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Load Reduction in Wind Energy Converters Using

Individual Pitch Control

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة عمادة الدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحثة/ **أماني سالم محمد أبو ريالة** لنيل درجة الماجستير في **كلية *الهندسة*** **قسم الهندسة الكهربائية–أنظمة التحكم** وموضوعها:

Load reduction in wind energy converters using Individual Pitch Control

وبعد المناقشة العلنية التي تمت اليوم السبت 12 رجب 1433هـ، الموافق 2012/06/02م الساعة العاشرة صباحاً بمبنى اللحيدان، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

د. هالة الخزندار	**مشرفاً ورئيساً**	....
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وبعد المداولة أوصت اللجنة بمنح الباحثة درجة الماجستير في **كلية *الهندسة*/** قسم <u>الهندسة الكهربائية–أنظمة التحكم.</u>

واللجنة إذ تمنحها هذه الدرجة فإنها توصيها بتقوى الله ولزوم طاعته وأن تسخر علمها في خدمة دينها ووطنها.

والله ولي التوفيق ،،،

عميد الدراسات العليا

أ.د. فؤاد علي العاجز

Dedication

For my parents, brother, sisters, husband and

my lovely son, *Mohammed* …

and my coming daughter

Acknowledgment

Thanks to ALLAH Almighty, the creator of everything and the sustainer. Secondly, I would like to express my deepest gratitude and appreciation to my supervisor, Dr. Hala Jarallah El-khozondar for her guidance, encouragement, patience and trust throughout this research. Special thanks are extended to Mr. Mathias Müller from Technische Universität München (TUM) and Eng. Asmhan Al-Juba for their help for me during this research. Thanks are connected to Prof. Dr. Mohammed Hussein, the examiner of my thesis for his guidance.

I would like to thank my family, especially my parents, who have always kept me in their prayers. Moreover I would like to express my appreciations to all friends and relatives for their support.

Abstract

With the increase in population, the needs of living a better life are demanding more energy supply. Moreover, environment and safety are important factors in development of any energy producing system. That's why renewable energy systems are most reliable if they are developed with qualitative and quantitative research. The wind energy converters are heavy machines used to convert wind energy to electrical power. The European Wind Energy Association (EWEA) has set different targets till 2020-30 to get more energy from renewable sources as well as wind energy converters. This thesis work is to develop the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient. For this purpose, reliable and efficient sensor, sensing bending moment, stresses and strains caused by wind, gravitational and centrifugal forces at the root of the blade, are very important. A simple model of the blade with analysis of the moments generated by the wind and the gravity of each blade, when the blade is rotating is provided and is checked by the real values measured by fiber Bragg grating sensors of Fos4x German Company.

ملخص البحث :

مع تزايد عدد السكان في العالم , تتزايد احتياجاتهم للعيش حياة أفضل مما يستدعي المزيد من إمدادات الطاقة لأغراض الحياة المختلفة. وعلاوة على ذلك، سلامة البيئة والعيش بأمان من العوامل اللازمة عند تطوير أي نظام لإنتاج الطاقة .هذا السبب جعل نظم الطاقة المتجددة هي الأكثر موثوقية والأكثر تطورا في مجال البحث النوعي والكمي ونخص بالذكر هنا طاقة الرياح كمصدر طاقة متجدد.

تعتبر محولات طاقة الرياح من الآلات الثقيلة حيث تستخدم لتحويل طاقة الرياح إلى الطاقة الكهربائية .وقد وضعت الجمعية الأوروبية لطاقة الرياح (EWEA) أهداف مختلفة وخطط مستقبلية للحصول على المزيد من الطاقة من المصادر المتجددة، فضلا عن محولات طاقة الرياح حتى عام 2020-2030.

يتضمن هذا البحث تطوير المفهوم الأساسي ل (individual pitch control) لمحولات طاقة الرياح للحصول على أقصى قدر ممكن من قيمة معامل الطاقة, يتطلب ذلك أجهزة استشعار (sensors) موثوقة وفعالة تغذي نظام التحكم بقيم الضغوط والتوترات الناجمة عن الرياح وقوى الجاذبية والطرد المركزي التي تؤثر على ذراع محولات طاقة الرياح, و هي مهمة جدا للحفاظ على كفاءتها لأطول وقت ممكن .

يقدم هذا البحث نموذجا تحليليا مبسطا لذراع محول طاقة الرياح بتمثيله كنصف اسطوانة وبالتالي يسمح بإجراء الحسابات النظرية لقيم الضغوط والتوترات المؤثرة المتولدة من الرياح عليها خلال الدوران وسيتم فحص هذه القيم النظرية مع القيم الحقيقية التي تقاس بواسطة أجهزة الاستشعار المصنعة من شركة (Fos4x) الألمانية لإثبات مدى كفاءة هذا النموذج المستخدم .

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CHAPTER 1
INTRODUCTION

1.1 Status of wind energy

1.1.1 History of wind energy

Approximately 2% of the energy of solar radiation causes the air currents to move from high temperature areas to low temperature region. As a result, we get steady wind and sometimes hurricanes and cyclones and finally the kinetic energy[2]. The concept of harnessing the wind's energy has been around for thousands of years. It is estimated that the Chinese built the first wind turbines in 200 B.C. . Wind energy has been used to mill grains, sail ships, and pump the water. The first electricity generating wind turbine was developed in Scotland in the 1880's by Professor James Blyth of Anderson's College, Glasgow[3]. Since then, wind turbines have made serious strides in technology that after the industrial revolution, things are not like past. The scientists and engineers had to think to utilize the wind power in modern manners. Through research and development of decades, the modern wind turbines came into being.

1.1.2 Worldwide consumption of energy

The 80% of our energy demand is fulfilled by natural resources like Oil, Gas etc. These natural resources came into being after specific temperature and pressure conditions since a period of thousands years and we are using them since last 200 years after the development of engine. Studies shows that these natural resources are no longer available, we can use them maximum till 6 decades except coal which can be utilized till several hundred years. But the disadvantage of using coal is the environmental pollution. If we want to generate 1MWh electricity from coal, an amount of 1000 kg of CO_2 will be generated. Whereas in case of natural gas, this amount is halved. It is also indicated that global pollution is increasing with a rate of 1% annually. Figure 1.1 shows some statistics (year 2005) that our total primary energy supply is 12.029 mtoe (million tons of oil equivalent) from which 31% is lost during energy conversion. The rest of the energy, which is approximately 70% of primary energy supply, is used in different sectors like industry, transport, residential etc. Taking in account the renewable resources except nuclear and hydro, the total primary supply is very low, approximately 7% of the total amount. But considering future energy demand and consumption of resources, one can most probably say that, in future we have to turn over to these renewable energy sources.

1.1.3 Wind energy usage

The total amount of economically extractable power available from the wind is considerably more than the present human power use from all sources. It is shown in figure 1.2 that at the end of 2010, worldwide nameplate capacity of wind-powered generators was 195 GW. Wind power now has the capacity to generate 430 TWh annually, which is about

2.5% of worldwide electricity usage. Over the past five years the average annual growth in new installations has been 27.6 percent. Wind power market penetration is expected to reach 3.35 percent by 2013 and 8 percent by 2018[2].

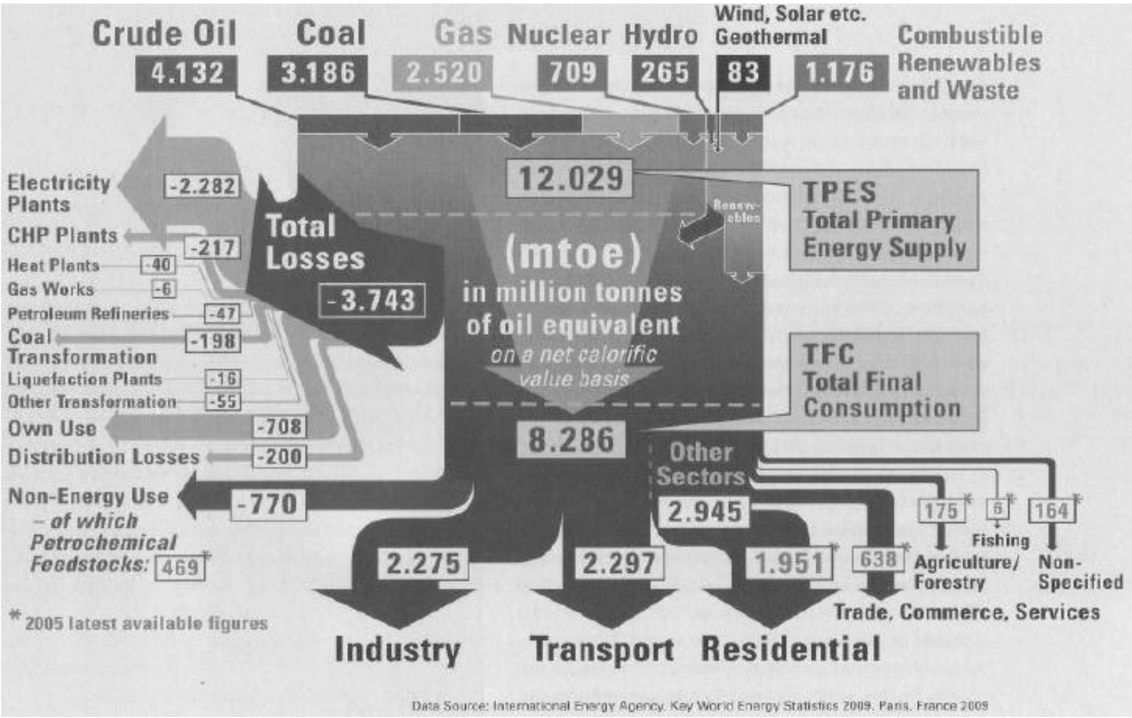


Figure 1.1: An overview of energy contribution, consumption and losses worldwide [2]

