. The e.m.f. is proportional to the rate of change of magnetic flux:

$emf = -\frac{d\Phi}{dt}$, where Φ is the magnetic flux, given in Webers (Wb). $\Phi = B \times A$, where B is the flux density, in Henry (H), and A is the area of the loop, in m^2.

It is then easily understood why a coil turning between two magnetic poles, or a magnet turning inside a coil generate electricity.

Considering that it is the rate of change of flux that gives the magnitude of generated voltage, it can be shown that the maximum of this voltage is:
$E_0 = 2\pi fBAN$, where f is the frequency with which the magnetic field alternates, given in Hz, and N is the number of turns the coil has.

The way of building the generator is to have a stator "sandwiched" between two disks that form the rotor. In the stator there are placed the coils. The rotor disks have permanent magnets placed in such a way that the North poles from one disk are facing the South poles from the other, and that any two adjacent poles from the same disk do not have the same sign.

This way, when the rotor turns, the stator windings are exposed successively to N and S poles, which causes electricity to flow in the coils.

To obtain a three-phase current, which is how all the modern generators work, there are required at least two poles and three windings, but there are also other combinations, like 4 poles and 6 windings, and so forth. For maximising the use of the available space and increase the frequency, the present generator will have 12 poles and 18 coils.

There are a few unknowns when designing a simple and basic generator like this one:

- The magnetic field produced by the magnets
- The cross sectinal area of the coils
- The number of turns
- The magnetic permeativity of the coil core
- The frequency with which the field changes sign.

It has to be stated clearly that once these factors are fixed, the voltage produced is decided. However, theoretically, there is no limit for the power. A generator will produce, or will have the tendency to produce all the power that is required from it. And it will work like that, as long as it is being delivered the necessary torque, and the intensity in the windings does not exceed a certain level, otherwise the wires will overheat and eventually burn. The problem is that generally when a conductor heats up, its electrical resistance increases as well, causing it to produce even more heat. That explains the fact that the maximum power that can be generated is just a function of the phisical limitations of the materials.

For a certain amount of power, there could be different combinations of voltage and intensity. Typically, it is preffered to have higher voltage and lower intensity, because high voltage currents are transmitted with better efficiency.
The design of the generator consists mainly of decide the values for the factors mentioned above.

The magnetic field produced by the magnets depends on the choice of the permanent magnet material. In the present case, the choice is for ceramic permanent magnets (hard ferrite), graded "ceramic 10", which present a few advantages:

- Cheap
- Higher magnetic flux than other non-rare earth magnets
- Hard to brittle, due to ceramic nature
- Can be delivered in the required shape and dimension

Their magnetic field strength is 4000 Oe (Oersted). However, in the ecuation it is needed the flux density, in Henrys, which is obtained by multiplying this value with the magnetic permeability of the medium inside the coils, i.e. the core.

The magnetic permeability of materials is generally given in relation to the permeability of the vacuum, which is: $\mu_0 = 4\pi \times 10^{-7} = 1.256 \times 10^{-6} \frac{H}{m}$, and $\mu = \mu_0 \times \mu_r$. For example, μ_r for air is 1, and for iron is 5000.

The cross sectional area of the coils can also be considered as the cross sectional area of the magnetic core around which the coils are wrapped. It has been decided that the core will have a diameter of 100mm, meaning the cross section has an area of 0.0078m^2, and it will be made of iron. There will be 35 turns on each coil.

The frequency with which the poles change is given by the number of poles on one disk and the angular velocity of the rotor. At maximum power this should be 20rad/s, and because there are 12 poles, the frequency is 19.2Hz.

Now all the information is available to calculate the magnitude of the alternating voltage produced by the generator at maximum power: $E_0 = 2\pi fBAN = 240V$.

It is known that the effective voltage is $\sqrt{2} = 1.41$ times lower than the value of the mugnitude, which means that the effective voltage is 170V. This leads to the conclusion that the effective current flowing through the coils, when the 18 windings are generating a power of 9000W, is 3A.

Considering that the resistivity of the copper wire, of 2mm thickness, is 1.71x10^{-4} Ω/m, and that there are approximately 11m of wire in every winding, it results that the total resistance of one coil is 0.002 Ω. Knowing that $P = IR^2$, it can be calculated that the power dissipated through heat, per coil, is 1.2x10^{-5}W, which is a very low value. As a common sense comparison, one can imagine the heat generated by an 100W light bulb, and then divide it by 10^7 to obtain the heat generated by the coil.

6.6 The Construction of the Generator

Similarly to the blade, the generator will be built from polyester resin, that will be poured in the corresponding moulds. The operations should be easier, however, because the shapes are basic: the rotor is made of two disks, and the stator has a toroidal shape. The free space at the center of the stator has the purpose of letting through the short shaft connecting the two rotor disks and at the same time avoid the waist of materials.

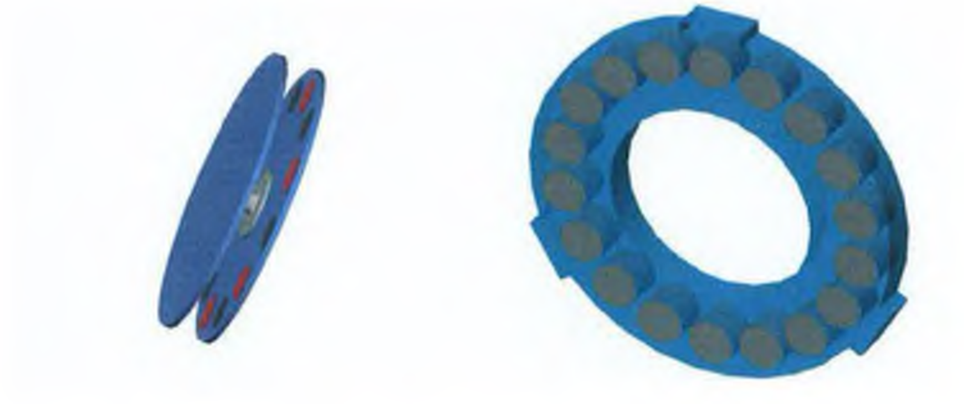


Fig 6.11 Generator components - rotor and stator

Figure 6.11 shows the rotor and the stator in their final shapes. There can be noticed the N and S alternance in the positioning of the permanent magnets in the rotor, and the windings with their cores inside the stator.

The procedure will be to place the magnets, or the core-winding assemblies at their correct positions inside the moulds, and then pour the mixture, which will fill naturally the remaining spaces. Because there is no high structural loading on the generator, the resin can be mixed with talcum powder, which is a cheap filler, and thus reduces the overall spendings.

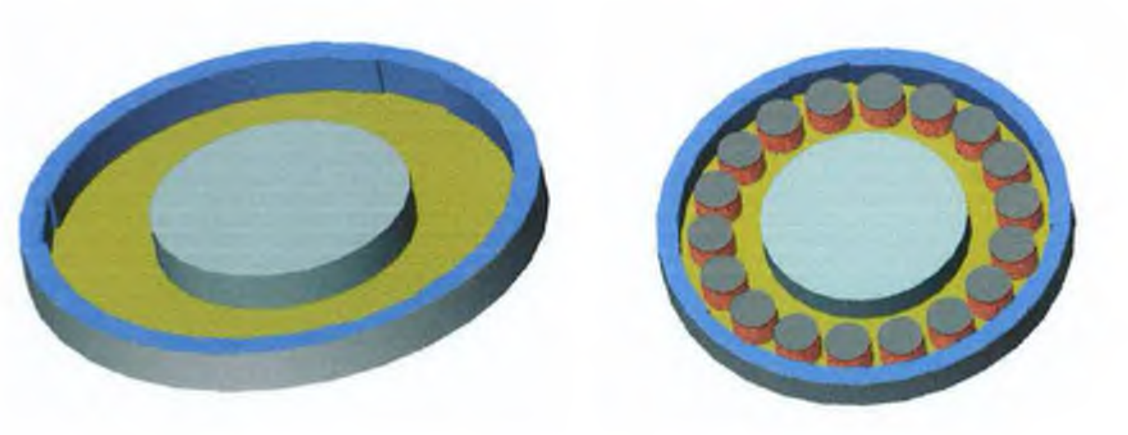


Fig. 6.12 Stator mould

In the figure above it can be seen a mould for the stator, and the positioning of the windings within the mould, before pouring the resin. Care should be taken when placing them, firstly that they should be equally spaced, and secondly that the orientation of the coils, i.e the winding direction should be the same.

Fig. 6.13 Iron core before and after the winding has been added

All the coil ends should be connected to wires that will all go out of the stator at the same place. Each wire should be labeled for knowing to which coil belongs, and which end. In this respect, the use of colured wires (black and red for example), would ease the work. For connection, it should be known that every third coil has the same phase, and their ends can be connected together, for example the "plus" wires from coils 1, 4, 7, 10, 13 and 16. After all the connections have been made, there should be 6 groups of wires, 2 for each phase. They can now be star or delta connected. The star connection of the three phases yields for higher voltage, the delta connection maintains the voltage from the single phase but increases the current. However, the generator connection to the electronic controller, and the controller itself are to be made subject of future developments.

In the end, there should be four elements available to be put together and form the generator: the two rotor disks, the shaft that connects them, and the stator. Actually, the generator does not exist as a separate part, it will become functional only when mounted in the top structure of the turbine, as shown in the following images.

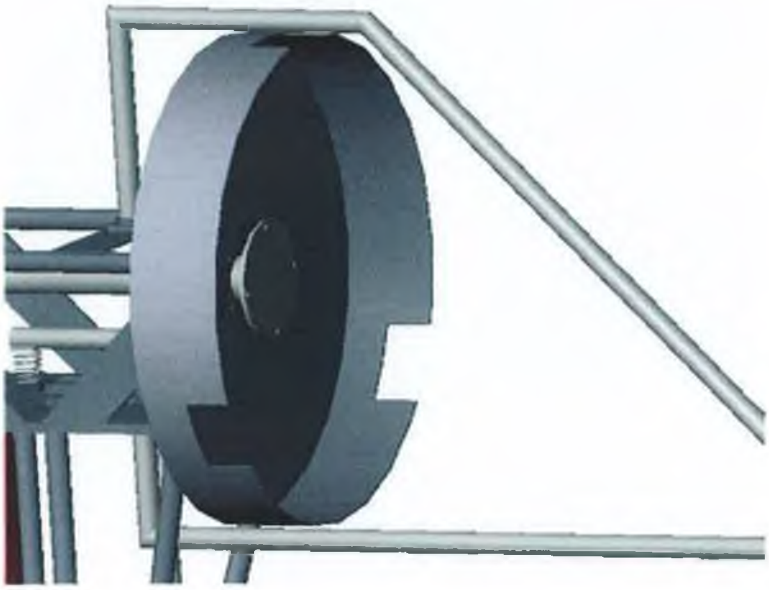


Fig. 6.14 Nacelle without generator

As it can be noticed, the main shaft, driven my the blades, ends on the generator's side with a flange, on which the first disk will be mounted. There are four holes in the flange that correspond to the four holes in the disk, through which M12 bolts are passed for fixing them together. The same bolts fix as well the flange of the second shaft that will drive the second disk.

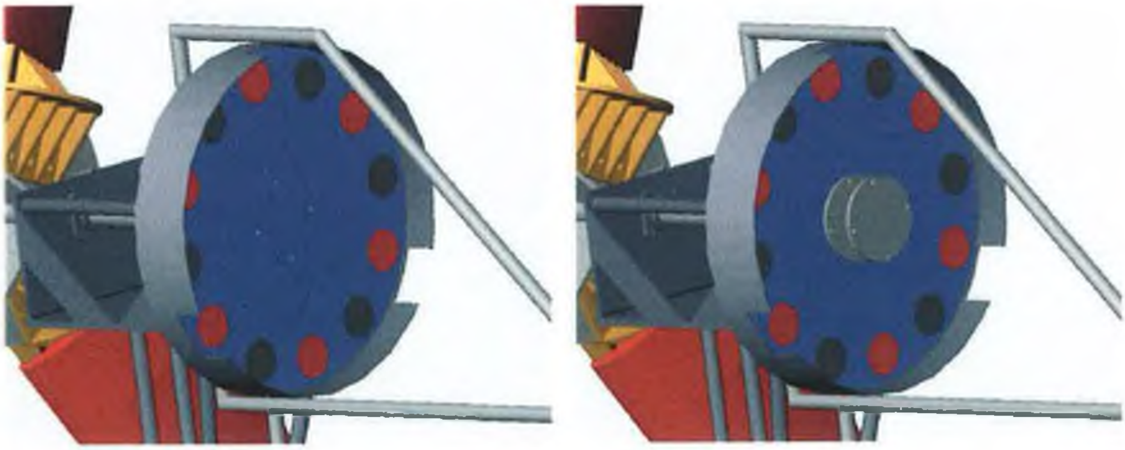


Fig. 6.15 The first rotor disk is mounted on the main shaft

As it can be noticed, the first disk is tghtened by the bolts between two identical flanges: the one from the main shaft and the one from the short shaft, which can be seen in the picture.

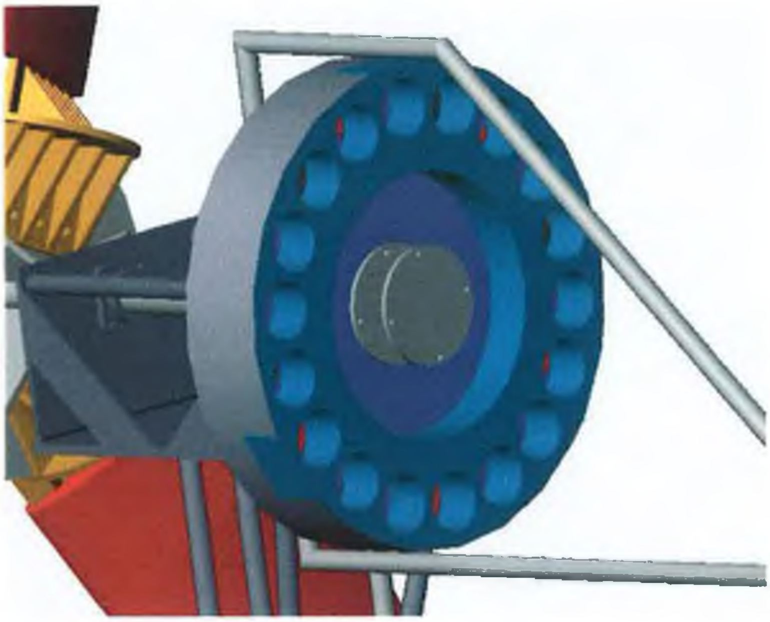


Fig. 6.16 The stator is fitted into its location

The second step is to mount the stator. The outside diameter of the stator should fit exactly the inside diameter of its location in the nacelle. It can also be noticed that the nacelle and the stator are shaped in such a way that it prevents the latter from spinning or sliding in too much and touch the first disk. Once in the position, two small holes (3-4mm) should be drilled through the stator housing and the stator itself and two wood screws screwed into these holes to prevent the stator from moving outwards and hit against the second disk, which is showed in its position in the figure below.

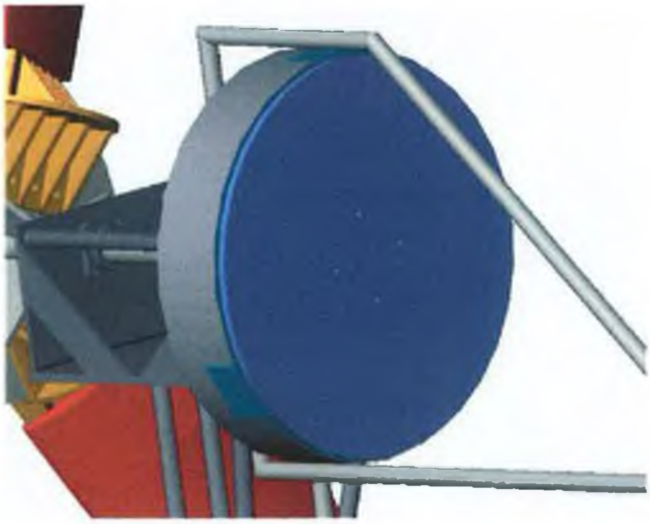


Fig. 6.17 Outside view of the completed generator assembly

When fitting the second disk, care should be taken at its exact position. As mentioned earlier, the N poles from one disk should be facing the S poles of the other disk.

6.7 The Nacelle

The nacelle is the structure that holds together mainly the rotor, the shaft and the generator, and it also provides the connection to the tower.

In its simplest shape it has to feature a base plate on which there are mounted the bearings that hold the shaft, the thrust bearing that allows the whole structure to rotate around the tower axis, and the generator.

The nacelle that has been designed for the present project is a simple welded steel structure, whose design started from the base plate, which has then be re-enforced in the places where it was most likely to yield high stresses and displacements. The nacelle has been designed for matching with a tower mount identical to the one that fits into the WT6000 top structure, as it is simple and no advantages would result from any changes in that area.

The bedplate has to withstand the loads due to the wind thrust and the top assembly weight, which concentrate in the thrust bearing that connects it to the tower mount. A structural analysis of the nacelle is described in the following chapter, and a detailed 2D drawing of it can be found in *Appendix 5*.

Fig. 6.18 3D model of the nacelle

Inside the nacelle can be found three identical tappered roller bearings, 70mm inside diameter and four bolt flanges, that should be able to withstand both radial and axial loading. The two bearings holding the shaft are loaded radially due to the blades and hub weight – 1000N, and the weight of the generator disks – 200N. The axial loading comes from the wind thrust, which is no higher than 2900N.

The thrust bearing bolted on the base plate should be the same with the previous two, for avoiding the errors that might occur because all of them have the same inside diameter, and consequently similar outside dimensions. Its axial loading is 5000N, due to the weight of the whole structure, and the radial loading is 2900N, from the wind thrust.

There are also three smaller bearings, 40mm inside diameter, out of which two of them support the furling tail and one holds the pulley that locks and unlocks the tail.

Inside the structure there will also be the main shaft, which at one end will carry a hub on which the blades will be mounted, and at the other end there will be fitted a flange for connecting to the generator rotor.

Fig. 6.19 Hub, main shaft and connecting flange

The hub and its gussets are welded to the shaft. Althaugh this is the cheapest way of assembling rigidly two pieces, it cannot be used as well for the flange end, because the shaft has to be slided firstly through the two bearings of the nacelle. Only after that the flange will be attached, by means of three M12 bolts that can be screwed into three threaded radial holes made in the shaft. The other option is to have normal holes into both the shaft and the flange, and use bolts and nuts. The nuts can be welded inside the shaft for easier tightening. Detailed drawings of these two parts can be found in *Appendixes 7* and *8*.

The material chosen for the top structure and the hub assembly is a typical structural steel, ASTM A242 steel type1, which is widely used in constructions and thus is comparatively cheao and offers good mechanical strength.

6.8 The Tower

The main choices for the tower have been presented already in chapter two, and the general requirements for a small turbine pole have been reviewed while presenting the mast of the WT 6000 in chapter five. However, the main aspects will be highlighted again in the following paragraphs.

There are mainly two types of tower for the turbines: tubular poles and lattice structure poles. Both of them can be either guyed towers, which means that the actual pole only takes over the weight of the turbine, the wind thrust being taken over by the guy cables, or they can be freestanding towers strong enough to take over all the loads, in which case they are bolted into a concrete foundation.

Typically, guyed masts are cheaper than freestanding ones and lattice structure towers are lighter and slightly cheaper then tubular ones while offering the same or even more strength. Consequently it appears that for a certain required height and strength a guyed lattice tower is the cheapest solution while the most expensive one is a tubular self-supporting tower. A brief search on the Internet reveals that a guyed tower costs around half the price of a freestanding one. [53]

Due to its construction, a lattice pole creates less turbulence, both upwind and downwind, improving the conditions in which the rotor works. A guyed mast, whether it is lattice or tubular, has typically less impact in the air flow as well, considering that a self supporting tower has greater outside dimensions to yield for higher strength. [40]

Apart from the funds available for purchasing a tower and the space available that can decide between a guyed and a freestanding tower, the aspect of the environmental impact has also to be discussed.

It is generally considered that a simple self-supporting tower is more visually pleasing than a truss one, and it can be noticed that all the modern large scale turbines are featuring this solution. However, the visual aspect is particularly sensitive in the case of large turbines, with rotor diameters of 40-60m and similar hub heights, which can obviously can be seen from very far away, especially that normally they are positioned higher than everything around them, for maximising the speed and minimising the turbulence of the wind reaching the turbine rotor. A small wind turbine, reaching a height of only 15-20m has far less impact on the scenery, and there are only the financial and the space considerations that decide the choice of the tower.

As a conclusion, the tower choice should be left for the potential buyer to decide upon, the task of the manufacturer being to state clearly the loads that it has to withstand. In order to fit the turbine to the tower, a tower mount should be made available for purchasing separately.

The tower mount and the tower suggested for the new turbine are identical to the ones used for the WT6000, as it is a visually pleasing solution and it is also suitable from the structural point of view, considering that the new turbine exerts 5 times less thrust than the Proven turbine, 2900N compared to 10000N, the difference coming from the fact that the new turbine is made to furl out of the high winds, rather than withstanding them.

6.9 Conclusions

In this chapter there have been presented the main choices that are available when designing a small wind turbine.

There has been decided to use an upwind configuration for the rotor, 3-bladed, with the blades including the stall control philosophy. For achieving that, the complex calculations that determine the blades shape have been performed. Using the calculations the final shape of the blade has been determined, and the fabrication process of the blade has been presented. There has also been designed a system for attaching the blade to the hub. The hub has been desgned as well.

The design of the generator has been completed, starting with the theoretical calculations for deciding parameters like voltage, current, power and frequency. The final shape has been decided and the manufacturing process has been detailed. Also instructions for assembling on the nacelle have been given.

The design of the nacelle has been performed by combining structural strength, ease of manufacturing by using basic shapes, and of course meeting the functional aspect, which is to accommodate the shaft, the generator and the system for tail furling.

For the tower there have only been presented the choices with their advantages and disadvantages, the decision of the tower having to be made by the potential buyer according to the particular situation.

The detailed 2D drawings of the parts that have been designed can be found in the appendixes at the end of the thesis.

Chapter 7 – Structural Analysis

7.1 Introduction

This chapter will present the structural verifications that have been undertaken for completing the design of the turbine. All the parts analysed have been designed with the Solid Works software, which is a powerful and at the same time user-friendly tool for 3D modeling. The parts have then been imported directly into the stress-analysis software, which can analyse both simple objects as well as assemblies, which can too be created with Solid Works. The simplest, and most realistic manner of doing an analysis would have been to analyse the whole assembly of the turbine. This assembly was created in Solid Works, as it can be seen in figure 6.1, but unfortunately the capabilities of the computer did not allow this entire analysis to be performed in only one step. The procedure was then to isolate and analyse separately the components that form the normal chain of load transmission: the blades, the hub and the shaft, and ultimately the top structure that in its turn transmits everything to the tower.

7.2 The Blades

As it has been described in the previous chapter, the blades are made of glass-reinforced plastics. The material consists of successive layers of epoxy resin and fibreglass cloth. Supposing that the layers are spread in an imaginary X-Y plane, with their thickness being represented on the Z axis, it can be understood why the GRP is stronger when the load is in the X-Y plane, a tension load on the Z axis would tend to tear apart the layers. The difference is due to the fibreglass cloth, which obviously can only take over tensile loads in the X-Y plane. However, the blade has to withstand mainly a bending moment due to the wind thrust and an axial force that tends to stretch the blade, which is the centrifugal force. Both are translated into tension and compression at the blade root, which means that the loads are located in the imaginary X-Y plane of the blade surface, which is obviously a desirable situation from the structural point of view.

The wind thrust also generates a shear stress, which is highest at the blade root. Considering that the thrust for one blade is approximately 650N, and that the area of the root section is 6000mm^2 (based on a chord length of 500mm and a wall thickness of 5mm), it results that the highest shear stress is 0.1MPa, which is insignificant.

The first step in the strength analysis is to state clearly what are the capabilities of the material. GRP, by deffinition, is a material composed of a hardening polymer reinforced with fibreglass. Its mechanical properties, which are of interest here, depend on a few factors like the type of the polymer resin used, the mass ratio between resin and fibreglass, and the type of fibreglass used, i.e whether the fibres in the cloth have or not a prefferential dierection.

The fibreglass mat that will be used for the blades should be symmetrical, so it will have the same strength regardless of the direction of the load, as long as it is contained in the layers plane.

As an indication, the content of fibreglass should be 30%, but it is difficult to control exactly. The initial quantities of resin and fibreglass that will be used could be prepaired to respect exactly the 30% proportion, but then the process of laying the layers being manual, can produce certain variations. Obviously, the more skilled are the persons performing this task, the better.

The typical values for cast epoxy resin, *non reinforced*, are the following: [55]

Ultimate tensile strength	$\sigma_u = 70$ MPa
Tensile yield strength	$\sigma_y = 60$ MPa
Modulus of elasticity	E = 2.6 GPa
Compressive yield strength	$\sigma_c = 140$ MPa
Density	$\rho = 1200$ kg/m^3

The mechanical properties of GRP, containing 30% fibreglass and obtained through the process of laying up in moulds, have been obtained from a company, Owens Corning, that have this domain of activity and have tested their materials by the American standards, ASTM D638. The properties are listed below:

Ultimate tensile strength	$\sigma_u = 82$ MPa
Tensile yield strength	$\sigma_y = 70$ MPa
Modulus of elasticity	$E = 7$ GPa
Compressive yield strength	$\sigma_c = 150$ MPa
Density	$\rho = 1370$ kg/m^3

The blade is exposed to two loads; one is due to the thrust and the other one due to the centrifugal force. First, an analysis over the thrust force will be presented, as there are some interesting details to be highlighted.

The maximum thrust on the Proven WT6000 is 10,000N, and correspond to a wind speed of 160km/h, or 45m/s. The thrust calculated for the nominal speed of the new turbine was approximately 1700N. However, it has to be reminded that the turbine will not furl until the wind reaches 28m/s or 100km/h.

Both turbines have the power rated for the same wind speed: 12m/s. Their behaviour beyond that speed is different. The WT6000 starts to bend the blades backwards, thus reducing the effective area and at the same time increase the pitch. Because of this pitch increasing, the drag forces on the blade are reduced, but on the other side the lift forces continue to act, as the blade does not stall.

The new turbine has fixed blades, but they reach their maximum efficiency in a 12m/s wind, after which the efficiency decreases, because the lift forces decrease. When the wind speed is 28m/s, the blades are already so deeply stalled that the only forces acting are the drag forces. The total surface of each blade has been calculated at 2.1m^2, which includes both faces of the blade, meaning that the area opposed to the wind is only 1m^2. Starting from that data, and performing a calculation similar to the one in the previous chapter where the drag force on the squared plate of the furling mechanism has been calculated, and considering that the *CD* coefficient is 1.9, it results that the total thrust on the blades, at 28m/s, is 2900N. That translates into 970N per blade.

For the analysis the root of the blade is fully restrained, which replicates the real situation, considering that the blade is rigidly attached to the hub, through the metalic root piece.

It has been decided that the blade will be hallow, and the two half-shells that will be glued together to form the blade will have a thickness of 5mm. Based on this thickness, the area of the blade 2.1m^2 and the GRP density 1400kg/m^3, it can be calculated the weight of the blade: 15kg.

The other load is an axial load, produced by the blade's own weight, 150N, and the centrifugal force. Throughout one cycle, the centrifugal force is constant, but the weight produces an alternating loading. However, the centrifugal force, given by the formula: $F_c = m\omega^2 r$ is 9000N, considering that the mass of the blade is concentrated at 1.5m from the rotor axis. This leads to the conclusion that only 1.7% of the axial force stretching the blade varies during one complete cycle, which brings it closer to a steady stress rather than an alternating one. Further more, the total axial load is not alternating above and below zero, it is just slightly pulsating around a nominal pozitive valua of 9000N given by the centrifugal force. The conclusion is that the main fatigue loads are due to the wind gusts, not the cyclical loadings. This makes difficult to predict, and consequently to calculate the blade taking into account the fatigue aspect, considering that a more sophisticated software would be required to simulate that kind of situations. The only solution at this stage is to allow for a factor of safety of 3, which should be sufficient, considering that the analysis is already performed in the conditions of a worst case scenario.

Fig. 7.1 Meshed blade

For the analysis the blade has been treated as a shell, with a thickness of 5mm. The elements are triangular, and the size is 30mm. Unfortunately, the software only allows for forces applied on edges or surfaces of the 3D model. Pressures and moments can also be applied. However, simulating the wind thrust as an equally distributed force over a surface might lead at a final lower stress than the real one. This is why the whole force has been applied at the top of the blade. This is a situation that produces higher stresses, but this is a design verification. If the blade is able to withstand this load, than it is strong enough to cope with the real situations as well.

In figure 7.2 it can be observed that the maximum stress that occurs is 26MPa. However, this is at the top, where the force has been applied. In real life this concentration cannot occur, but the stresses at the blade root can. The colour coding of the analysis reveals that the stresses at the base are ni higher than 20MPa. The tensile yield strength is 70MPa. This allows for a safety factor of 3.5.

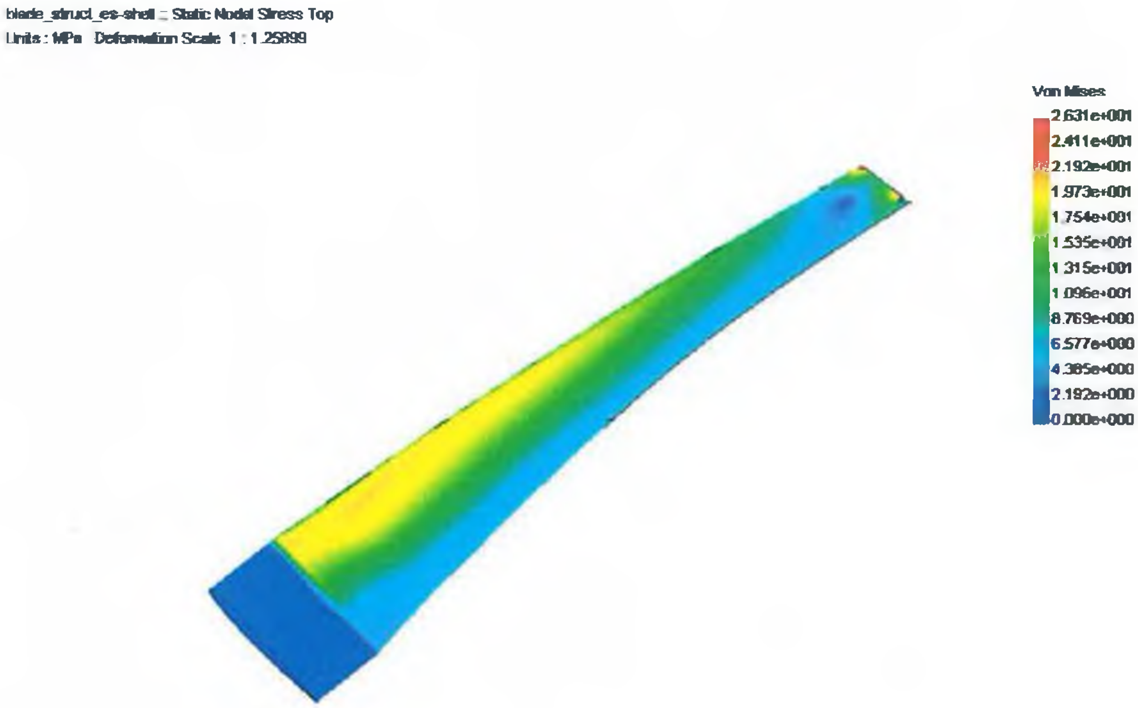


Fig. 7.2 Blade stresses

In the picture above it can be noticed that the lower part of the blade does not take over any loads, which is because they are transmitted to the metal piece inside the blade, which fixes it to the hub.