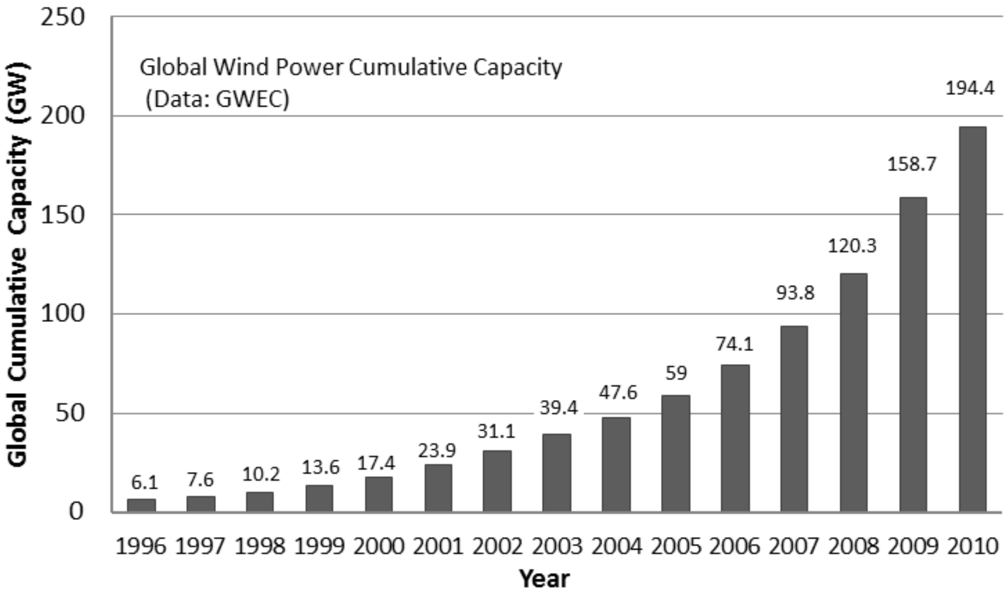


Figure 1.2: Global wind power cumulative capacity till 2010 [25]

Several countries have already achieved relatively high levels of wind power penetration, such as 21% of stationary electricity production in Denmark, 18% in Portugal, 16% in Spain, 14% in Ireland and 9% in Germany in 2010. As of 2011, 83 countries around the world are using wind power on a commercial basis.

About Germany, according to the world wind energy association (WWEA) , its total installed capacity is 27215.0 MW and the added capacity is 1551.0 MW. It has a grow rate of 5.6%, It shares 6% of wind energy consumption in 2009 as shown in figure 1.3. Its Rank in Europe is 1 and worldwide is 3.

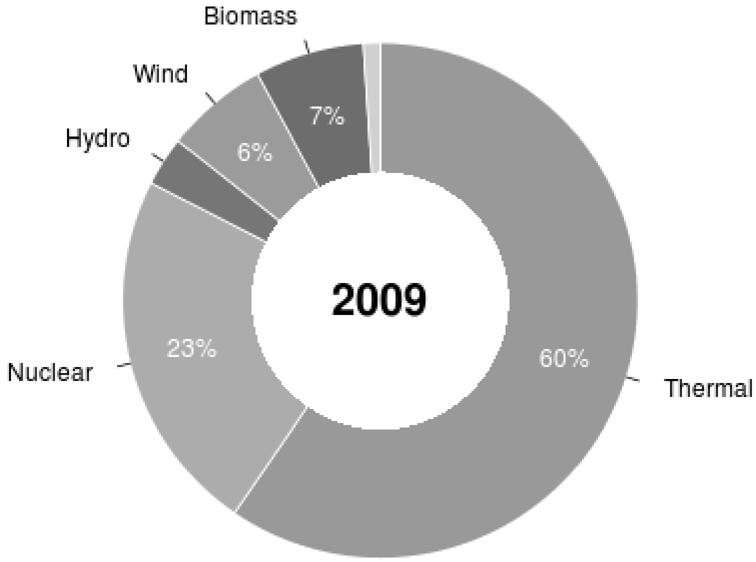


Figure 1.3: Germany – Electricity from all sources

1.1.4 Future view

The world's population could hit 9 billion in 2050. That is like adding another China or India to the planet. More people are also shaking off energy poverty, buying their first fridge, computer or car. The result is surging energy demand and rising environmental concerns. Figure 1.4 shows the possible energy contribution from different resources in future till 2100.

A range of sources will be needed to meet rising global energy demand over the coming decades. We believe that renewable sources could provide 30% of the world's energy by 2050. But fossil fuels will still meet the bulk of energy demand.

According to European Wind Energy Association (EWEA), the target till 2020 is 180GW from which 20% will come from offshore wind parks. Whereas till 2030, 300GW is decided to generate from wind energy and the contribution of offshore wind is approximated to 40%[2].

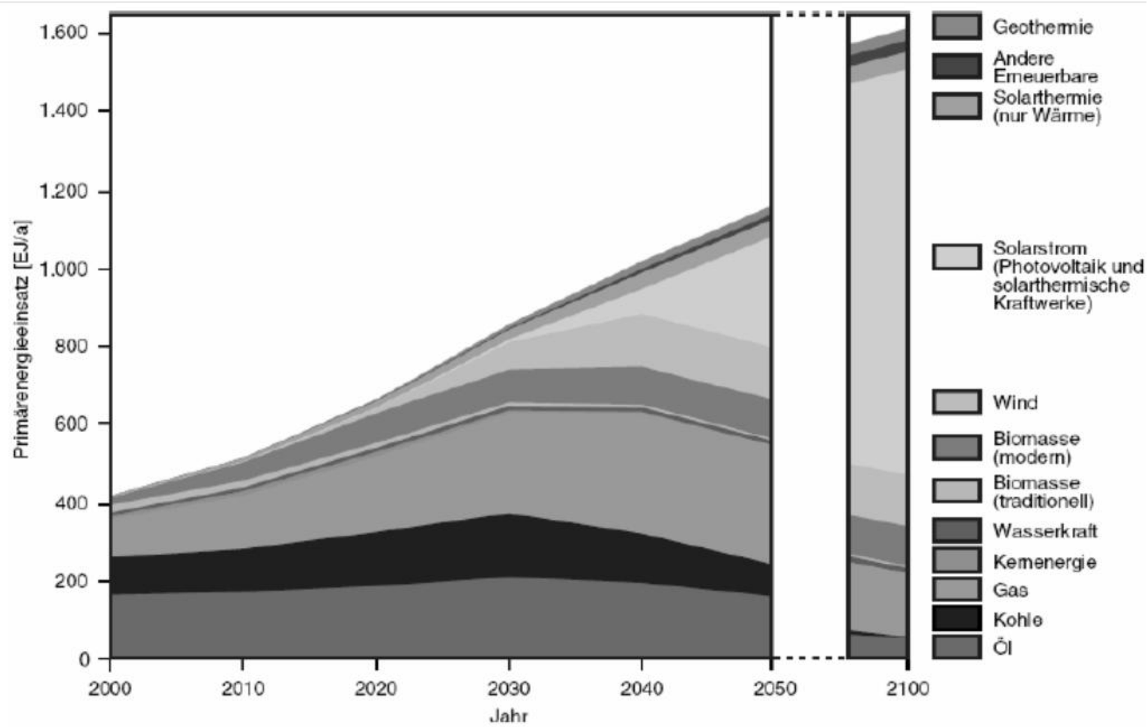


Figure 1.4: Possible energy contribution from different resources in future till 2100

It has been estimated by the Global Wind Energy Council (GWEC) that wind power could supply one third of the world's electricity by 2050. This is a big challenge not only for the wind energy sector, but for the entire electricity supply system. This shows the importance of research and development in this field. This master thesis is one of the attempts to contribute in this matter. The objective is to use the available knowledge and technology to develop appropriate tools for wind energy converters to get maximum efficiency with reliability.

1.2 Advantages and disadvantages

Wind energy offers many advantages, which explains why it is the fastest-growing energy source in the world. Research efforts are aimed at addressing the challenges to increase the use of wind energy[3].

1.2.1 Advantages

- A wind turbine which is made for capturing wind energy, needs little land to be built. The rest of the land can be effectively used for agricultural purposes.

- These turbines produce energy which does not contain any pollutants or green house gases. Hence there is no radioactive waste, thereby making this method of generating electricity, environment friendly.

- The wind is free, and we are able to cash in on this free source of energy and newer technologies are making the extraction of wind energy much more efficient.

- Wind turbines are a great resource to generate energy in remote locations, such as mountain communities and remote countryside. Also ,wind turbines can be a range of different sizes in order to support varying population levels.

- One of the major advantages of using wind power is that this method does not use any of the non renewable resources for generating electricity, thereby assisting in conservation of energy.

- Another advantage of wind energy is that when combined with solar electricity, this energy source is great for developed and developing countries to provide a steady, reliable supply of electricity.

1.2.2 Disadvantages

- The main disadvantage regarding wind power is down to the winds unreliability factor that it depends on the wind velocity, which could be high on some days and quite low on other days. Hence, power generated may not be the same on all days. Also, in many areas, the winds strength is too low to support a wind turbine or wind farm. Solar power and geothermal power are good alternatives in such regions.

- The noise pollution from commercial wind turbines is sometimes similar to a small jet engine. This is fine if you live miles away, where you will hardly notice the noise, but what if you live within a few hundred meters of a turbine? You will suffer from the high decibel levels which are perilous to health. This is a major disadvantage.

- Birds that fly at great heights, often get killed when they accidentally get cut by the rotating massive blades. However this disadvantage is just unavoidable.

- Wind turbine construction can be very expensive. On the other hand, It has the risk of getting damaged during thunderstorms and sudden bursts of lightning.

- Wind turbines generally produce allot less electricity than the average fossil fuelled power station, requiring multiple wind turbines to be built in order to make an impact.

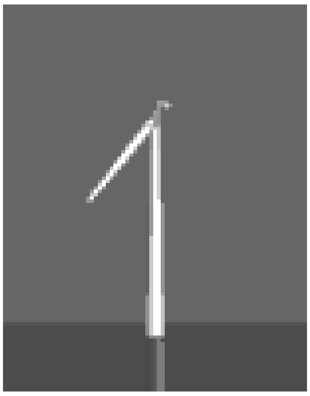
1.3 Types of wind energy converters (WEC)

Wind turbines can rotate about either a horizontal or a vertical axis. Main types of the WEC are discussed in the following subsections.

1.3.1 Horizontal Axis Converter

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. In this type of design the axis of rotation is parallel to the wind direction. It can be with one, two, three or multi-blades. This will affect the speed of its rotation.

Fast Rotation converters consist of only a few aerodynamically optimized rotor blades. Figure 1.5 shows the one and two bladed converters. These converters can deliver power ranging from 10 kW to some MW. The efficiency of this type of wind energy converters in comparison with other types of windmills is very high.



a) One bladed converter

b) Two bladed converter

Figure 1.5: Blade orientation

On the other hand, the slow rotation converters as the multi-bladed wind energy converter shown in figure 1.6 is another conventional (older) type of horizontal axis rotor. They have a high starting torque which makes them suitable for driving mechanical water pumps. The number of rotations is low, and the blades are made from simple sheets with an easy geometry. The rotor is turned in the direction of the wind by using a so called wind-sheet in leeward direction.

The mechanical stability of such "slow speed converters" is very high, some have had operation periods of more than 50 years. In order to increase the number of rotations, this type of converter had been improved and equipped with aerodynamically more efficient blades facilitating the production of electricity, where the area of a blade is smaller.

The most popular type of horizontal axis is the three bladed wind energy converter for generating electricity, worldwide. It is shown in figure 1.7. It is used usually in wind farms for commercial production of electric power and pointed into the wind by computer-controlled motors. The blades are usually colored light gray to blend in with the clouds.

Figure 1.6: Multi-bladed horizontal axis converter

Figure 1.7: Three bladed horizontal axis converter

1.3.2 Vertical axis converter

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable, for example when integrated into buildings. The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train.

With a vertical axis, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, hence improving accessibility for maintenance. At the following subsections , there are a brief description of types of the VAWTs :

1.3.3 Darrieus

Darrieus wind converter is shown in figure 1.8. They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source, or an additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

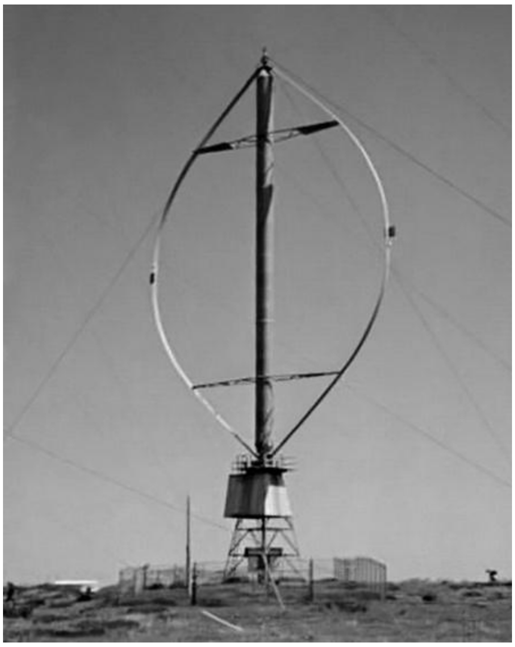


Figure 1.8: Darrieus wind converter

Giromill is a subtype of Darrieus turbine with straight, as opposed to curved, blades as shown in figure 1.9. It is typically powered by two or three vertical aerofoils attached to the central mast by horizontal supports. While it is cheaper and easier to build than a standard Darrieus turbine, it is less efficient, also requires strong winds (or a motor) to start, and can sometimes struggle to maintain a steady rate of rotation. However, they work well in turbulent wind conditions and are an affordable option where a standard horizontal axis windmill type turbine is unsuitable.

1.3.4 Savonius

These are drag-type devices as shown in figure 1.10 with two (or more) scoops that are used in anemometers, (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops.

1.3.5 Twisted Savonius

It is a modified Savonius, with long helical scoops as shown in figure 1.11 to give a smooth torque, this is mostly used as roof wind turbine or on some boats.

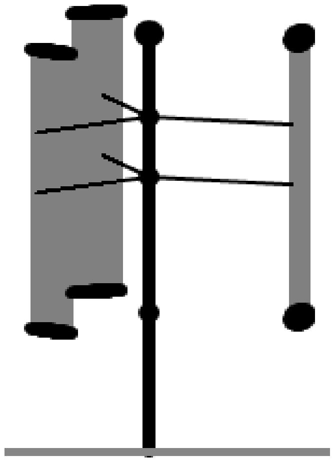


Figure 1.9: Giromill wind converter

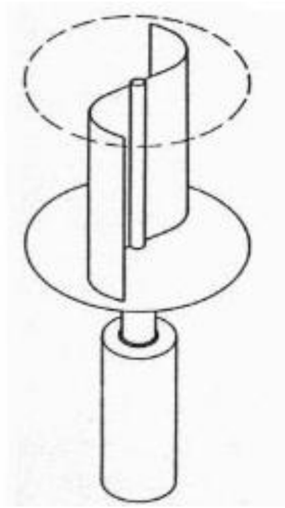


Figure 1.10: Savonius wind converter

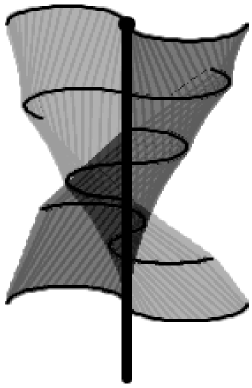


Figure 1.11: Modified Savonius converter

1.3.6 Upstream power station

The last technique to deal with is known as Up-Stream-Power-Station or thermal tower. In principle, it can be regarded as a mix between a wind converter and a solar collector. The top of a narrow, high tower contains a wind wheel on a vertical axis driven by the rising warm air. A solar collector installed around the foot of the tower heats up the air. The design of the collector is simple; a transparent plastic foil is fixed several meters above the ground in a circle around the tower. Therefore, the station needs a lot of space and the tower has to be very high. Such a system has a very poor efficiency, only about 1%. The advantage of such a design is its technical simplicity, which may enable developing countries to construct it by themselves.

1.4 Literature review

[1] T.G. van Engelen**,** derived a simple model for the combined design of collective and individual pitch control of 3 bladed HAWTs. He designed control loops for a typical 3 MW variable speed wind turbine and the performance was evaluated in aero-elastic simulations.

[2] Eduard Muljadi, investigated the operation of variable-speed wind turbines with pitch control. The system he considered is controlled to generate maximum energy while minimizing loads. The maximization of energy was only carried out on a static basis and only drive train loads were considered as a constraint.

[3] E. A. Bossanyi, suggested the possibility of using individual pitch control for load alleviation. His recent work demonstrates that some very significant reductions in loading can be achieved and that the control algorithms required for this may be relatively simple.

[4] Stoyan Kanev, Tim van Engelen, presented a novel application of IPC and rotor balancing. They introduced detailed nonlinear simulations to validate the proposed IPC algorithms.

[5] Holger Söker, Deutsches Windenergie, gave a user’s view on typical wind turbine systems and tried a structured approach to the essentials of rotor blade condition monitoring.

[6] T K Barlas and G A M van Kuik, researched the active rotor control and smart structures for load reduction. They presented an overview of available knowledge and future concepts on the application of active aerodynamic control and smart structures for wind turbine applications. They gave a perspective on the current status and future directions of this special area of research.

1.5 Thesis contribution

This thesis presents the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient. The half cylinder simple model to represent the blades of the wind energy turbines is proposed. This model is used to make an analytical measurements of the moments generated by the wind and the gravity of each blade then the stress and strain exerts each blade. The results will be compared by the real values measured by fiber Bragg grating sensors of Fos4x German Company

1.6 Thesis outlines

This thesis is organized as follows: chapter one gives an overview introducing the thesis , the second chapter introduces the main construction of the wind turbine, chapter three explains the basic principles of physics on which any wind turbine works, the fourth chapter presents the concepts of the individual pitch control, the fifth chapter shows the simple model that calculate the measurable quantities including stress and strain, the sixth chapter illustrates the simulation and results of this research and the final chapter covers the conclusion, recommendation and future work.

CHAPTER 2
WIND TURBINE CONSTRUCTION

Today the most common design of wind turbine and the only kind discussed in this thesis in the view of aerodynamic behavior is the three bladed horizontal-axis wind turbines. Figure 2.1 shows the main components of the Wind Energy Converter which will be described in the following sections.