It should also be taken into account that the blade should have at least a 25 year life, which means the fatigue could also be a factor leading to failure. Although the random fatigue loading characteristic to wind turbines does not allow for an accurate simulation, as stated earlier, it can be considered that typically the fatigue yield stress is half of the static yield stress. That being taken into account, the safety factor becomes 1.5 when related to the fatigue allowable stress. Considering also that GRP is one of the best materials in what concerns fatigue-withstanding capabilities, it can be considered that the blade is strong enough and it will be able to meet its functional purpose.

7.3 The Hub

The bending moment from the blades, as well as the centrifugal forces, are transmitted to the hub, through the blades mountings.

All these have been analysed together, as an assembly, because otherwise it is difficult to simulate the fact the the blade roots, once attached tightly to the hub, are strengthening it up.

For all the components the material chosen is the same structural steel used for the nacelle. The reason for choosing it is that it represents a very good compromise between strength and price, and it also has good welding capabilities, which is of utmost importance for the present case.

The properties of structural steel, ASTM A242 type 1:

Density	$\rho = 7800 kg/m^3$
Tensile yield strength	$\sigma_{yt} = 345 MPa$
Ultimate tensile strength	$\sigma_u = 485 MPa$
Modulus of elasticity	$E = 210 GPa$
Shear modulus	$G = 80 GPa$
Poisson's ratio	$\nu = 0.28$

Composition:

C	0.15 %
Cu	0.2 %
Fe	98 %
Mn	1 %
P	Max. 0.15 %
S	Max. 0.05 %

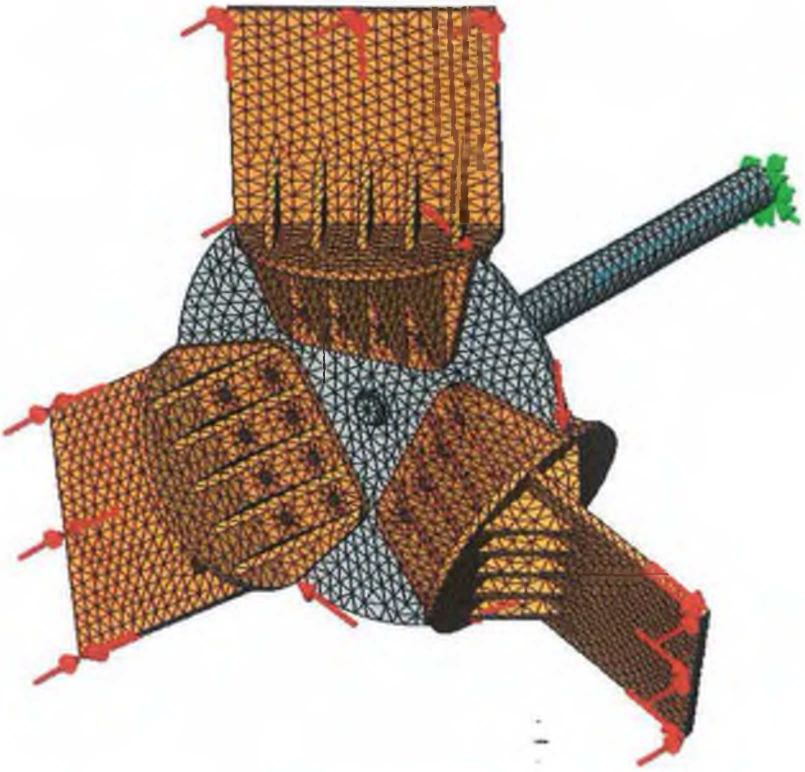


Fig. 7.3 Hub assembly - mesh

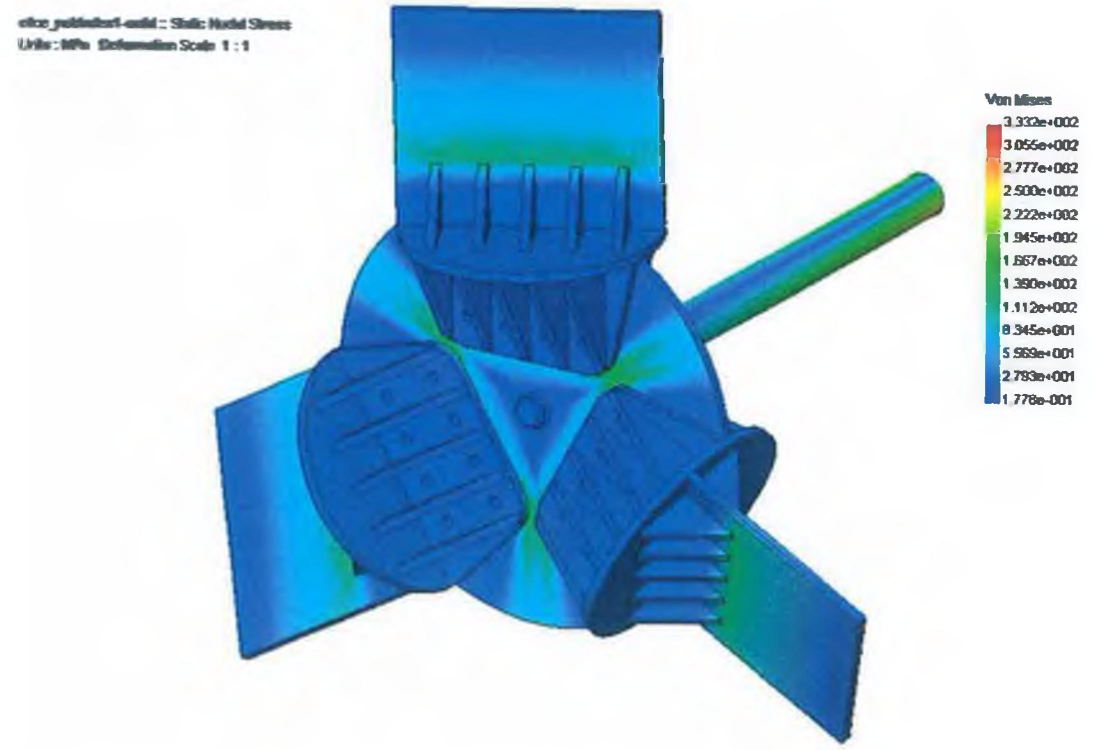


Fig 7.4 Hub assembly - stresses

The hub assembly has been meshed as a solid, with tetraedrical elements. The size of the elemnts is 30mm, but it decreases up to 10 times around holes and other special shapes. The figures 7.3 and 7.4 reflect the final version of the design. Initially, the gussets the reinforce the joint between the hub and the shaft wer smaller. After increasing their size, there were still appearing locally high stresses due to the sharp corners of the blade roots. Applying fillets solved the problem. The detailed drawings of the components can be found in appendixes 6, 7 and 8.

At the top of the connecting pieces there have been apllied the forces that have to be taken over from the blade: one that reflects the bending moment due to the thrust and the other is the centrifugal force. The axial force for each connecting piece is 10200N and the radial one is 9000N, being the centrifugal force. The 722Nm torque has also been applied to the hub plate, for simulating the load thet occurs in the shaft when transmitting it to the generator rotor.

The maximum stress that occurs is 330 MPa, which falls within the 345 MPa limit, which is the yield strength of the material. Considering that this is a worst case scenario, that the comparison is made to the yield strength not the ultimate strength and that the highest stresses occur under compression not under tension, the result can be considered satisfactory.

7.4 The Nacelle

The philosophy behind the shape that is being proposed for the nacelle has been described in the previous chapter. The nacelle is a welded structure and the properties of the structural stell used for building it have been presented in the previous section.

The bedplate has a 20mm thickness and the rest of the steel plates used are 10mm thick. All the beams used have identical cross sections, 40mm outside diameter and 5mm wall thickness. A detailed 2D drawing of the nacelle can be found in *Appendix 5*.

Fig. 7.5 Meshed model of the top structure for finite element analysis

The figure above represents the 3D model of the nacelle, meshed for the finite element analysis, the element size being the same as in the hub's case. As before, there have been used tetraedrical elements to mesh it as a solid. The red arrows represent the loads, the wind thrust and the rotor and generator weights, and the green arrows represent the restraints. The loads taken over by the front plate and front shaft bearing are 2900N axially due to the wind thrust, and 1000N due to the combined weight of the blades and the hub.

It can also be noticed that actually the generator stator is rigidly attached to the rest of the structure, becoming part of it, while the generator rotor is connected to the shaft. It concludes that the back bearing only carries the weight of the generator rotor, 400N, the rest of the generator weight, 550N, being taken over directly by the structure, not through the bearing. Other forces that have been applied are: the load due to the weight of the plate-lever assembly that locks/unlocks the tail with respect to the wind speed, which is 250N, and the reactions in the bearings that allow the tail to swivel. The tail weight is 400N, applied approximately at 2.5m distance from the hinges, which produces 3500N horizontal reactions in the bearings to conter-act the moment of the tail weight. There is as well a 400N vertical reaction to compansate for the weight itself.

The restraints have been applied in the thrust bearing and at the bottom of the structure. In the thrust bearing there is only one degree of freedom, which is the rotation around the tower axis, which is the Z axis. At the bottom there is a constraint condition regarding the translation in the X-Y plane, and there is a free rotation around the Z axis. These are exactly the moving possibilities from the real situation, where the tower mount passing through the bottom of the structure only allows for rotation around its axis. This rotation cannot occur in the present simulation because all the loads are symmetrical, there is obviously no misalignement with the wind direction to cause a swivel.

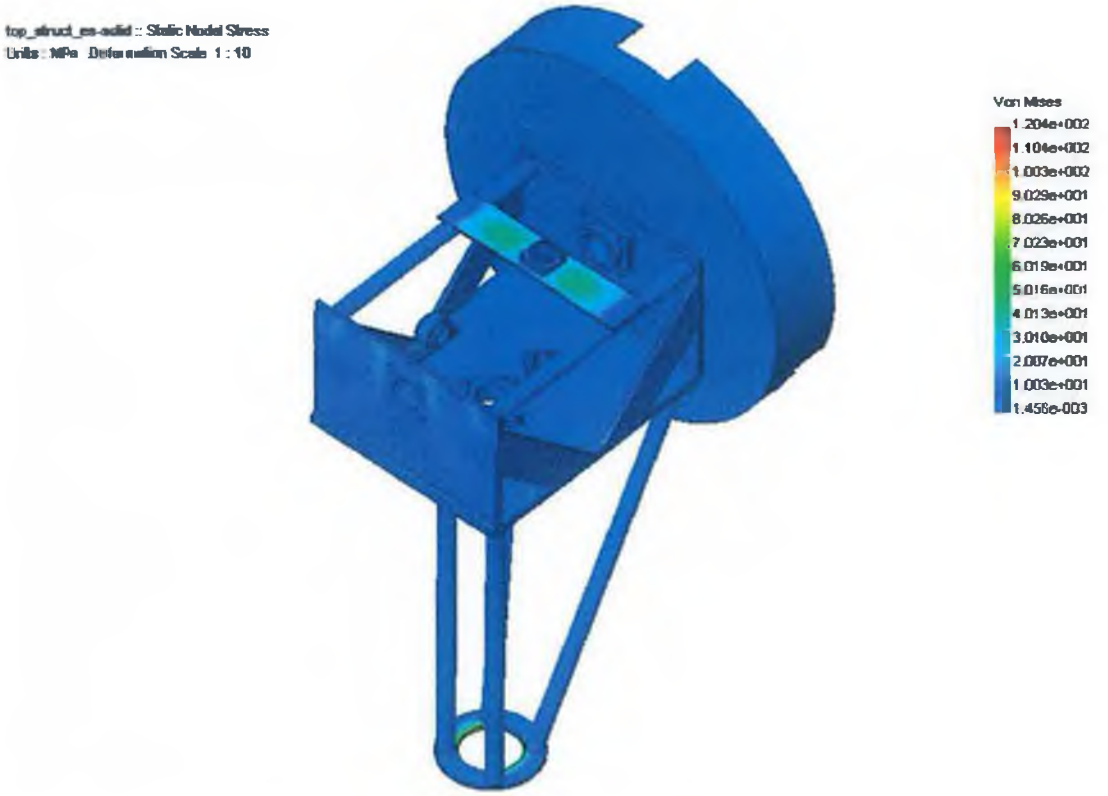


Fig. 7.6 View of the nacelle under the maximum occurring loads

The figures 7.6, shows the loaded nacelle, revealing where are the most stressed points and which is the maximum stress. The highest stresses were expected to occur at the joints between the front plate and the circular beams. However, the software allows for a different design check, which is to desplay the areas that are under a certain factor of safety. The design check with a 3 safety factor did not reveal any red areas, and with a value of 4 for the safety factor they were barely visible. The design check against a 5 safety factor revealed the highest streess point, pictured in figure 7.7.

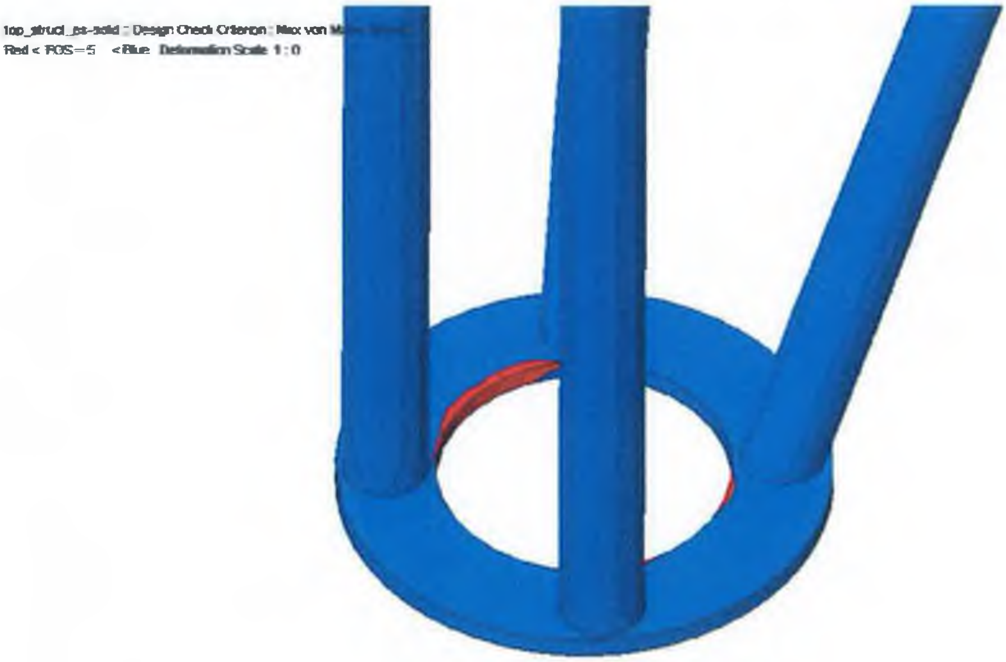


Fig. 7.7 Areas below a safety factor of 5

The maximum stresses are not higher than 120 MPa, and comparing to the maximum allowable stress which is 345 MPa, it results a sefatey coefficient of 2.9.