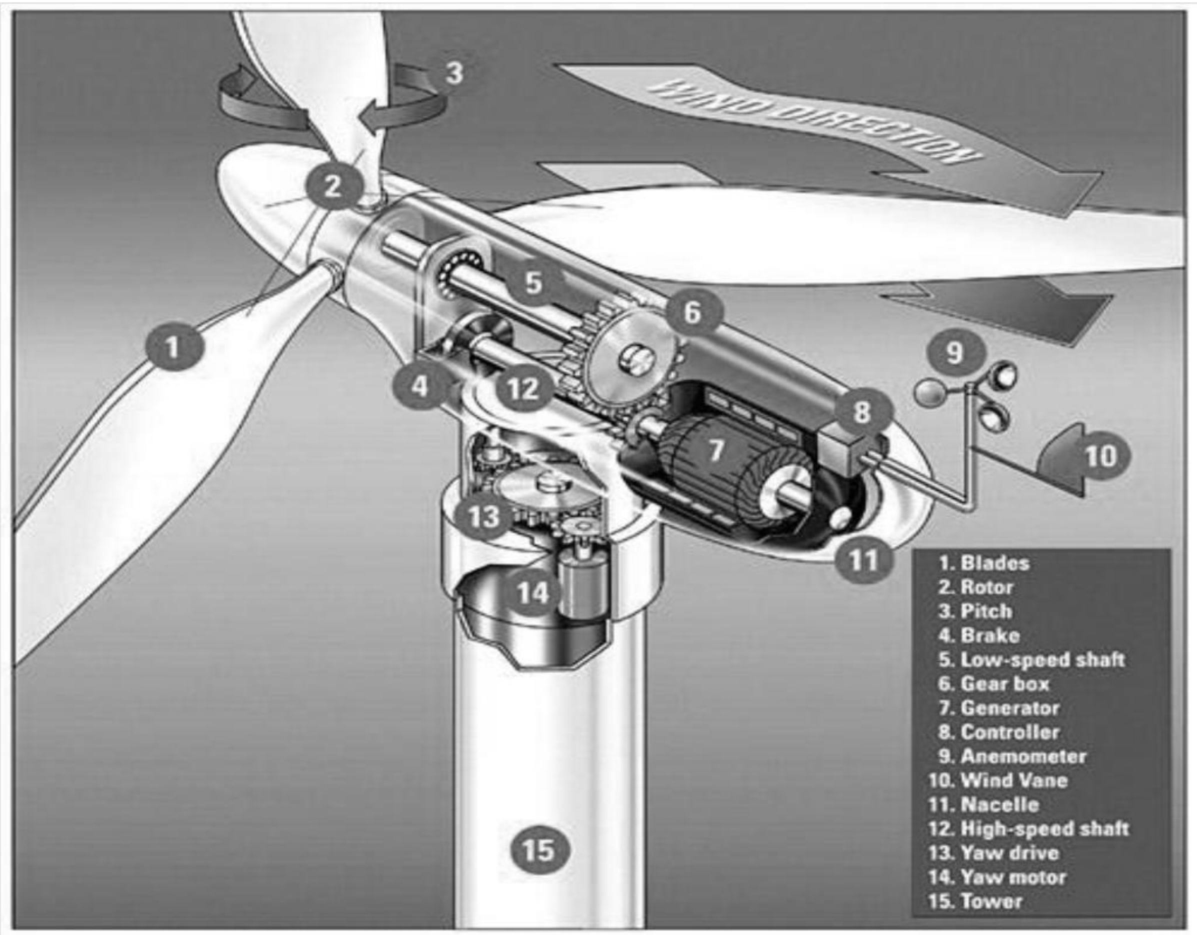


Figure 2.1: The main components of the Wind Energy Converter

2.1 Blades

The most common design is the three-bladed turbine. The most important reason is the stability of the turbine. The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability. Noise emissions are affected by the location of the blades upwind or downwind of the tower and the speed of the rotor. Most modern rotor blades on large wind turbines are made of glass fiber reinforced plastics, (GRP), i.e. glass fiber reinforced polyester or epoxy. Using carbon fiber or aramid (Kevlar) as reinforcing material is another possibility, usually such blades become necessary in large turbines in the range of 3–6 MW capacity.

For a given survivable wind speed, the mass of a turbine is approximately proportional to the cube of its blade-length. Wind power intercepted by the turbine is proportional to the square of its blade-length. The maximum blade-length of a turbine is limited by both the strength and stiffness of its material. Figure 2.2 shows a person standing beside medium size modern turbine blades.

Figure 2.2: A person standing beside medium size modern turbine blades

2.2 Rotor

Rotor is the main front area of a wind energy converter that converts the wind power to the mechanical power. It is composed of rotor blades. Since the power captured by the wind energy converter is directly proportional to the area of rotor, that's why to get more energy we have to increase the size of the blade. But as the size increases, it gives rise to cost factor. Moreover, vibration and instability factor in wind turbine increase due to the variation of wind speed with height.

2.3 Pitch

Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.

2.4 Brake

Braking action may be required for several reasons. There are several types of braking a turbine rotor: aerodynamic brakes , electro brakes and mechanical brakes.

In case of aerodynamic braking, the blade is turned in such a direction that the lift effect which causes rotation, does not appear.

In case of electro-magnetic braking, energy produced by the generator of a wind turbine is dumped into a resistor bank shown in figure 2.3, thereby converting it into heat. Another type of braking is conventional mechanical braking for which disc brakes are provided in the nacelle. A mechanical drum brake or disk brake is also used to hold the turbine at rest for maintenance. Such brakes are also applied after blade furling and electro braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed.

In large wind turbines, normally there is a combination of at least two brakes, most turbines use aerodynamic brakes together with mechanical braking or even also with an electro braking system.

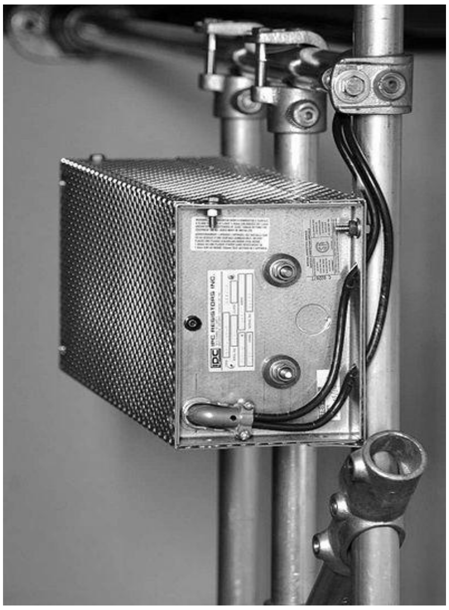


Figure 2.3: Dynamic braking resistor for wind turbine

2.5 Gearbox

It provides speed and torque conversions from a rotating power source to another device using gear ratios. Normally the rotational speed of the rotor is 15-20rpm but the rated speed of generator is 1700rpm (for example), so to increase this rotational speed of the shaft, gearbox is used.

2.6 Generator

It is the main component that is used to convert the wind energy (mechanical energy) to electrical energy. It can be synchronous or asynchronous (induction) generator. It is attached at one end to the wind turbine, which provides the mechanical energy and at the other end, it is connected to the electrical grid.

Small generators require less force to turn than larger ones, but give much lower power output. It is less efficient, i.e. if you fit a large wind turbine rotor with a small generator it will be producing electricity during many hours of the year, but it will capture only a small part of the energy content of the wind at high wind speeds.

On the other hand, large generators are very efficient at high wind speeds, but unable to turn at low wind speeds, i.e. if the generator has larger coils, and/or a stronger internal magnet, it will require more force (mechanical) to start in motion.

Generators need to have a cooling system to make sure there is no overheating. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for cooling by air, but a few manufacturers use hydraulically cooled generators. Hydraulically cooled generators may be built more compactly, but they require a heat exchanger (radiator) in the nacelle to get rid of the heat from the liquid cooling system.

2.7 Anemometer

Before actuating the controlling actions, measurement of wind speed and direction is necessary in every wind turbine. It is usually done using a cup anemometer . The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically.

Normally, the anemometer is fitted with a wind vane to detect the wind direction. Other anemometer types include ultrasonic or laser anemometers which detect the phase shifting of sound or coherent light reflected from the air molecules. Hot wire anemometers detect the wind speed through minute temperature differences between wires placed in the wind and in the wind shade (the leeward side).

The advantage of non-mechanical anemometers may be that they are less sensitive to icing in cold countries and jamming due to dust in hot locations.

2.8 Wind vane

It is an instrument for showing the direction of the wind as shown in figure 2.4. They are typically used as an architectural ornament to the highest point of a building. It is really just a flat piece of metal or wood on a swivel that catches the wind and points toward and away from the wind.

Figure 2.4: Wind vane

2.9 Nacelle

Nacelle is the main downstream box of the wind turbine and it has large importance because it has all the important components inside it for example the Gear Box, the Generator, the controller and other important sensors and actuators.

2.10 Yaw system

It is the component responsible for the orientation of the wind turbine rotor towards the wind. Figure 2.5 shows the schematic representation of the main wind turbine components. The yaw system is located between the wind turbine nacelle and tower.

Vertical axis wind turbines do not need a yaw system since their vertical rotors can face the wind from any direction and only their self rotation gives the blades a clear direction of the air flow. Horizontal axis wind turbines however need to orient their rotors into and out of the wind and they achieve that by means of passive or active yaw systems.

The active yaw systems are equipped with some sort of torque producing device able to rotate the nacelle of the wind turbine against the stationary tower based on automatic signals from wind direction sensors or manual actuation (control system override). By contrast, the passive yaw systems utilize the wind force in order to adjust the orientation of the wind turbine rotor into the wind .

Windward is the direction upwind from the point of reference. Leeward is the direction downwind from the point of reference. Figure 2.6 shows an example image showing definitions of windward (upwind) and leeward (downwind) . Figure 2.7 shows that the response of the turbine to the wind depends on the type of its yaw system and the direction of wind facing it.

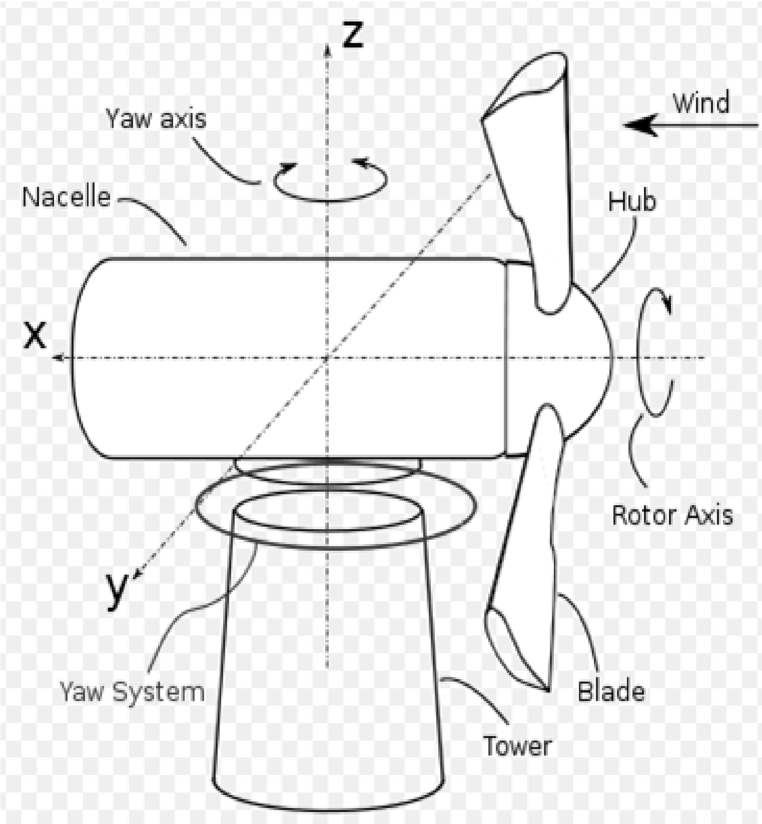


Figure 2.5: Yaw system

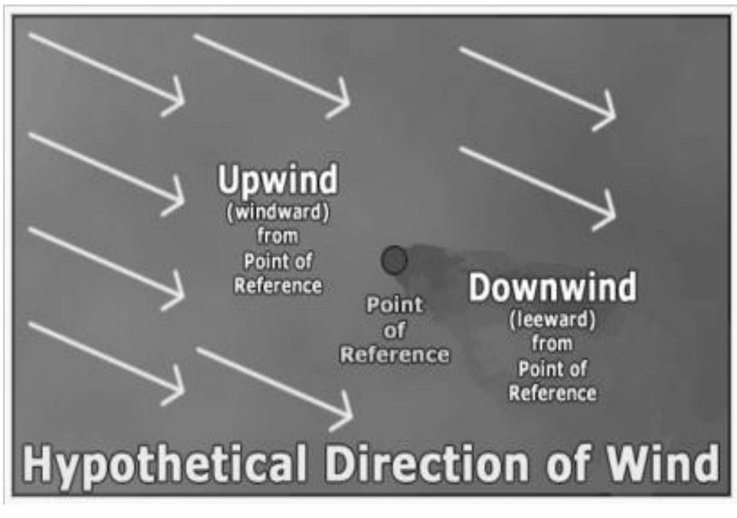
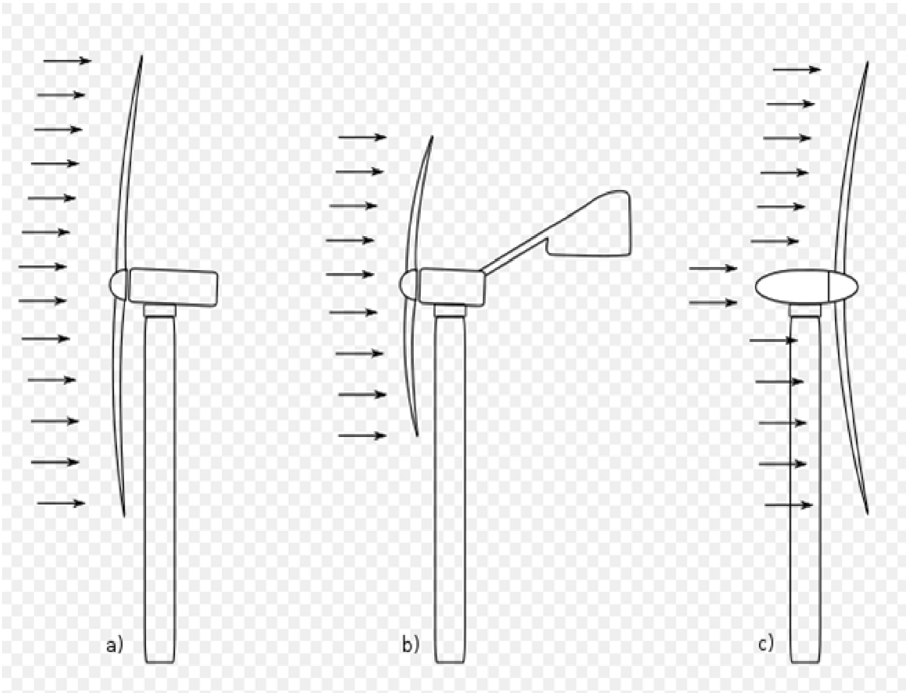


Figure 2.6: Example image showing definitions of windward and leeward



— a)Upwind wind turbine equipped with an active yaw system,
— b) Upwind wind turbine equipped with a passive yaw system,
— c) Downwind wind turbine equipped with a passive yaw system

Figure 2.7: Response of the wind turbine according to the type of its yaw system

2.11 Controller, Power Electronics, Sensors and Actuators

When the wind turbine is directly connected to the grid then it has constant speed and constant frequency (50Hz). However It is wanted to run it on different speeds then power electronics is needed to rectify the power. Sensors are needed to detect the wind speed and direction. Power converter system coupled to the generator and interconnected to generate an output power and provide it to the load. To rotate the blade along the pitch axis and to rotate whole rotor about the y-axis, hydraulic and pneumatic actuators are needed. The controller controls all the necessary actions and movements according to the commands and input parameters.

2.12 Tower and Foundation

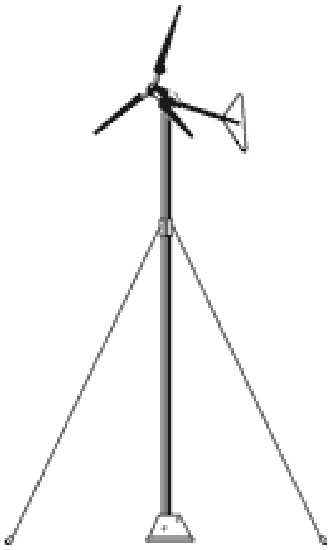
Tower is the main supporting part of the turbine because whole of the components are above its head. It must be strong enough to sustain all the vibrations, wind and hurricane forces to keep all the system stable. It needs to be as tall as possible, because the wind speed increases with height. However, the height is optimized by analyzing the cost of the increase in tower height and the gain in energy output due to increased wind velocity at a greater height.

Towers for large wind turbines may be either tubular steel towers, lattice towers, or concrete towers. Guyed pole towers are only used for small wind turbines. These different types are shown in figure 2.8.

a) Tubular steel tower

b) Lattice tower

c) Concrete tower



d) Guyed pole tower

Figure 2.8: Types of WEC towers

But there is one other thing, that is hidden, but it is the backbone for tower as well and it is called foundation of the tower. Foundation plays a very important role in stabilizing the wind turbine. Due to the large height, heavy weight at the nacelle and large rotor area which faces wind forces, the role of a foundation becomes very important.

While in case of onshore installations, the type of foundation depends upon the nature of the soil, they are made by civil engineering technology by digging up to some meters inside the ground. In case of offshore turbines shown in figure 2.9, it becomes an even more serious issue. It is very complicated and must be designed with care.

Figure 2.9: Offshore wind turbine

Some common types of foundations, used for offshore turbines, are monopole, tripod etc are shown in figure 2.10. For shallow waters of depth 0-30m monopole foundation is used in which a steel pipe is driven into the seabed approximately 10-20m. In gravity foundation, a heavy type of foundation rests on the seabed to support the wind turbine. For deep waters, tripod type foundation is used.

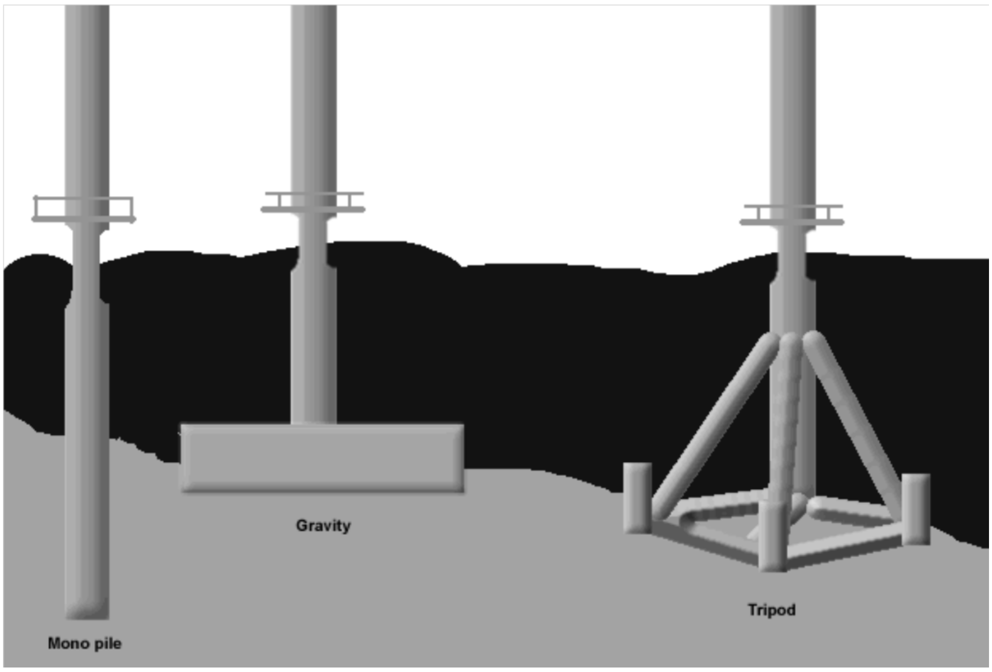


Figure 2.10: Different types of foundations used in offshore turbines

CHAPTER 3

PHYSICS OF WIND ENERGY

The basic principles of physics on which any wind turbine works are explained in this chapter. These concepts will be helpful in understanding the science and technology behind the operation and control of wind turbines in order to harvest maximum energy from the wind.

3.1 Power in the Wind

The importance of accurate wind speed data becomes clear when one understands how the speed affects the power. Consider a disk of area A with an air mass dm flowing through that area. In a time dt the mass will move a distance $u\,dt$, creating a cylinder of volume $A\,u\,dt$, which has a mass $dm = A\,\rho\,u\,dt$, where ρ is the density of air. The power contained in the moving mass is the time rate of change in kinetic energy, given by

$$P = d(KE)/dt = d\left(\frac{1}{2}\ m\,u^2\right)/dt = \frac{1}{2}\ u^2\,(dm/dt) = \frac{1}{2}\ A\,\rho\,u^3 \tag{3.1}$$

Therefore, the power is proportional to the wind speed cubed. It is important to know the wind speed precisely, because any error is magnified when calculating power. Equation 3.1 verifies that the amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

3.1.1 Power curve characteristics

The power curve of a wind turbine indicates which electrical power output will be available at different wind speeds as shown in figure 3.1. Usually, wind turbines are designed to start running at wind speeds somewhere around 3–5 m/s. This is called the cut in wind speed. Below this speed of wind, the energy in wind is not sufficient to overcome the inertia of the rotor; hence, the machine does not produce any power below this speed of wind.