7.5 The tower

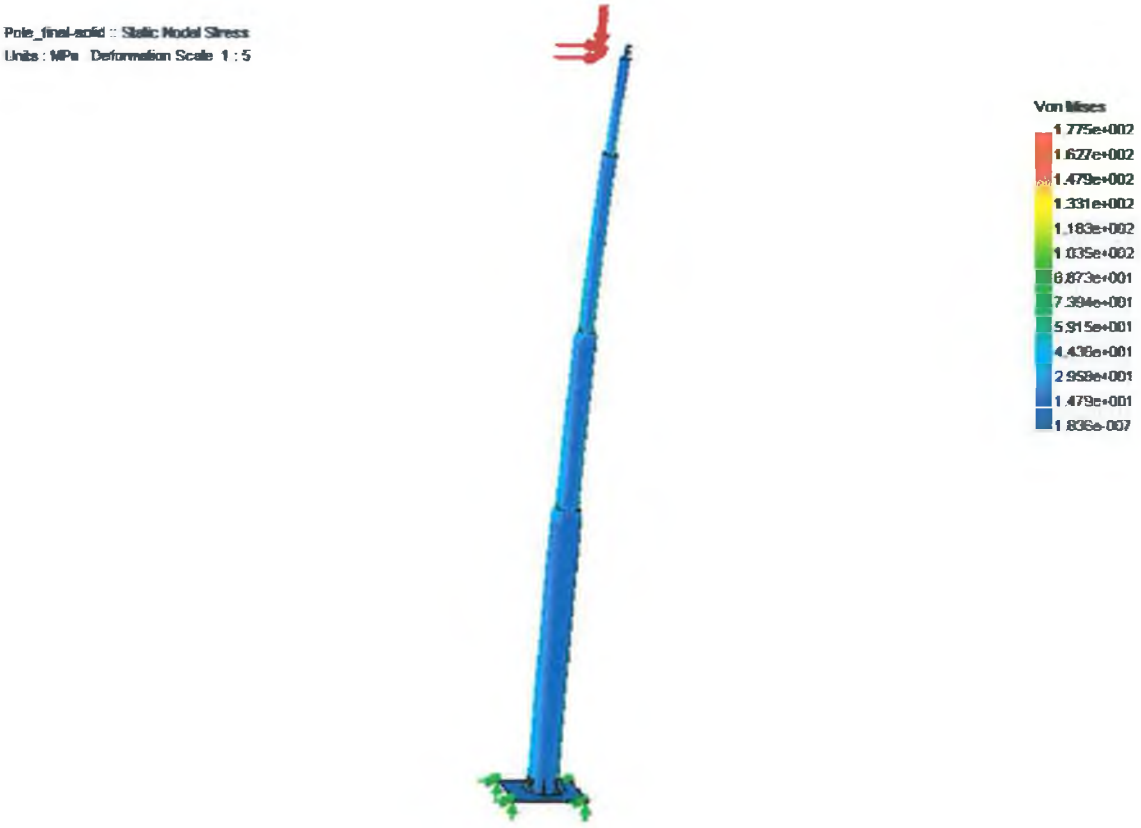


Fig 7.8 Tower under load

The figure above shows a typical design verification for the tower. The base of the tower is fully restrained and the loads are applied at the top, which resembles the real situation in which the main loads are taken over from the nacelle through the thrust bearing. The tower, being the same with the one from WT6000, should be able to withstand a wind thrust of 10000N and a nacelle weight of 6000N (which is the weight of the new nacelle, slightly higher) the maximum stress being 177MPa. This yields for a 1.9 factor of safety, which can be considered sufficient if it is taken into account that this is a worst-case scenario. The material used for the analysis was structural steel because there is no data about the real material, but it is possible for the tower to be made of a stronger alloy steel, which would obviously allow for a higher safety factor.

7.6 Conclusions

The structural analysis has revealed that the turbine will cope well with even the most extreme conditions. The situations used for load simulation were worse than what can occur in reality, and still no stress was higher than the allowable limit of the material. It can be concluded that at this stage the turbine can be considered safe to be fabricated and tested.

Chapter 8 – Price Estimation

8.1 Introduction

This chapter will present the expected cost for purchasing the parts and the materials required by the turbine construction, an annual power output will be calculated, and based on the obtained data there will be performed an estimation of the period in which the turbine produces an amount of energy equivalent to the initial investment for purchasing the machine and its peripherals. Nevertheless, it has to be stated from the beginning that what the present design represents is a functional prototype, not a series product. At this stage of the design, a price estimation can only achieve the purpose of showing the price magnitude for a prototype. Manufacturing the prototype, testing it, obtaining input data from the suppliers and manufacturers and modifying the design accordingly, and even a marketing study are all future stages that have to be undertaken before a realistic estimate of the market price can be made. However, the price estimation performed here shows the general direction that should be taken, and also the final price obtained could be considered as an upper limit, as typically a series product costs considerably less.

8.2 Price Estimation

8.2.1The Blades

It has been calculated that the surface of a blade is approximately 2.1m^2, and the thickness of the GRP has to be 5mm. For building the blade, there are required two half moulds in which there are to be deposed the layers of fibreglass to form the two halves of the blade. The GRP consists mainly of epoxy resin, which is reinforced by the actual fibreglass mat inserts. It is expected that three layers of fibreglass tape will be required to make up the 5mm thickness, obviously depending on how much resin is used for each layer.

Considering that one blade is calculated to have 15kg, there should be 30kg of resin purchased for the construction of one rotor, the difference to 45kg being made up by the weight of the actual fibreglass tape. The sheets used should be 2800mm long and 600mm wide at the base ant 300mm wide at the tip. Obviously a sheet like this will be cut from a tape roll, 600mm wide. One metre of fibreglass tape 600mm wide costs around €7.5, and there are required 51m, which will consequently cost €380.
At a price of €3.5/kg the resin will cost €105. [45]

There is also the hardener to take into account. There are required 20cm^3 of catalyst for 1*l* of resin. There are 30kg of resin, which translate into 25*l* at a density of 1.2g/cm^3. There are required 0.5*l* of catalyst, which will cost €5.5, at a price of €11/*l*. [45]

The total cost for the blades material adds up to €500.

The moulds are also built from GRP, and they can be considered “the negative” of one blade. However, they have to be much stronger, and a 20mm thickness was recommended, which means that the moulds will require four times the material of one blade, which means that the moulds will cost around €650. Once built, they can be used for producing more blades, a minimum number of 20 is given in the literature. It results that the moulds will ad €32.5 per blade, or €97.5 per rotor.

It concludes that the total cost for the blades should be €600.

8.2.2 The Nacelle

The nacelle is a welded galvanised steel structure, weighting 500kg, without the generator. It is made from steel plates and bars. In this weight there are also included the rest of the metal parts that will have to be used, like the hub assembly, the blade connecting pieces, the tail vane and the part used for unlocking the tail in high winds. A search on the Internet reveals that the average price per tone of steel plates and bars is about €750 [46]. This means that the materials for the nacelle should cost around €450.

There are also six bearings, each of them having a cast iron, 4-bolt flange casing, which can be found in industrial components catalogues, priced no higher than €50 each.

Putting together the data, the total price for the nacelle can be expected to be around €850. Because building this structure is a complex activity, there have been added €100 for un-predicted expenses.

8.2.3 The Generator

The generator is a multi-pole permanent magnet alternator. The generator is generally made of GRP resin that is poured in moulds in such a way that it incorporates after hardening the permanent magnets and the windings.

The permanent magnets are expected to cost around €300. [47] The cores of the windings can be manufactured cheaply on a milling machine, the price of the materials being no higher than €50. For windings, approximately 200m of 2mm copper wire are required. One roll of 50m costs €15, so the total price for the wire is €60.

The volume of resin required is 55*l*, which at a density of $1.2 g/cm^3$ weights 66kg. As said earlier, the price is €3.5/kg, so the resin should cost €230. The catalyst will add €15 to the cost.

A simple addition indicates that the price of the generator will rise up to €655. However, the moulds should be included in the price as well. A method for building the moulds has not been established, as they have a very basic shape. For example, disks and rings of wood could be cut and then sticked together to form the mould.

The final estimation is that €700 should be allocated for the generator'construction.

8.2.4 The Overall Price

From the calculations and estimations above it results that the sum spent with all the materials and the items to be purchased for building one turbine is around €2150. To allow for the rest of the comparatively reduced cost items like bolts, nuts, washers, welding electrodes, drills and so forth, the total sum should be rounded up to €2350. It is likely that two people will be required on average to complete the construction of the turbine in two weeks, which means that adding the workforce brings the cost up to **€3550,** based on an estimation of €300/week/person.

	Price/unit	Quantity	Total
Epoxy resin	€ 3.5/kg	95kg	€ 335
Catalyst	€ 11/l	1.8l	€ 20
Fibreglass tape	€ 7.5/1m / 600mm wide	51m	€ 380
Blade moulds	€ 100	-	€ 100
Steel plates & bars	€ 750/tone	600kg	€ 450
Nacelle extras	€ 100	-	€ 100
Cast iron casing bearings	€ 50 / item	6	€ 300
Permanent Magnets	€ 12	24	€ 300
Copper wire rolls – 50m	€ 15	4	€ 60
Iron cores	€ 2.5	18	€ 45
Generator wooden moulds	€ 50	-	€ 50
Other materials	€ 200	-	€ 200
Work force	€ 300/week/worker	4	€ 1,200
			€ 3,550

Table 8.1 Overall price estimation

As it was stated at the beginning of the chapter, this price is the one of a prototype. The final price will have to include in its calculation the initial investment, which will cause it to increase, but at the same time evrerything else will decrease because the cheapest and simplest way of solving the different problems will be found as experience is gainded with the product, and also materials will be purchased in larger quantities, which will also have a positive effect over the final cost.

8.3 Annual Output Estimation

It has to be stated from the beginning that the output of a wind turbine depends greatly on the site. For example, the estimation given by Proven Engineering about their WT6000 is that the turbine produces between 7000-18000kWh per year, depending on site.

Therefore, the calculation that will be presented only holds true for the particular site for which it has been performed.

Considering that it has been calculated that the expected output of the new turbine is 8.9kW in a 12m/s wind, and that the theoretical power of the wind crossing the rotor swept area is 28kW, it results that the power coefficient of the turbine is 0.32.

Therefore, considering that the turbine maintains the same power coefficient for a larger range of wind speeds, which could be true because it has variable rotor speed that enables it to settle in at the most efficient rotor angular velocity for every given wind speed, it can be stated that the formula of the instantaneous power, according to the theory presented in chapter three, is: $W = 0.32 \times \frac{1}{2} \rho A V^3$, where V is the wind speed, ρ is the air density and A is the rotor swept area.

Met Eireann, The Irish Meteorological Service, has made available the statistical data about the wind speed in the region of Galway, acquired over a 10-year period (1981-1990).

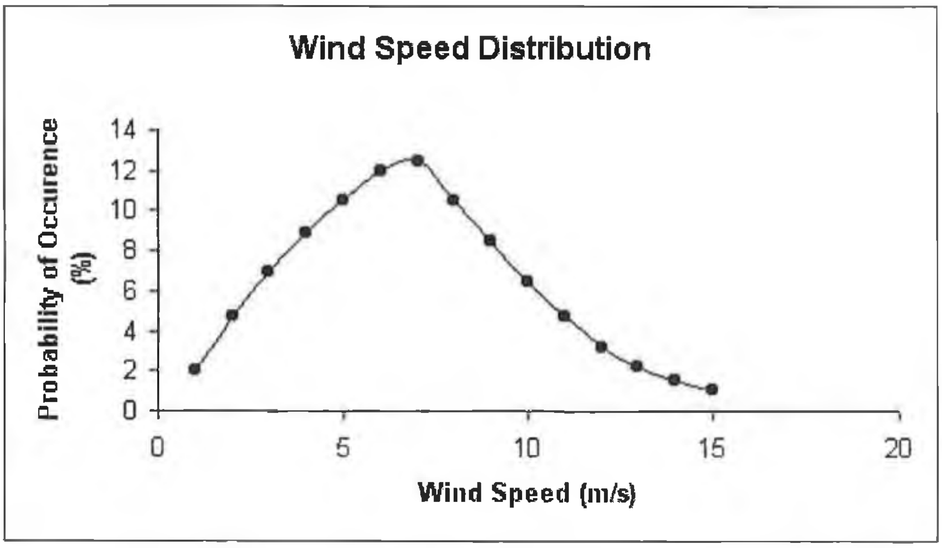


Fig. 8.1 The probability of occurrence for winds of different speeds

The way of using this data is to assume that in one year, the 9% probability for example that the wind will blow with 4m/s, translates into the fact that during that year it is certain that the wind will have 4m/s speed for exactly 788 hours, taking into account that there are 8760 hours in one year.

Wind speed (m/s)	Probability (%)	hours/year	Instantaneous power for the given wind speed (kW)	Energy (kWh)
1	2	175.2	0.000	0
2	4.7	411.72	0.000	0
3	7	613.2	0.000	0
4	8.9	779.64	0.000	0
5	10.5	919.8	0.648	596
6	12	1051.2	1.119	1177
7	12.5	1095	1.778	1946
8	10.5	919.8	2.653	2441
9	8.5	744.6	3.778	2813
10	6.5	569.4	5.183	2951
11	4.75	416.1	6.898	2870
12	3.2	280.32	8.955	2510
13	2.25	197.1	8.900	1754
14	1.5	131.4	8.500	1117
15	1.1	96.36	8.000	771
			Total	**20946**

Table 8.2 Annual energy production estimation

The table displays the wind speed, its probability of occurrence, the instantaneous power output for that wind speed, the total energy obtained due to a certain wind speed, and then it sums all this energies for obtaining the annual output. It can be noticed that there is no instantaneous power for wind speeds below 4m/s, as the wind speed is not sufficient for starting the rotor, although there would be reduced power generation if the rotor were already spinning. As well, it can be noticed that the power starts to decrease beyond 12m/s wind speed, due to the stall control design of the blades.

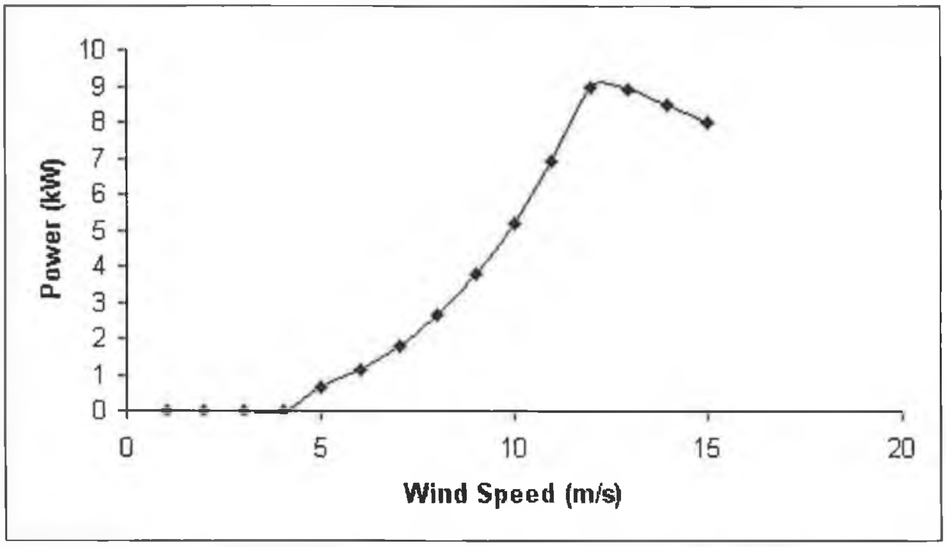


Fig. 8.2 Power output with respect to wind speed

As a conclusion, it could be stated that if the turbine were erected in Galway, and the weather would follow the pattern established by the Met Eireann report, the turbine would generate approximately 21000kWh during one year.

8.4 Payback Time Estimation

Assuming that the turbine will cost €5000-6000 and that it cannot work without at least a controller and a battery bank, which cost around €7000 each, it results that the total cost of the system will be around €20000. The turbine produces 21000kWh/year, which priced at €0.10/kWh, have a value of €2100 per year. The conclusion is that, considering the price for 1 kWh remains the same, the turbine will pay back its price in 9 and a half years.

The literature review shows that the wind machines in this size range operate for periods of 20-25 years without failure and they only require minimum maintenance, which takes place usually once a year.