The wind turbine will be programmed to stop at high wind speeds above, say, 25 m/s, in order to avoid damaging the turbine or its surroundings. The stop wind speed is called the cut out wind speed. The “rated wind speed” is the wind speed at which the “rated power” is achieved. This value for megawatt size turbines is about 12– 15 m/s, and it corresponds to the point at which the conversion efficiency is near its maximum. The power output above the rated wind speed is mechanically or electrically maintained at a constant level, because the high output would destroy the equipment.

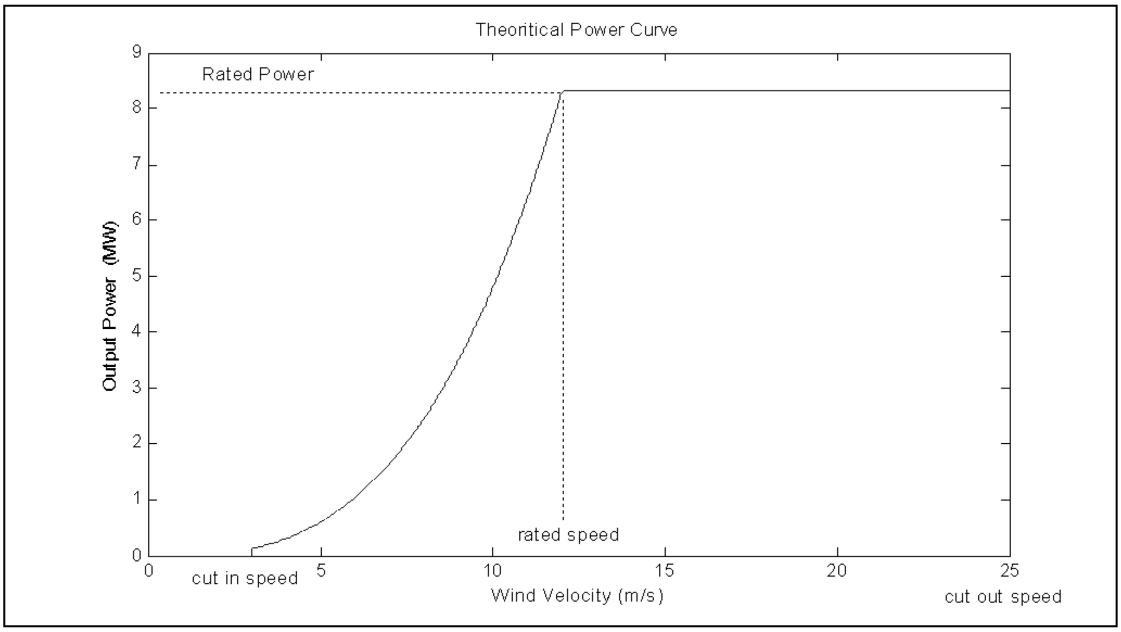


Figure 3.1: Relationship between wind velocity and power of wind

Besides the above three important speeds of any power curve, there is one more speed which is specific together with the power curve; survival speed. It is that minimum speed at which the wind converter would not be able to sustain for its survival. The survival speed being more than cut-off speed, is not shown in the power curve. Its value is around 50–60 m/s. This value becomes one very important factor when selecting a wind turbine. It should be ensured that the maximum ever wind velocity in that location is lower than the survival speed of the machine.

It can be noted from the power curve that at lower wind speeds, the power output drops off sharply. This can be explained by the cubic power law which is proved in equation(3.1), which states that the power available in the wind increases eight times for every doubling of wind speed and decreases eight times for every halving of the wind speed.

Using the power curve, it is possible to determine roughly how much power will be produced at the average or mean wind speed prevalent at a site. However, it is recommended to use the Weibull distribution for estimating the power output in connection with the power curve. Measurements at different places show that the distribution of wind velocity over the year can be approximated by a Weibull-equation[3]. Figure 3.2 shows a Weibull distribution plot between wind velocity and probability for a particular site which has a mean wind speed of 7 m/s, and the shape of the curve is determined by a so called shape parameter of 2. The statistical distribution of wind speed varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface.

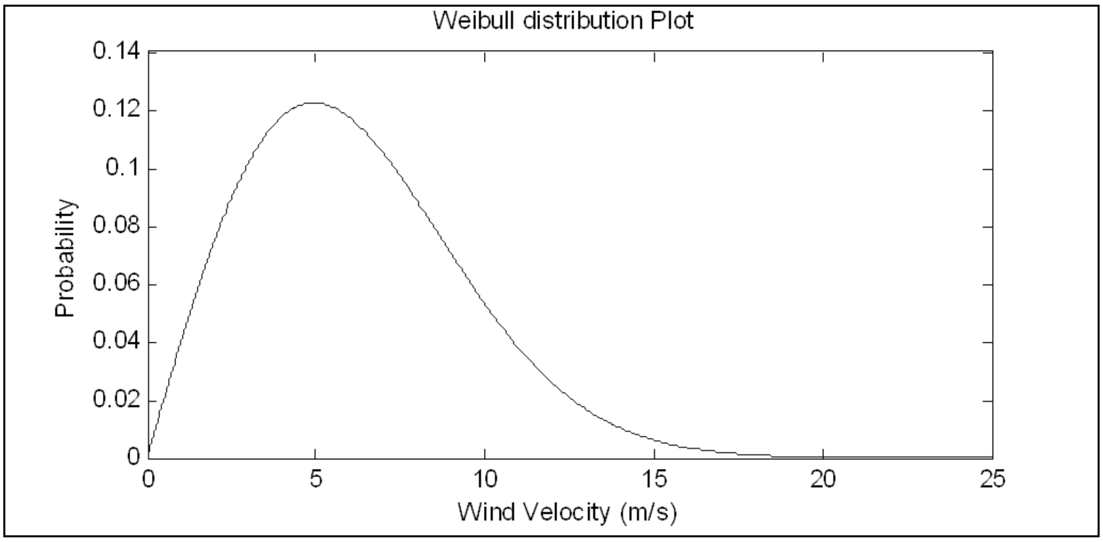


Figure 3.2: Weibull distribution plot between wind velocity and probability

3.1.2 Power Coefficient

The wind turbine rotor must obviously slow down the wind as it captures its kinetic energy as shown in figure 3.3 and converts it into rotational energy. This means that the wind will be moving slowly after leaving the rotor as compared to its movement before entering the rotor. Farther downstream, the turbulence in the wind will cause the slow wind behind the rotor to mix with the faster moving wind from the surrounding area. The wind shade behind the rotor will therefore gradually diminish as one moves away from the turbine.

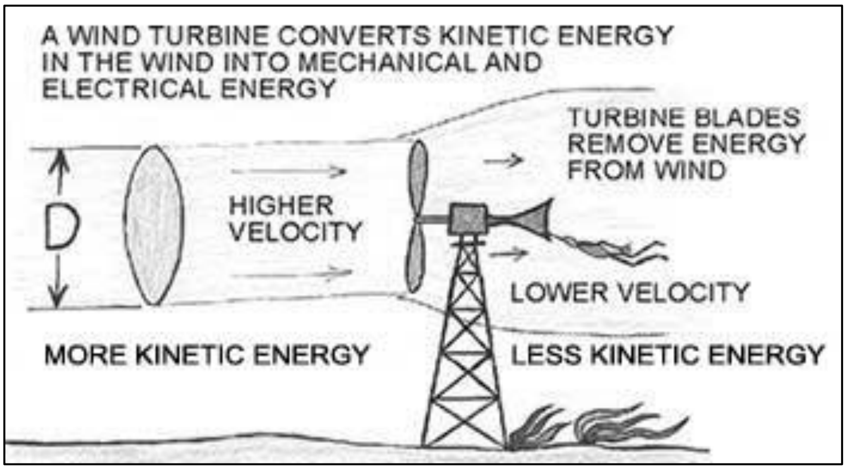


Figure 3.3: Energy conversion at the wind turbine rotor

The question of how much of the wind energy can be transferred to the blade as mechanical energy. Consider once again the cylinder of air used to calculate the power in the wind. The stream tube travels towards the rotor of the wind turbine, as shown in figure 3.4, with an initial velocity u and slows to u_1 (due to pressure changes) by the time it reaches the rotor. The rotor captures some of the energy so that air flowing out behind it moves even more slowly, at a velocity u_2, but the same amount (mass) of air coming towards the rotor also leaves behind the rotor.

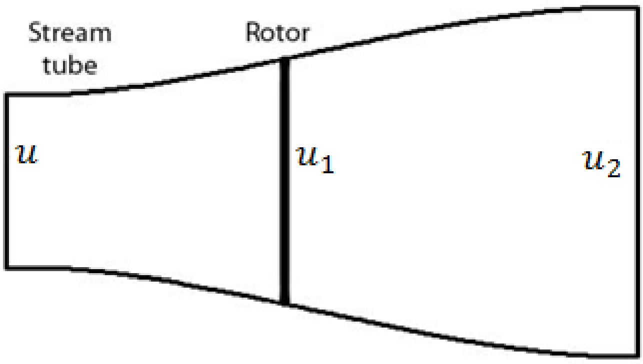


Figure 3.4: Stream tube around a rotor, showing the velocities at various points[16]

Because linear momentum is always conserved, a force must act on the wind to make it slow down. From Newton's third law, this force on the wind is equal to and opposite the thrust, T, the force of the wind on the turbine. The thrust force comes from a change in pressure as the wind passes the rotor and slows down. Conservation of linear momentum dictates that the thrust must be equal and opposite the change in momentum. We can look at the initial velocity of the air before the rotor, u, and the final velocity of the air after the rotor, u_2, along with the mass flow, to find the change in momentum:

$$T = \frac{dm}{dt}(u - u_2) = u\,(\rho\, A\, u) - u_2(\rho A u)_2 = \frac{1}{2}\rho A(u^2 - {u_2}^2) \tag{3.2}$$

Defining the flow velocity at the rotor u_1 is the average of the velocities before and after:

$$u_1 = \frac{1}{2}\,(u + u_2) \tag{3.3}$$

Defining the axial induction factor a, the fractional decrease in the wind velocity once it has reached the rotor, due to a change in pressure (depending on how much energy the rotor captured to slow the wind) :

$$a = \frac{1}{u}\,(u - u_1) \tag{3.4}$$

then

$$a\,u = u - u_1$$
$$u_1 = u\,(1 - a) \tag{3.5}$$

From equation 3.3 and equation 3.5, we have:

$$\frac{u + u_2}{2} = u\,(1 - a) \tag{3.6}$$

Then

$$u_2 = u\,(1 - 2a) \tag{3.7}$$

From equation 3.2, The power transferred to the wind turbine P_R is given by:

$$P_R = T\,u_1 = \frac{1}{2}\,\rho\,A\,(\,u_2 - u_2{}^2)\,u_1 \tag{3.8}$$

Substituting for u_1 and u_2 from equations (3.5) and (3.7) into equation (3.8), it yields the power in the rotor P_R as follows:

$$P_R = \frac{1}{2}\rho\,A\,u\,(1 - a)\,(\,u^2 - (u\,(1 - 2\,a))^2) \tag{3.9}$$

$$P_R = \frac{1}{2}\rho\,A\,u^3\left[\,(1 - a)\big(\,1 - (1 - 2\,a)^2\big)\right] \tag{3.10}$$

$$P_R = \frac{1}{2}\rho\,A\,u^3\,[\,(1 - a)\,(4\,a - 4\,a^2)\,] \tag{3.11}$$

$$P_R = \frac{1}{2}\rho\,A\,u^3\,[\,4\,a\,(1 - a)^2\,] \tag{3.12}$$

The relationship between the mechanical power of the rotor blade P_R and the power of wind P in the rotor area is given by the power coefficient c_p which indicates the efficiency of the turbine :

$$c_p = \frac{P_R}{P} = 4\,a\,(1 - a)^2 \tag{3.13}$$

Taking the derivative of the power coefficient with respect to a and setting it equal to zero:

$$dc_p/da = 0 \tag{3.14}$$

$$\frac{d}{da}\,(4\,a\,(1 - a)^2) = 0 \tag{3.15}$$

$$3a^2 - 4a + 1 = 0 \tag{3.16}$$

$$(3a - 1)(a - 1) = 0 \tag{3.17}$$

$$a = \frac{1}{3}\;or\;a = 1 \tag{3.18}$$

It yields the axial induction factor of $1/3$ which maximizes the power coefficient. At this value of a, the power coefficient equals 0.5926. Theoretically, this is the maximum possible value of power coefficient and is called “Betz coefficient”, but maximum value obtained in practice varies from 0.45 to 0.50. This number is not high because the wind on the back side of the rotor must have a high enough velocity to move away and allow more wind through the plane of the rotor. Therefore, from equation 3.4, the turbine will slow down the wind by $2/3$ of its original speed. Notice that when a equals 1, it will be the case at which the power coefficient is minimum.

3.1.3 Tip speed ratio

A wind energy converter is classified through the characteristic tip speed ratio λ . λ_r is the local speed ratio, i.e. the ratio of the rotor speed at radius r to the wind speed at r.

$$\lambda_r = \frac{\omega\, r}{u} \qquad (3.19)$$

Where ω is the angular velocity of the blade. When $r = R$ where R is the length of the blade, $\lambda_R = \omega R/u = \lambda$, the tip speed ratio. The tip speed ratio is a very important parameter selected in the design of every wind turbine, because a greater tip speed ratio implies a greater power coefficient. The tip speed ratio can range from 5 to about 10 for electricity-generating applications.

Figure 3.5 shows an example of the relationship between the c_p and λ according to the approximation of $c_p(\lambda, \varphi)$ characteristic by the following form:

$$c_p(\lambda\,, \varphi) = c_1 \left(c_2 \frac{1}{\beta} - c_3\varphi - c_4\varphi^x - c_5 \right) e^{-c_6 \frac{1}{\beta}} \qquad (3.\ 20)$$

Since the function depends on the wind turbine rotor type, the coefficients $c_1 - c_6$ and x can be different for various wind turbines. The proposed coefficients [24] are: c_1 = 0.5, c_2 = 116, c_3 = 0.4, c_4 = 0, c_5 = 5, c_6 = 21 (x is not used because c_4 = 0). Additionally, the parameter β is also defined as:

$$\beta = \frac{1}{1/(\lambda+0.08\,\varphi) - 0.035/(1+\varphi^3)} \qquad (3.21)$$

These values are used for the plot in figure 3.5 by taking different values of the pitch angle φ = 0, 5, 10, 15, 20. It shows that the tip speed ratio has a strong influence on the efficiency of a wind energy converter. When λ is small, the circumferential velocity is also small which results in an increase in the angle of attack α. Thus the wind flow breaks away from the blade profile and becomes turbulent, thus dramatically reducing the lift force acts on the blade. If the tip speed ratio is too large, the lift force will reach its maximum value and decrease afterwards, thus reducing the power efficiency of the converter.

3.2 Aerodynamics of Blades

A careful choice of the shape of the blades is crucial for maximum efficiency. Today's wind turbines use airfoils, which are specially designed for use on rotors. They use the concept of lift, as opposed to drag, to harness the wind's motion. In Figure 3.6, there are some examples of the cross sections of blades (airfoils) used for wind turbines.

There are many parameters to characterize an airfoil as shown in Figure 3.7. The shape determines the performance of the airfoil, and often changes along the span of the blade. For instance, the blade is always much thicker at the base than at the tip, mostly for support.

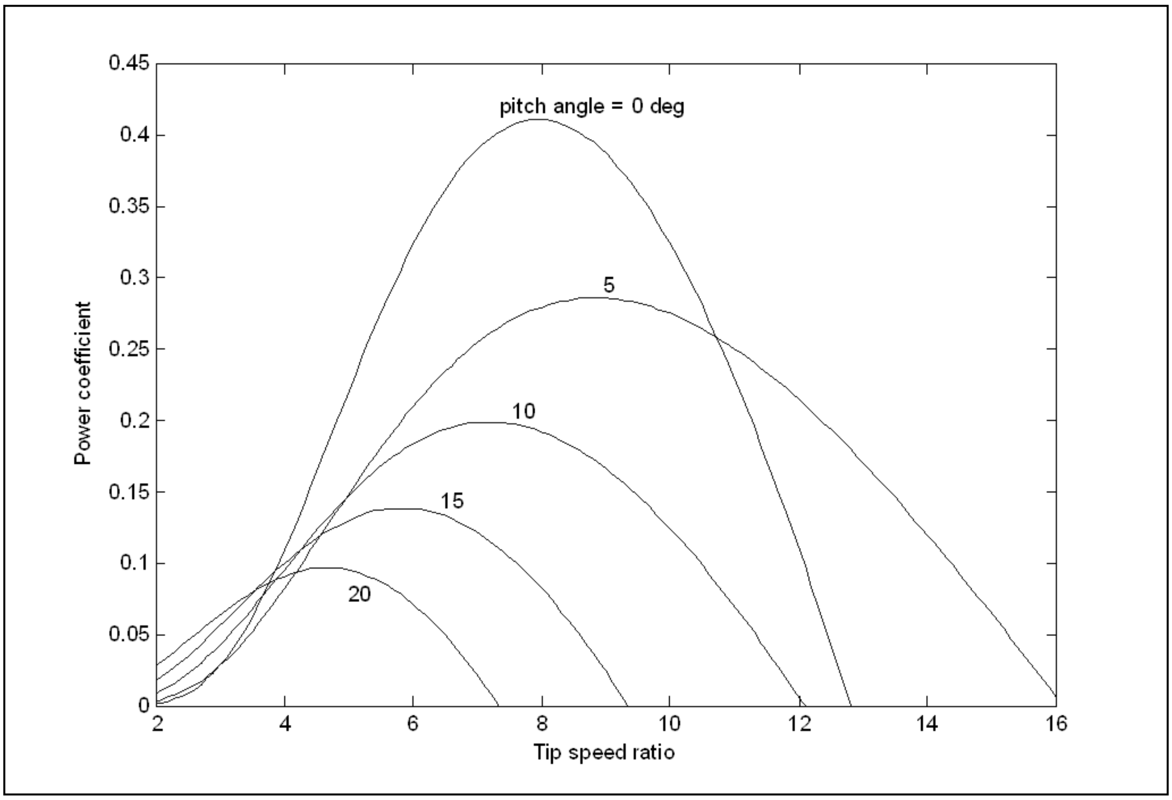


Figure 3.5: Example of the relationship between the c_p and λ

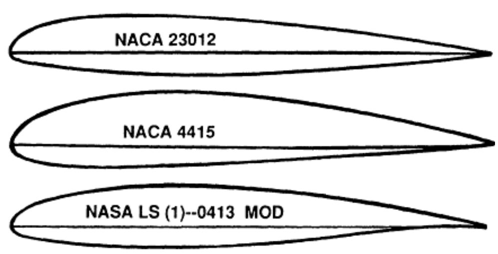


Figure 3.6: Example airfoils

3.3 Blade element theory

Blade element theory (BET) is a mathematical process determines the behavior of propellers[25]. It involves breaking a blade down into several small parts as shown in figure 3.8 then determining the forces on each of these small blade elements. These forces are then integrated along the entire blade and over one rotor revolution in order to obtain the forces and moments produced by the entire rotor.