Chapter 9 – Conclusions, Recommendations and Applicability

Conclusions

The project has achieved its goal of designing a new wind turbine. The process was significantly more difficult than what was thought in the beginning, because very different subjects were approached, from the aerodynamic calculations of the blades, and the calculations typical to an electrical generator, to imagining solutions for building the parts cheaply, and designing a totally new, completely mechanical solution for furling the tail to protect the turbine in stormy conditions. The price estimation is much more than what it seems to be, firstly because looking for suppliers and getting to an agreement with them is a very long and time consuming process mainly due to the various human factors envolved, and it becomes even more difficult when the typical industries are not located close to the where the research is taking place. On the other hand, there are several other steps to be undertaken before the estimation could be accurate, as it was already stated in the introduction of the previuos chapter.

Attempting a comparison between the new design and the WT6000, it can be concluded that the main differences are:

- The design phylosophy is different, mainly because of the behaviour in high winds. The WT6000 withstands them, while the new turbine turns away, avoiding thus the necessity of making it stronger that it normally needs to be, resulting in a price reduction. The overall material used for the nacelle structure is almost the same, because while WT6000 needs a longer structure due to its down-wind configuration, the new turbine needs a smaller one, but it needs a long tail vane due to its upwind configuration.
- The blades are simple and made of GRP, and their shape that incorporates the stall approach, not only limits the power but also helps reducing the structural load on the blades. Consequently, they result significantly cheaper than the ones from WT6000 that are built of two materials, wood and rubber, thus involving expensive technology, and they also feature groups of springs that allows them to

flex backwards in the wind, adding again to the price. The other difference is that the new blades produce significantly more power, 8.9kW compared to 6kW.

- The new generator, although it has the same general configuration with the one from WT6000, it has a higher power rating, and a much simpler design and fabrication process, while employing cheaper materials. It is made mainly of GRP resin, while the one from WT6000 uses metal parts to accommodate the magnets and windigns, resulting in being heavier and more expensive.

Recommendation and Applicabilty

Taking into account the calculations in Chapter 8 it becomes clear that a small wind turbine is not a viable source of electricity for regions where the national grid supply is readily available.

Wind becomes an interesting alternative for remote areas, and obviously for wind enthusiasts. In Australia for example, it is estimated that the cost of connecting a remote site to the national grid are in the region of $4000/km. If the site has a difficult location, the connection could be more expensive or even impossible.

This explains why wind energy is an interesting option only for remote applications. However, it is obviously not enough for a place to be isolated, it also has to be windy enough for justifying an investment into a wind system.

Probably the reason that has the most influence nowadays for searching for alternative sources of energy is the environmental aspect, rather than the lack of conventional resources. Nevertheless, for the countries not having their own resources that would enable them to produce energy in conventional ways, making use of the energy in the wind is definitely an option, helping them to improve their economical independence, and consequently their political one. However, this point of view should not be taken to any extremes, as obviously wind turbines are comparatively vulnerable sources of energy in case of an aerial attack.

It has to be stated that small wind turbines are not a solution for energy resources or environment improvements on a global level.

Looking at this problem from a mathematical point of view, the power of a wind turbine varies linearly with the rotor swept area and with the cube of the wind speed. The swept area varies with the square of the rotor radius, which in turn varies linearly to its mass. It becomes clear that the ratio of the power to the turbine mass, and thus cost, improves significantly as the size increases. For example a 20% increase in the rotor size will produce a 44% increase in the power, and a 50% increase in the rotor mass will produce a 125% power increase. A bigger turbine has also the advantage of being higher, and considering the wind speed gradient with altitude, it may experience a 30% faster wind at a 60m hub height, than at the 15m of a small turbine, this having the massive influence of doubling the power.

It becomes clear that the bigger the turbine the faster it will pay back the investment. It has been calculated that a large wind turbine placed in a good windy site, can produce enough electricity to pay back its price in as low as six month. [18] This could seem a slightly optimistic figure. If it is considered that the installation of 1kW of wind power averages at €1000, and considering a Danish 1.2MW wind turbine which costs a resulting €1.2mil and produces 6GWh per year, at a price of €0.1/kW, it can be calculated that the payback period is 2 years, which compares to the almost 10 year period calculated for 9kW turbine designed in the present project.

At the end of 1998 there were 6,500MW installed in the EU, and the European Commission has set the target of 40,000MW installed by the end of 2010. [49]

This underlines once again that small wind turbines are likely to remain restricted to their traditional use, like remote houses and small communities, and TV and radio repeaters located on the mountain peaks. It is up to their much bigger counterparts to fight against global warming and greenhouse effects.

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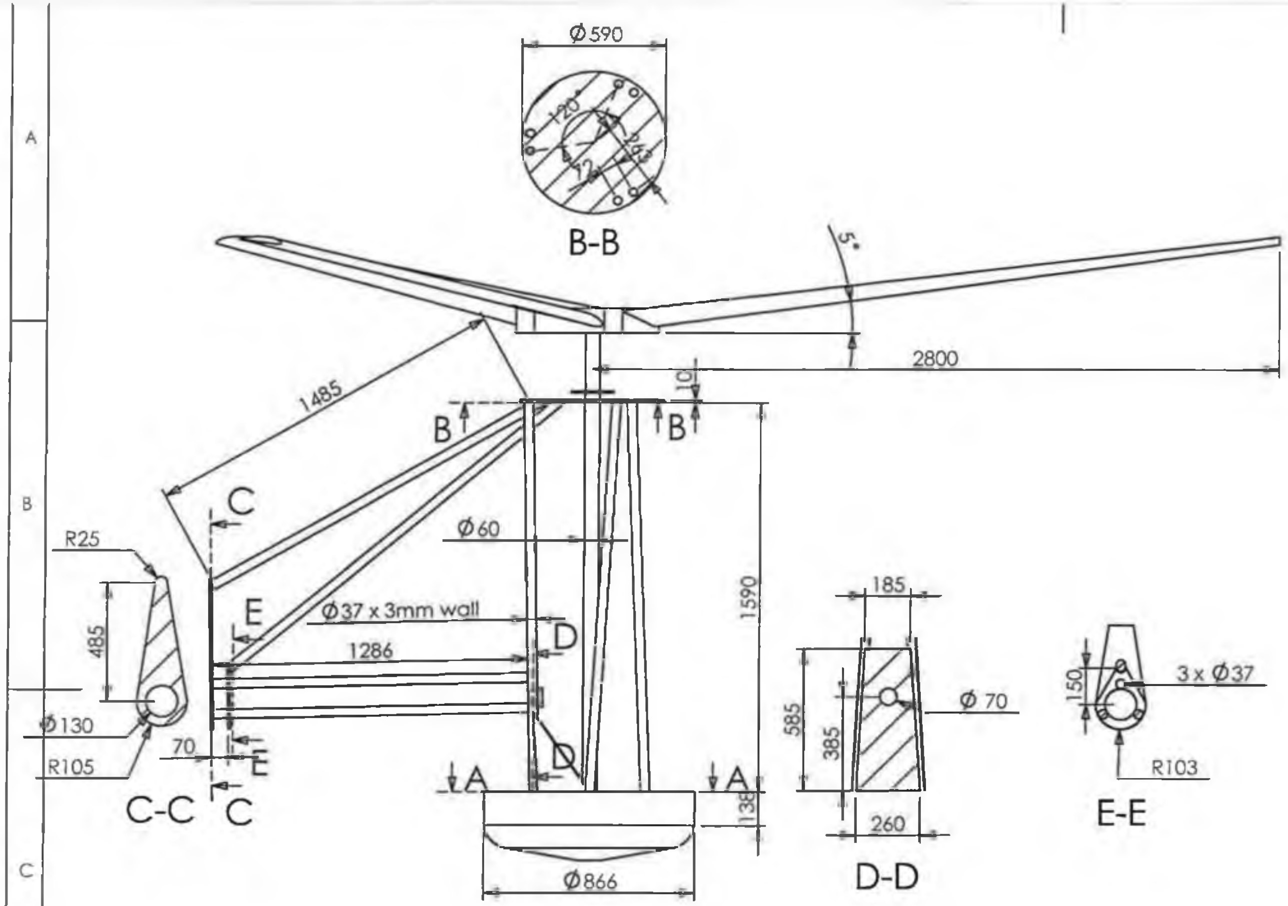
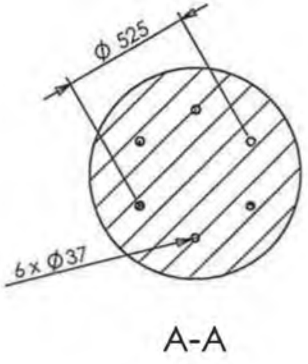
Appendix 1





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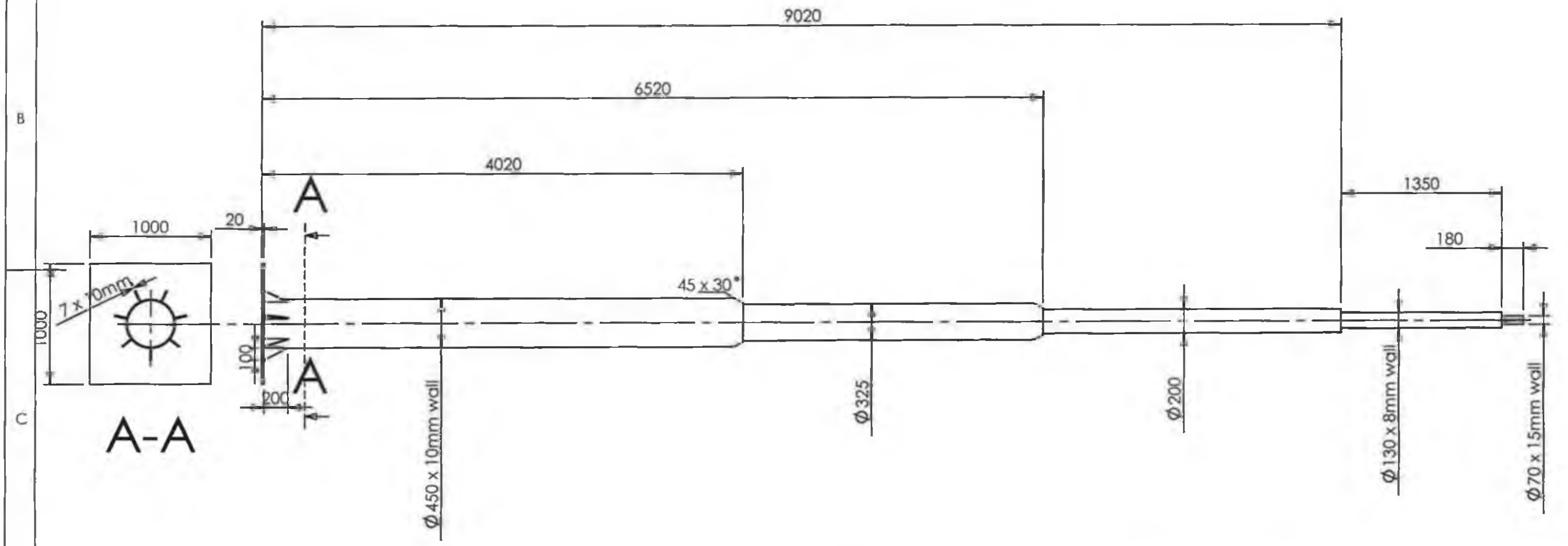
Appendix 2



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Q.A			

TITLE: POLE

MATERIAL: GALVANISED STEEL

DWG NO.

A4

WEIGHT: 450 KG

SCALE:1:50

Appendix 3

R	r	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2.8	12	18	0.25	0.082	4	0.2119	0.2088	11.96	0.2073	0.9783	0.1	0.1
2.9	2.8	12	18	0.25	0.082	4	0.196	0.1936	11.09	0.1924	0.9813	0.2337	0.0122
2.9	2.8	12	18	0.25	0.082	4	0.1888	0.1866	10.69	0.1855	0.9826	0.262	0.0121
2.9	2.8	12	18	0.25	0.082	4	0.1851	0.1831	10.49	0.182	0.9833	0.2764	0.012
2.9	2.8	12	18	0.25	0.082	4	0.1832	0.1811	10.38	0.1802	0.9836	0.2842	0.0119
2.9	2.8	12	18	0.25	0.082	4	0.1821	0.1801	10.32	0.1791	0.9838	0.2885	0.0119
2.9	2.8	12	18	0.25	0.082	4	0.1814	0.1795	10.28	0.1785	0.9839	0.291	0.0119
2.9	2.8	12	18	0.25	0.082	4	0.1811	0.1791	10.26	0.1782	0.984	0.2923	0.0119
												0.2931	0.0119

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2.7	12	18	0.26	0.086	4	0.2197	0.2163	12.39	0.2146	0.9767	0.1	0.1
2.9	2.7	12	18	0.26	0.086	4	0.2023	0.1996	11.44	0.1983	0.9801	0.2367	0.0132
2.9	2.7	12	18	0.26	0.086	4	0.1943	0.1919	11	0.1907	0.9816	0.267	0.013
2.9	2.7	12	18	0.26	0.086	4	0.1901	0.1879	10.77	0.1868	0.9824	0.2828	0.0129
2.9	2.7	12	18	0.26	0.086	4	0.1879	0.1857	10.64	0.1846	0.9828	0.2914	0.0128
2.9	2.7	12	18	0.26	0.086	4	0.1866	0.1844	10.57	0.1834	0.983	0.2963	0.0128
2.9	2.7	12	18	0.26	0.086	4	0.1858	0.1837	10.53	0.1827	0.9832	0.2992	0.0127
2.9	2.7	12	18	0.26	0.086	4	0.1854	0.1833	10.5	0.1823	0.9832	0.3009	0.0127
												0.3018	0.0127

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2.6	12	18	0.27	0.089	4	0.2281	0.2243	12.85	0.2224	0.9749	0.1	0.1
2.9	2.6	12	18	0.27	0.089	4	0.2094	0.2064	11.83	0.2049	0.9788	0.2385	0.0141
2.9	2.6	12	18	0.27	0.089	4	0.2007	0.1981	11.35	0.1968	0.9804	0.2702	0.0139
2.9	2.6	12	18	0.27	0.089	4	0.1962	0.1937	11.1	0.1925	0.9813	0.2868	0.0137
2.9	2.6	12	18	0.27	0.089	4	0.1937	0.1913	10.96	0.1901	0.9818	0.296	0.0137
2.9	2.6	12	18	0.27	0.089	4	0.1922	0.1899	10.88	0.1887	0.982	0.3013	0.0136
2.9	2.6	12	18	0.27	0.089	4	0.1914	0.1891	10.83	0.1879	0.9822	0.3044	0.0136
2.9	2.6	12	18	0.27	0.089	4	0.1908	0.1886	10.8	0.1875	0.9823	0.3063	0.0136
												0.3074	0.0136

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2.5	12	18	0.28	0.093	4	0.2373	0.233	13.35	0.2309	0.973	0.1	0.1
2.9	2.5	12	18	0.28	0.093	4	0.2171	0.2138	12.25	0.2122	0.9772	0.2398	0.0152
2.9	2.5	12	18	0.28	0.093	4	0.2078	0.2049	11.74	0.2035	0.9791	0.2726	0.0149
2.9	2.5	12	18	0.28	0.093	4	0.203	0.2002	11.47	0.1989	0.98	0.2898	0.0147
2.9	2.5	12	18	0.28	0.093	4	0.2002	0.1976	11.32	0.1963	0.9805	0.2995	0.0146
2.9	2.5	12	18	0.28	0.093	4	0.1986	0.1961	11.23	0.1948	0.9808	0.3051	0.0146
2.9	2.5	12	18	0.28	0.093	4	0.1977	0.1952	11.18	0.1939	0.981	0.3085	0.0146
2.9	2.5	12	18	0.28	0.093	4	0.1971	0.1946	11.15	0.1934	0.9811	0.3104	0.0145
												0.3116	0.0145

R	r	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2.25	12	18	0.31	0.102	4	0.2636	0.2578	14.77	0.2549	0.967	0.1	0.1
2.9	2.25	12	18	0.31	0.102	4	0.2407	0.2362	13.54	0.2341	0.9722	0.2387	0.019
2.9	2.25	12	18	0.31	0.102	4	0.2303	0.2263	12.97	0.2244	0.9745	0.272	0.0187
2.9	2.25	12	18	0.31	0.102	4	0.2248	0.2212	12.67	0.2194	0.9756	0.2894	0.0185
2.9	2.25	12	18	0.31	0.102	4	0.2218	0.2183	12.51	0.2165	0.9763	0.299	0.0184
2.9	2.25	12	18	0.31	0.102	4	0.2201	0.2166	12.41	0.2149	0.9766	0.3046	0.0183
2.9	2.25	12	18	0.31	0.102	4	0.219	0.2156	12.35	0.214	0.9768	0.3079	0.0183
2.9	2.25	12	18	0.31	0.102	4	0.2184	0.215	12.32	0.2134	0.977	0.3098	0.0182
												0.311	0.0182

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	2	12	18	0.34	0.111	4	0.2966	0.2883	16.52	0.2843	0.9587	0.1	0.1
2.9	2	12	18	0.34	0.111	4	0.2744	0.2678	15.35	0.2646	0.9643	0.2261	0.0223
2.9	2	12	18	0.34	0.111	4	0.2649	0.259	14.84	0.2561	0.9666	0.2531	0.0219
2.9	2	12	18	0.34	0.111	4	0.2604	0.2547	14.6	0.252	0.9677	0.2661	0.0217
2.9	2	12	18	0.34	0.111	4	0.2581	0.2526	14.47	0.2499	0.9683	0.2726	0.0216
2.9	2	12	18	0.34	0.111	4	0.2569	0.2515	14.41	0.2488	0.9686	0.2761	0.0216
2.9	2	12	18	0.34	0.111	4	0.2563	0.2509	14.37	0.2482	0.9687	0.2779	0.0215
2.9	2	12	18	0.34	0.111	4	0.2559	0.2505	14.36	0.2479	0.9688	0.2788	0.0215
												0.2793	0.0215

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	1.75	12	18	0.36	0.12	4	0.339	0.3268	18.72	0.321	0.9471	0.1	0.1
2.9	1.75	12	18	0.36	0.12	4	0.3146	0.3048	17.46	0.3001	0.9539	0.2188	0.0287
2.9	1.75	12	18	0.36	0.12	4	0.3047	0.2958	16.95	0.2915	0.9566	0.2438	0.0281
2.9	1.75	12	18	0.36	0.12	4	0.3002	0.2916	16.71	0.2875	0.9578	0.2552	0.0279
2.9	1.75	12	18	0.36	0.12	4	0.298	0.2896	16.59	0.2856	0.9583	0.2607	0.0278
2.9	1.75	12	18	0.36	0.12	4	0.2969	0.2887	16.54	0.2847	0.9586	0.2633	0.0278
2.9	1.75	12	18	0.36	0.12	4	0.2964	0.2882	16.51	0.2842	0.9588	0.2647	0.0277
2.9	1.75	12	18	0.36	0.12	4	0.2962	0.2879	16.5	0.284	0.9588	0.2653	0.0277
												0.2656	0.0277

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	1.5	12	18	0.39	0.129	4	0.3955	0.3766	21.58	0.3677	0.9299	0.1	0.1
2.9	1.5	12	18	0.39	0.129	4	0.3687	0.3532	20.24	0.3459	0.9383	0.2084	0.0377
2.9	1.5	12	18	0.39	0.129	4	0.3586	0.3443	19.73	0.3375	0.9413	0.2307	0.037
2.9	1.5	12	18	0.39	0.129	4	0.3543	0.3405	19.51	0.3339	0.9426	0.2401	0.0367
2.9	1.5	12	18	0.39	0.129	4	0.3524	0.3388	19.41	0.3324	0.9432	0.2442	0.0366
2.9	1.5	12	18	0.39	0.129	4	0.3515	0.3381	19.37	0.3316	0.9434	0.2461	0.0366
2.9	1.5	12	18	0.39	0.129	4	0.3512	0.3377	19.35	0.3313	0.9435	0.2469	0.0365
2.9	1.5	12	18	0.39	0.129	4	0.351	0.3376	19.34	0.3312	0.9436	0.2473	0.0365
												0.2475	0.0365

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	1.25	12	18	0.42	0.138	4	0.4745	0.4431	25.39	0.4287	0.9034	0.1	0.1
2.9	1.25	12	18	0.42	0.138	4	0.444	0.4179	23.94	0.4058	0.9139	0.1951	0.0514
2.9	1.25	12	18	0.42	0.138	4	0.4337	0.4092	23.44	0.3979	0.9174	0.2146	0.0504
2.9	1.25	12	18	0.42	0.138	4	0.4297	0.4059	23.26	0.3948	0.9188	0.222	0.0501
2.9	1.25	12	18	0.42	0.138	4	0.4282	0.4046	23.18	0.3936	0.9193	0.2248	0.0499
2.9	1.25	12	18	0.42	0.138	4	0.4276	0.4041	23.15	0.3932	0.9195	0.226	0.0499
2.9	1.25	12	18	0.42	0.138	4	0.4274	0.4039	23.14	0.393	0.9195	0.2264	0.0499
2.9	1.25	12	18	0.42	0.138	4	0.4273	0.4038	23.13	0.3929	0.9196	0.2266	0.0499
												0.2267	0.0499

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	1	12	18	0.45	0.147	4	0.5932	0.5354	30.68	0.5102	0.8601	0.1	0.1
2.9	1	12	18	0.45	0.147	4	0.5538	0.5058	28.98	0.4845	0.8748	0.1789	0.0748
2.9	1	12	18	0.45	0.147	4	0.5425	0.4971	28.48	0.4769	0.879	0.197	0.0731
2.9	1	12	18	0.45	0.147	4	0.5389	0.4943	28.32	0.4744	0.8803	0.2028	0.0726
2.9	1	12	18	0.45	0.147	4	0.5377	0.4933	28.26	0.4735	0.8808	0.2047	0.0724
2.9	1	12	18	0.45	0.147	4	0.5372	0.493	28.25	0.4733	0.8809	0.2054	0.0723
2.9	1	12	18	0.45	0.147	4	0.5371	0.4929	28.24	0.4732	0.881	0.2056	0.0723
2.9	1	12	18	0.45	0.147	4	0.5371	0.4929	28.24	0.4731	0.881	0.2057	0.0723
												0.2057	0.0723

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	0.75	12	18	0.47	0.156	4	0.7909	0.6692	38.34	0.6203	0.7843	0.1	0.1
2.9	0.75	12	18	0.47	0.156	4	0.7219	0.6253	35.83	0.5853	0.8108	0.1608	0.1236
2.9	0.75	12	18	0.47	0.156	4	0.7073	0.6156	35.27	0.5775	0.8164	0.1816	0.1184
2.9	0.75	12	18	0.47	0.156	4	0.7037	0.6132	35.13	0.5755	0.8178	0.1866	0.1173
2.9	0.75	12	18	0.47	0.156	4	0.7027	0.6126	35.1	0.575	0.8182	0.1879	0.1171
2.9	0.75	12	18	0.47	0.156	4	0.7025	0.6124	35.09	0.5748	0.8183	0.1882	0.117
2.9	0.75	12	18	0.47	0.156	4	0.7024	0.6124	35.09	0.5748	0.8183	0.1883	0.117
2.9	0.75	12	18	0.47	0.156	4	0.7024	0.6123	35.08	0.5748	0.8183	0.1884	0.117
												0.1884	0.117

R	R	Vo	ω	c	σ	X	tan(ϕ)	ϕ	ϕ-deg	sin(ϕ)	cos(ϕ)	a	a'
2.9	0.5	12	18	0.50	0.165	4	1.1864	0.8704	49.87	0.7646	0.6445	0.1	0.1
2.9	0.5	12	18	0.50	0.165	4	0.9737	0.7721	44.24	0.6976	0.7165	0.1431	0.276
2.9	0.5	12	18	0.50	0.165	4	0.9582	0.764	43.78	0.6918	0.7221	0.1811	0.2392
2.9	0.5	12	18	0.50	0.165	4	0.9559	0.7629	43.71	0.691	0.7229	0.1847	0.2367
2.9	0.5	12	18	0.50	0.165	4	0.9556	0.7627	43.7	0.6909	0.723	0.1852	0.2364
2.9	0.5	12	18	0.50	0.165	4	0.9555	0.7627	43.7	0.6908	0.723	0.1853	0.2363
2.9	0.5	12	18	0.50	0.165	4	0.9555	0.7627	43.7	0.6908	0.723	0.1853	0.2363
2.9	0.5	12	18	0.50	0.165	4	0.9555	0.7627	43.7	0.6908	0.723	0.1853	0.2363
												0.1853	0.2363

The rows of the previous tables are the different iterations, the columns are explained next.

R - the maximum radius of the rotor.

r - the local radius, defining the position of the analysed slice.

V_0 - the wind speed.

ω - the angular velocity of the rotor.

c - the chord length.

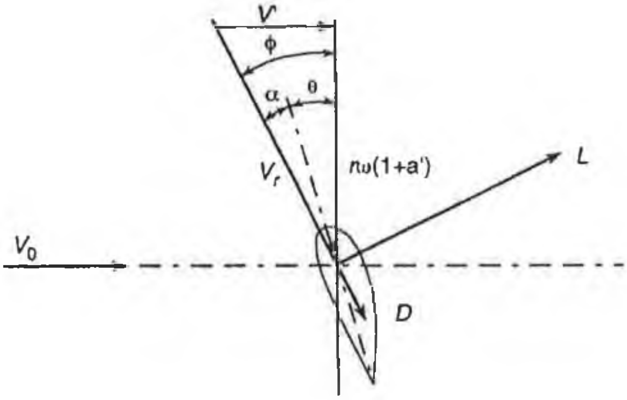
σ - the local solidity, $\sigma = \frac{Bc}{\pi R}$. Although it appears when looking at its expression that the solidity is constant throughout the length of the blade, it is not, because the local chord varies with the radius, $c = c(r)$.

X - the tip speed ratio, $X = \frac{\omega R}{V_0}$.

ϕ - given both in radians and degrees, it is the angle between the relative speed (wind speed plus the blade movement) and the plane in which the blade rotates: $\phi = \alpha + \theta$, where α is the angle of attack and θ is the pitch angle.

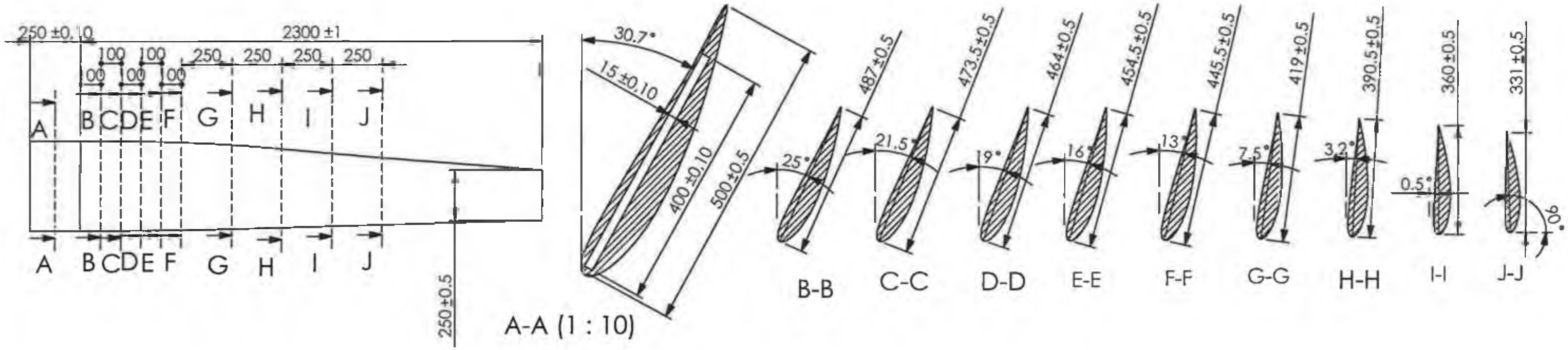
a – the axial interference factor.

a’ – the tangential interference factor.



The picture above has been discussed in chapter three, and it is being displayed here again for facilitating the comprehension of the parameters listed above.

Appendix 4



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS	FINISH:	DEBUR AND BREAK SHARP EDGES	GMIT

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: BLADE

MATERIAL: FIBREGLASS REINFORCED EPOXY RESIN, 30 PERCENT FIBREGLASS

DWG NO.

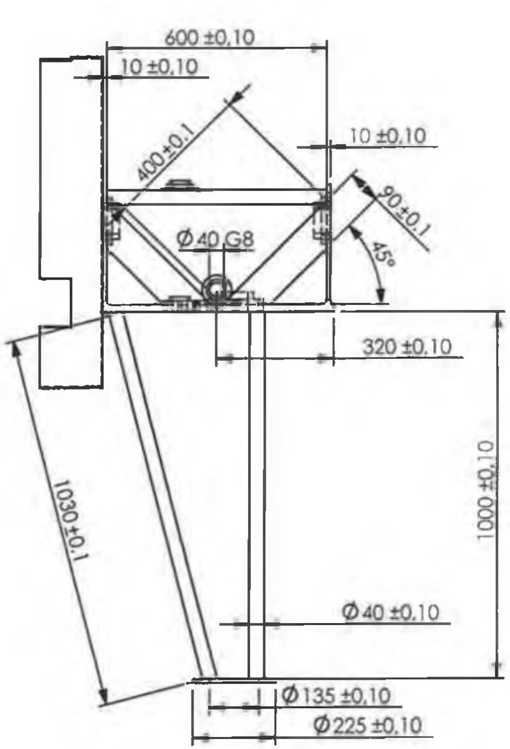
A4

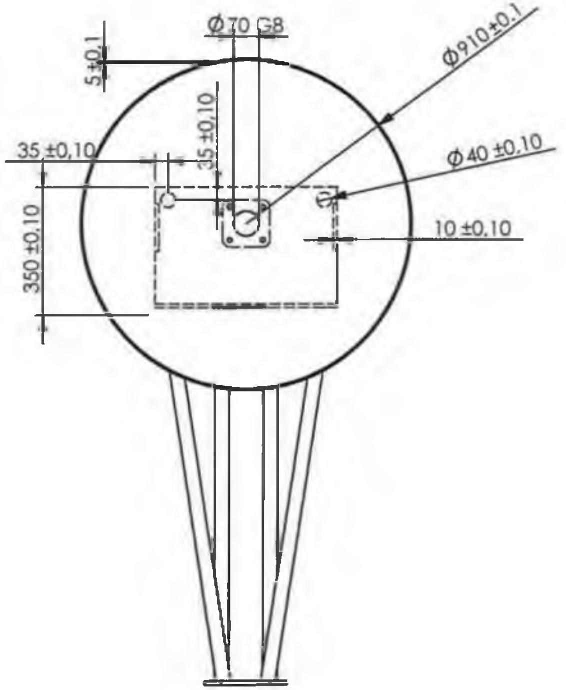
WEIGHT: 15 KG

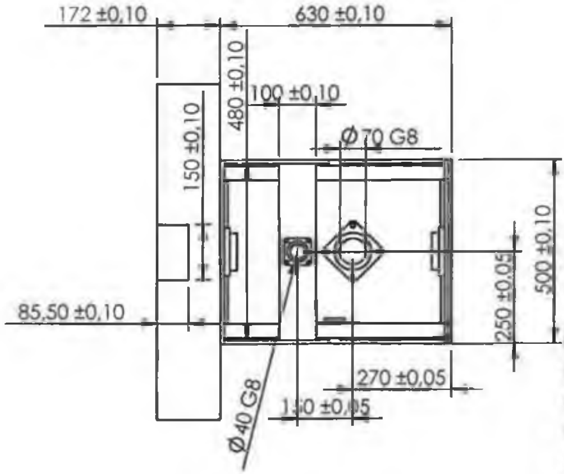
DO NOT SCALE DRAWING

SHEET 1 OF 1

Appendix 5







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DEBUR AND
BREAK SHARP
EDGES

GMIT

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Nacelle

MATERIAL: STRUCTURAL STEEL
ASTM A 242

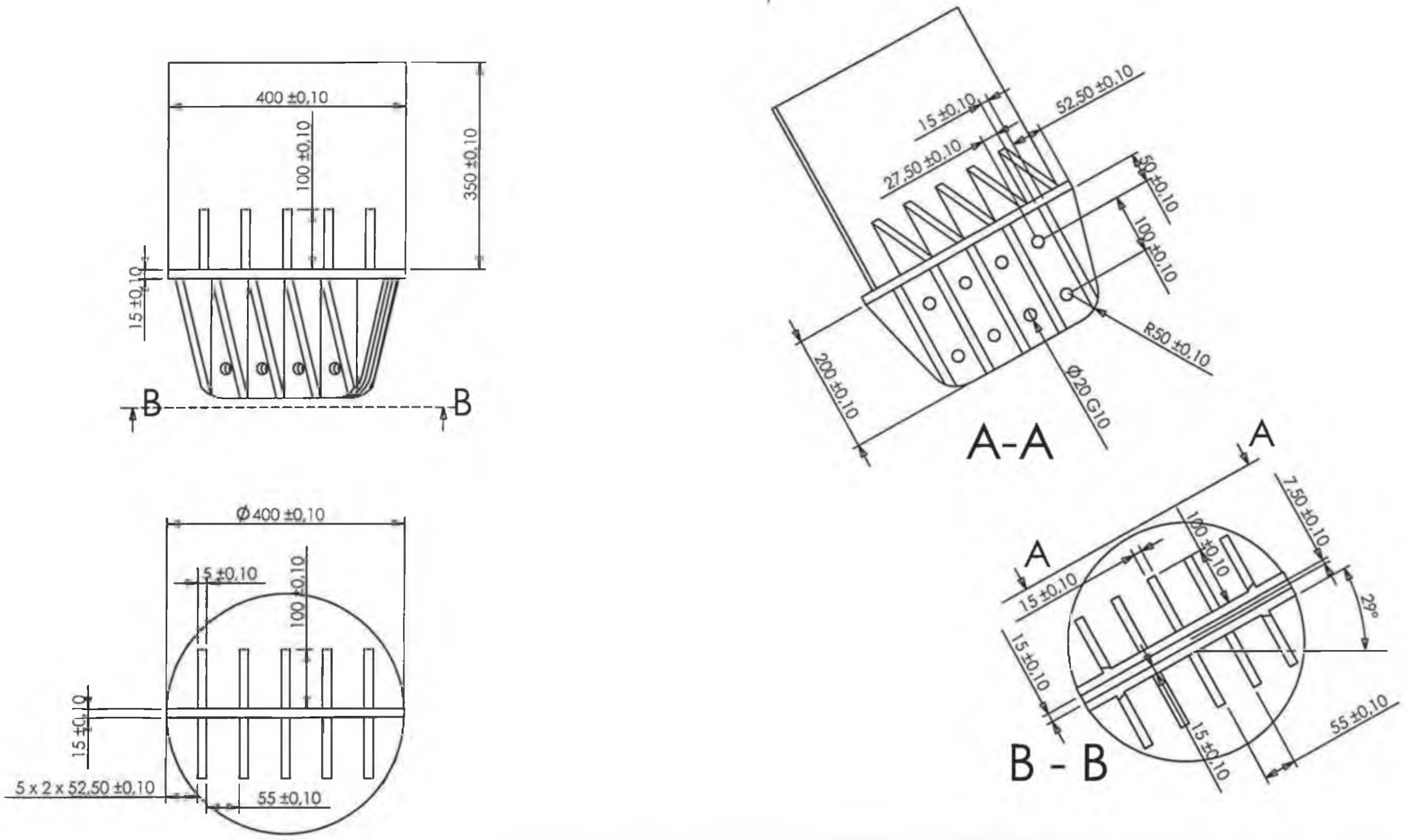
DWG NO.

A4

WEIGHT:

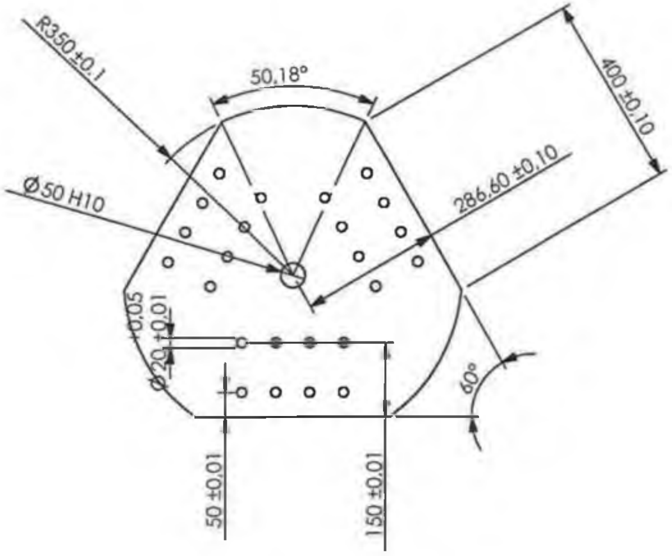
SCALE:1:20

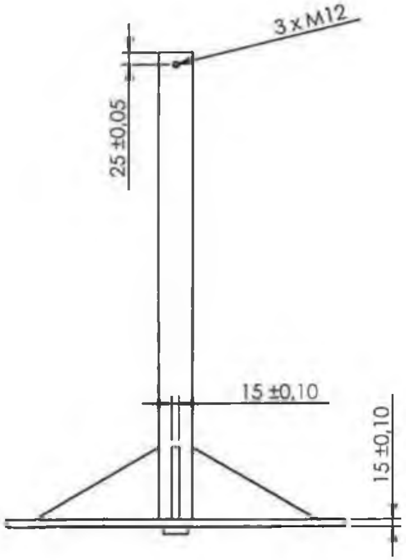
Appendix 6

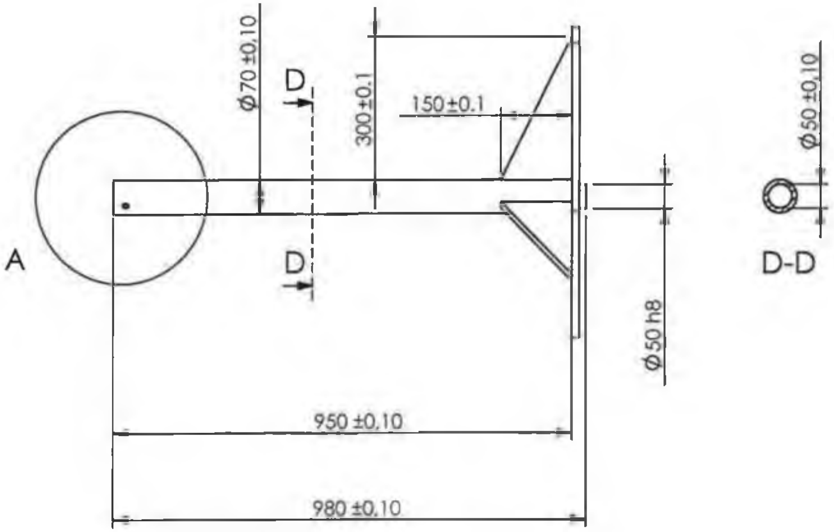


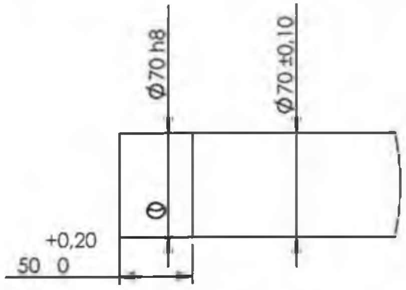
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS	FINISH:		DEBUR AND BREAK SHARP EDGES	GMIT
	NAME	SIGNATURE	DATE	TITLE: PIECE ATTACHING THE BLADE TO THE HUB
DRAWN	VLAD SOARE			
CHK'D				
APPV'D				
MFG				
Q.A			MATERIAL: STRUCTURAL STEEL ASTM A242	DWG NO. A4
			WEIGHT: 20 KG	SCALE:1:10

Appendix 7









A (1 : 5)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: STRUCTURAL STEEL ANSI A242

WEIGHT: 20kg

GMIT

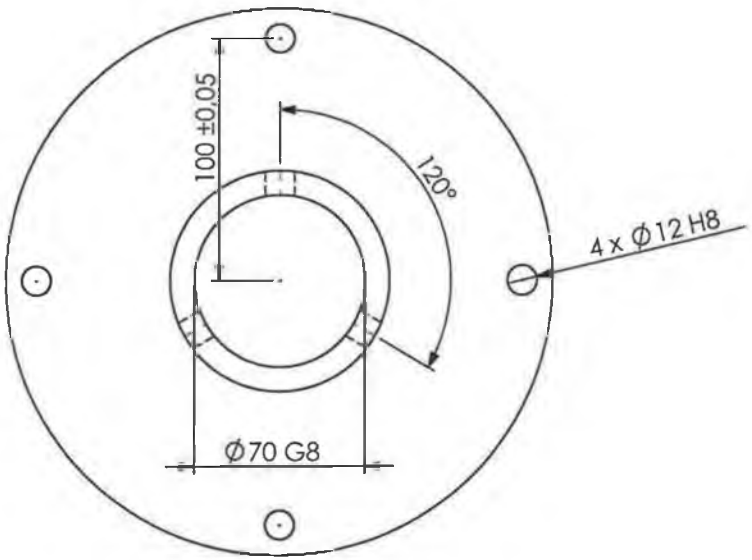
TITLE: HUB AND SHAFT

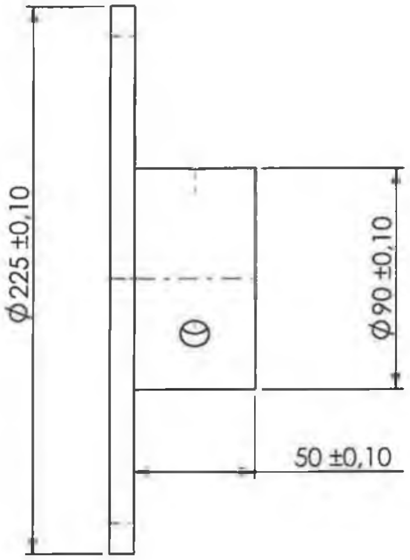
DWG NO.

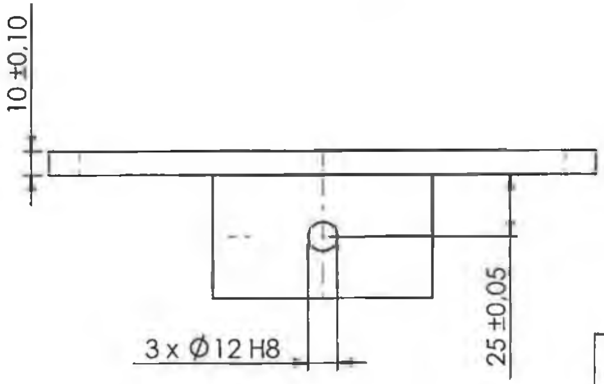
A4

SCALE:1:15

Appendix 8







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DEBUR AND
BREAK SHARP
EDGES

GMIT

TITLE: FLANGE CONNECTING THE SHAFT TO THE GENERATOR ROTOR

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: STRUCTURAL STEEL
ASTM A242

DWG NO.

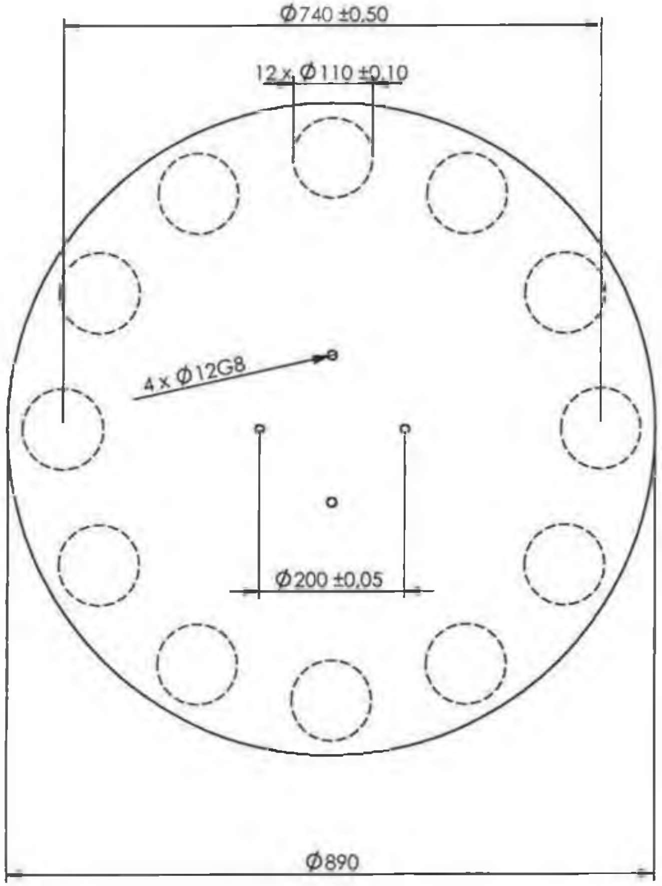
A4

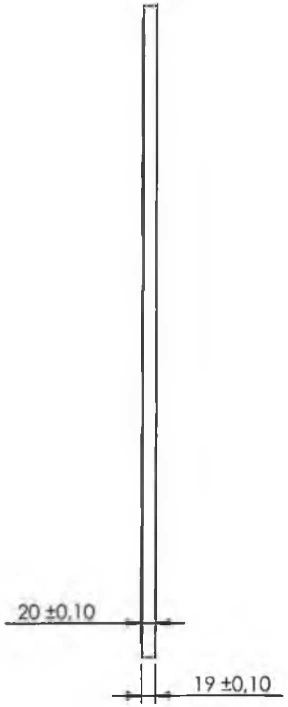
WEIGHT: 3.7 KG

SCALE: 1:3

☒

Appendix 9





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS	FINISH:	DEBUR AND BREAK SHARP EDGES	GMIT

	NAME	SIGNATURE	DATE
DRAWN	Vlad Soare		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: GENERATOR DISK

MATERIAL: POLYESTER RESIN,
□PERMANENT MAGNETS,
□CERAMIC 10 GRADE

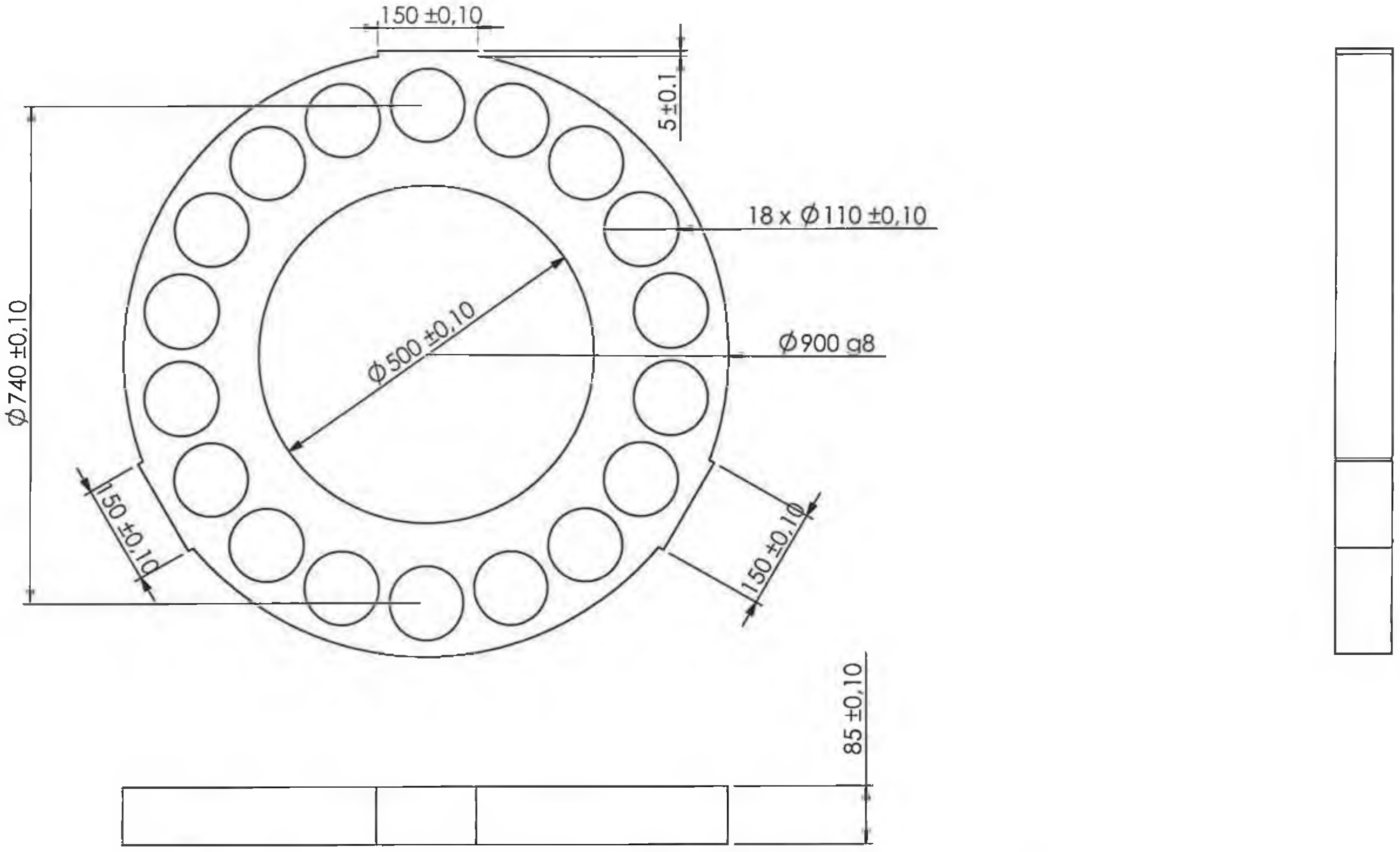
DWG NO.

A4

WEIGHT: 20KG

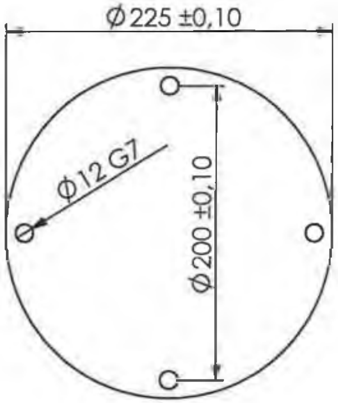
SCALE:1:10

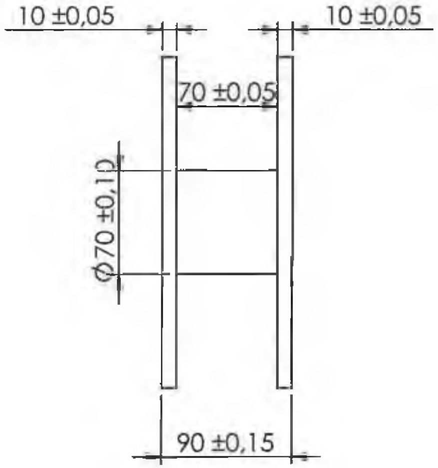
Appendix 10



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		FINISH:				DEBUR AND BREAK SHARP EDGES	GMIT
	NAME	SIGNATURE	DATE				TITLE: GENERATOR STATOR
DRAWN	VLAD SOARE						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: GRP POLYESTER RESIN			DWG NO. A4
				WEIGHT: 55KG			SCALE: 1:10

Appendix 11





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS	FINISH:	DEBUR AND BREAK SHARP EDGES	GMIT

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: SHFT CONNECTING THE TWO DIKS OF THE GENERATOR ROTOR

MATERIAL: STRUCTURAL STEEL
□ASTM A242, TYPE1

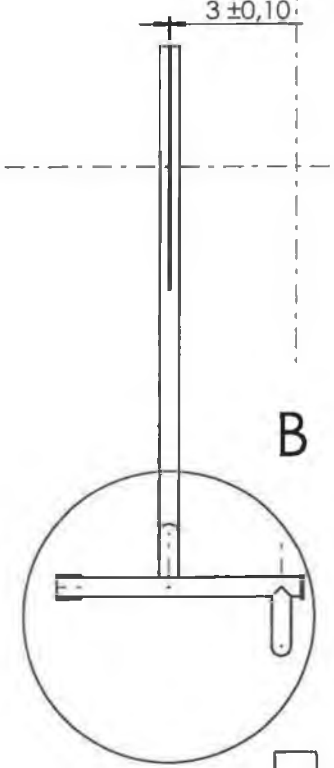
DWG NO.

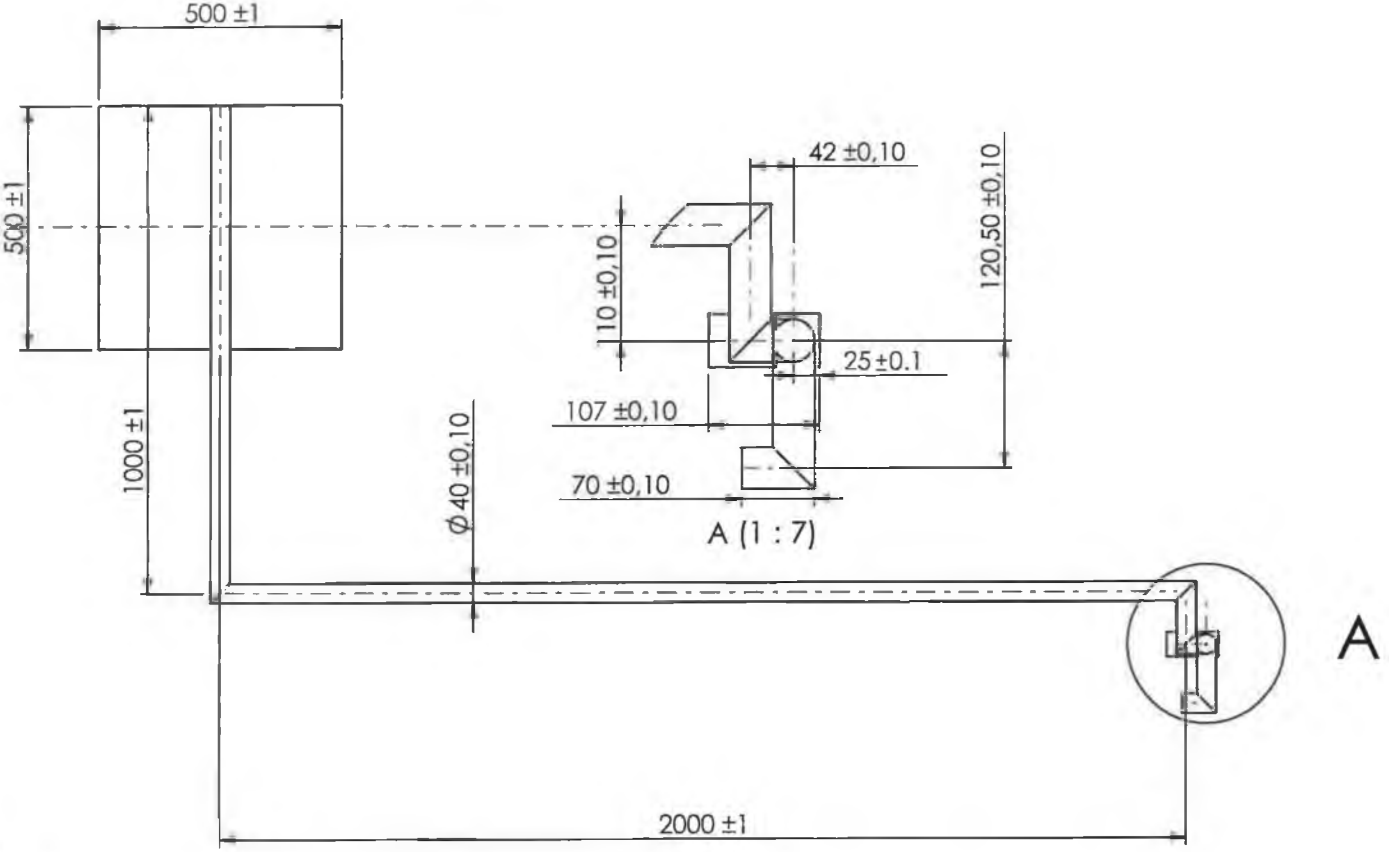
A4

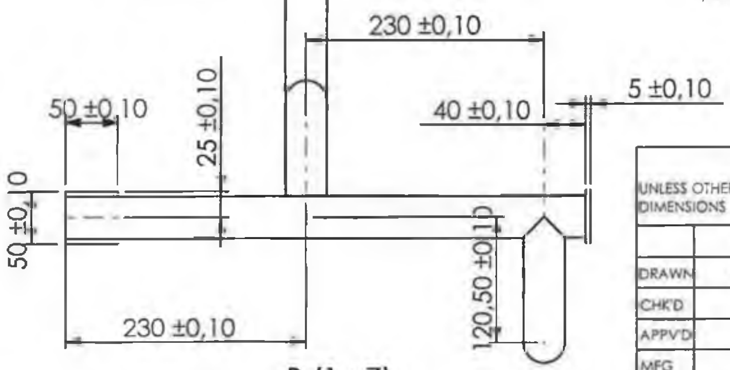
WEIGHT: 5KG

SCALE:1:5

Appendix 12







B (1 : 7)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DEBUR AND
BREAK SHARP
EDGES

GMIT

TITLE: FURLING LEVER FOR BLOCKING THE BLADE IN ITS WORKING POSITION AND UNLOCKING IT IN HIGH WINDS

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: STRUCTURAL STEEL

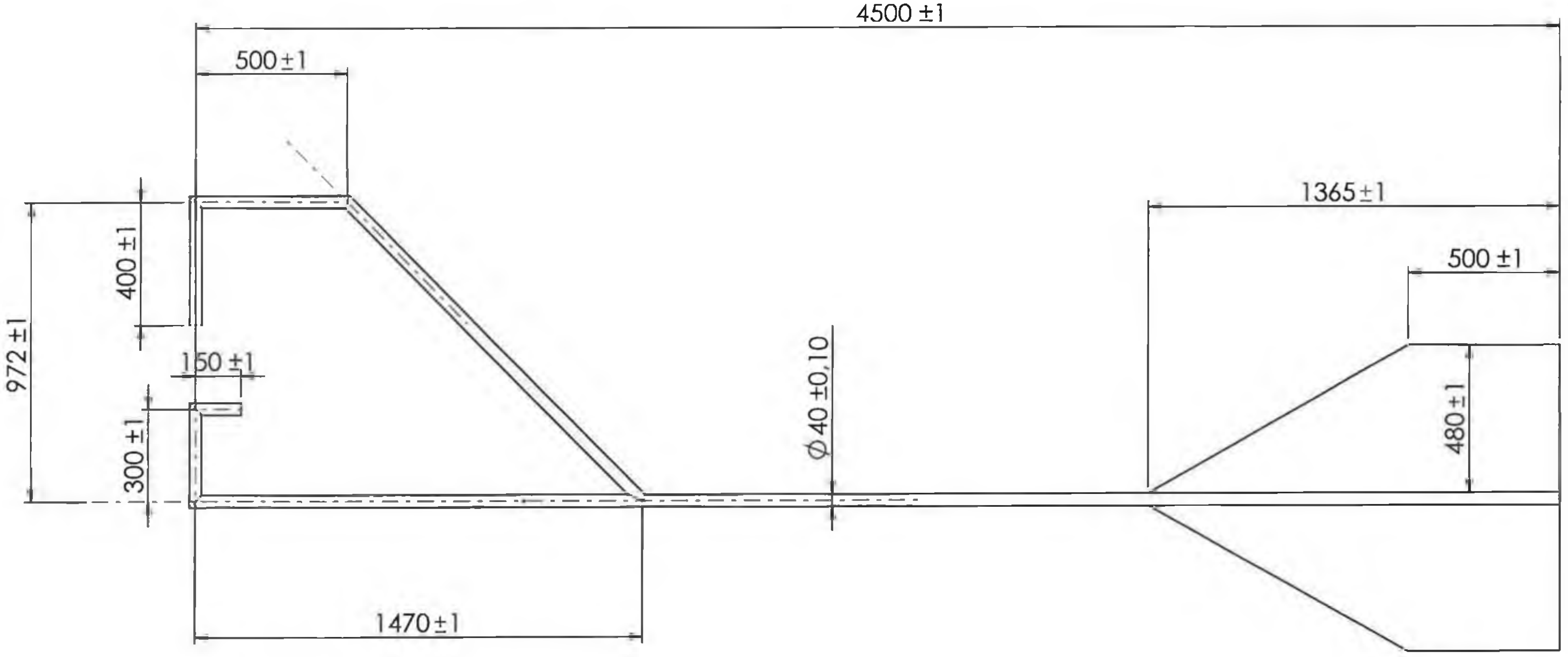
DWG NO.

A4

WEIGHT: 25KG

SCALE: 1:15

Appendix 13



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DEBUR AND
BREAK SHARP
EDGES

GMIT

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: TALE VANE

MATERIAL: STRUCTURAL STEEL

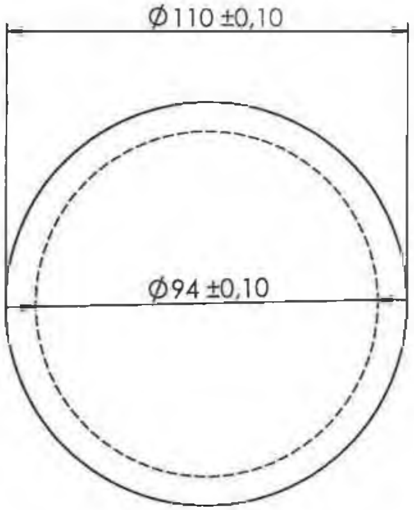
DWG NO.

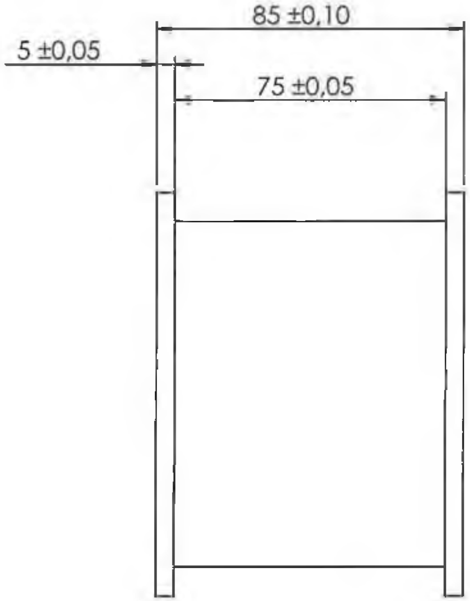
A4

WEIGHT: 40KG

SCALE: 1:20

Appendix 14





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

FINISH:

DEBUR AND BREAK SHARP EDGES

GMIT

	NAME	SIGNATURE	DATE
DRAWN	VLAD SOARE		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: IRON CORE

MATERIAL: IRON

DWG NO.

A4

WEIGHT: 0.5KG

SCALE:1:2