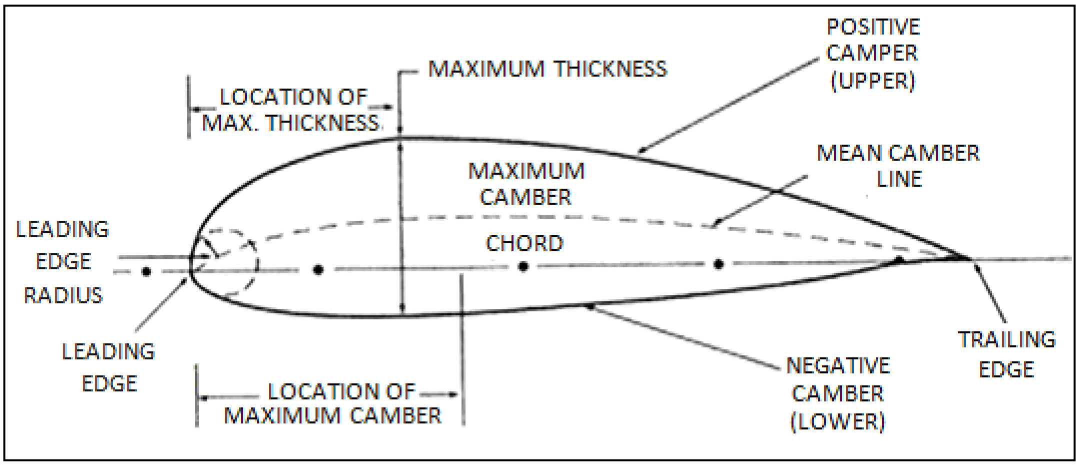


Figure 3.7: Airfoil terminology

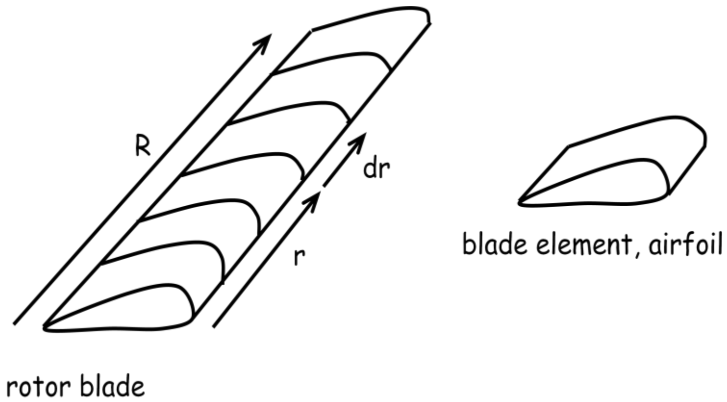


Figure 3.8: Blade element theory concept

3.4 Energy Conversion at the Blade

The wind flows perpendicular to the plane of the rotor at an angle of attack α, which is the angle between the wind direction and the chord line of the airfoil, as shown in figure 3.9. The two main forces acting on the rotor blade are the lift force F_L and the drag force F_D. The drag force acts parallel to the initial direction of movement and the lift force acts perpendicular to it as shown in figure 3.9 . The lift force is the greater force in normal operating conditions and arises due to the unequal pressure distribution around an aerofoil profile. The pressure on the upper surface is lower than that on the underside, therefore the air has a higher velocity when passing over the upper surface of the profile.

The lift force is determined by the following formula:

$$F_L = \frac{1}{2}\, \rho\, c_L\, u^2\, A \tag{3.22}$$

where c_L is the lift force coefficient. The drag force is determined by a similar formula,

$$F_D = \frac{1}{2}\, \rho\, c_D\, u^2\, A \tag{3.23}$$

where c_D is the drag force coefficient, and is caused by air friction at the surface of the profile[16].

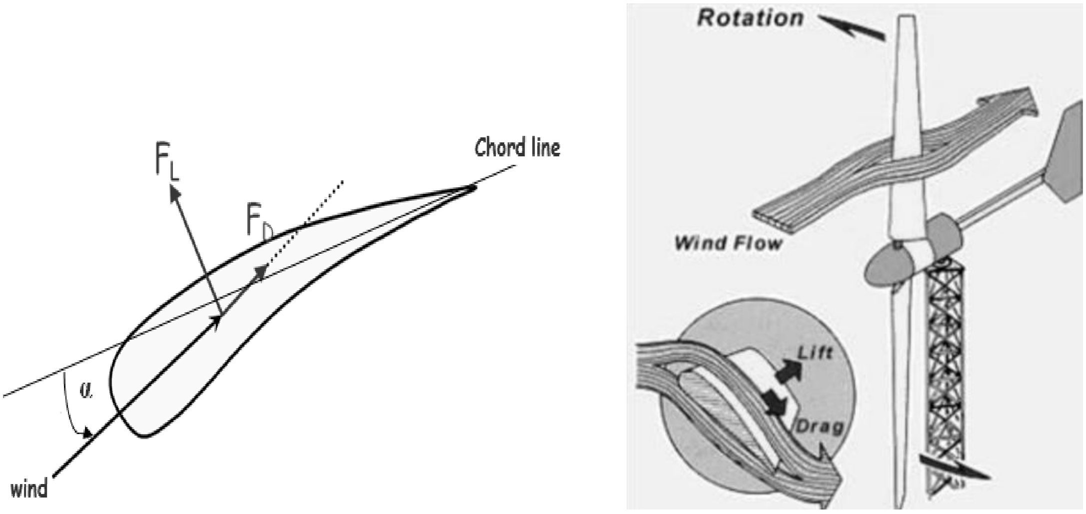


Figure 3.9: Forces acting on the airfoil due to wind

CHAPTER 4

INDIVIDUAL PITCH CONTROL

The global market for the electrical power produced by the wind energy converters has been increasing steadily, which directly pushes the wind technology into a more competitive arena. Thus, a reliable control system is needed to increase the lifetime and efficiency of the wind turbines.

4.1 Pitch Control

Blade pitch refers to turning the angle of attack of the blades of a wind turbine rotor into or out of the wind to control the production or absorption of power. It is used to adjust the rotation speed and the generated power.

On a pitch controlled wind turbine, the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again. The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in figure 4.1.

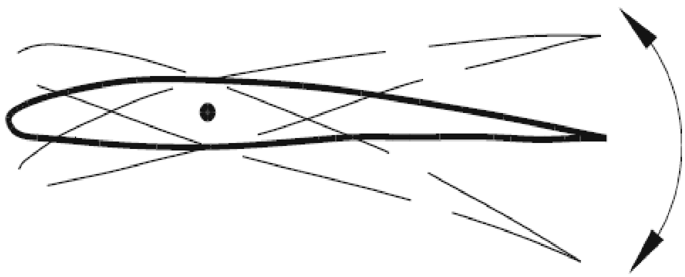


Figure 4.1 :Variable pitch blades[3]

Blade pitch control is a feature of nearly all large modern horizontal-axis wind turbines. While operating, a control system adjusts the blade pitch to keep the rotor speed within operating limits as the wind speed changes. Feathering the blades stops the rotor during emergency shutdowns, or whenever the wind speed exceeds the maximum rated speed. During construction and maintenance of wind turbines, the blades are usually feathered to reduce unwanted rotational torque in the event of wind gusts.

During normal operation, the blades will pitch by fraction of a degree at a time and the rotor will be turning at the same time. The pitch mechanism can be operated using hydraulic systems. But in most cases, individual electric drives are used to actuate control of blades as shown in figure 4.2.

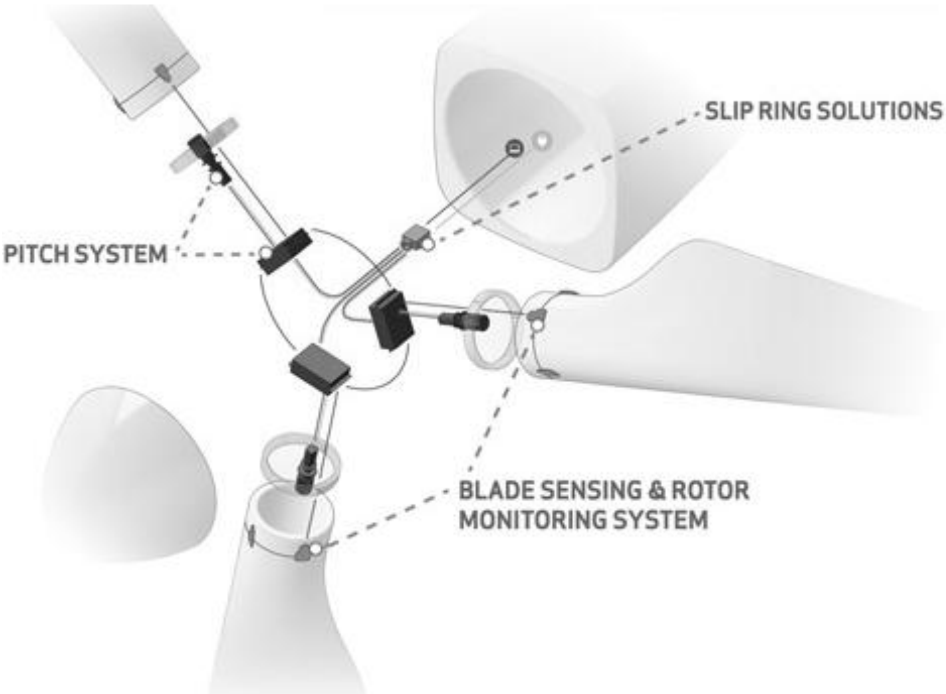


Figure 4.2: The pitch mechanism

From equation 3.1 , the total power of the wind is:

$$P = \frac{1}{2} A \rho u^3 \quad (4.1)$$

Recalling equation 3.13, the received power is :

$$P_R = c_p . P \quad (4.2)$$

And from equation 3.20 :

$$P_R = c_p(\lambda , \varphi) . P \quad (4.3)$$

From equation 3.19 :

$$\lambda_r = \frac{\omega r}{u} = \lambda(u) \quad (4.4)$$

Thus ;

$$P_R = c_p(\lambda (u) , \varphi) . P$$

$$= c_p(\lambda(u) , \varphi) . \frac{1}{2} A \rho u^3 \quad (4.5)$$

$$= P_R(u, \varphi)$$

It is concluded that the received power is a function of the wind speed and the pitch angle. Figure 4.3 shows a plot of the received power versus the wind speed at different values of pitch angle. It shows how the maximum output power varies with the pitch angle. So a control strategy is needed to give the best pitch angle according to the input wind data.

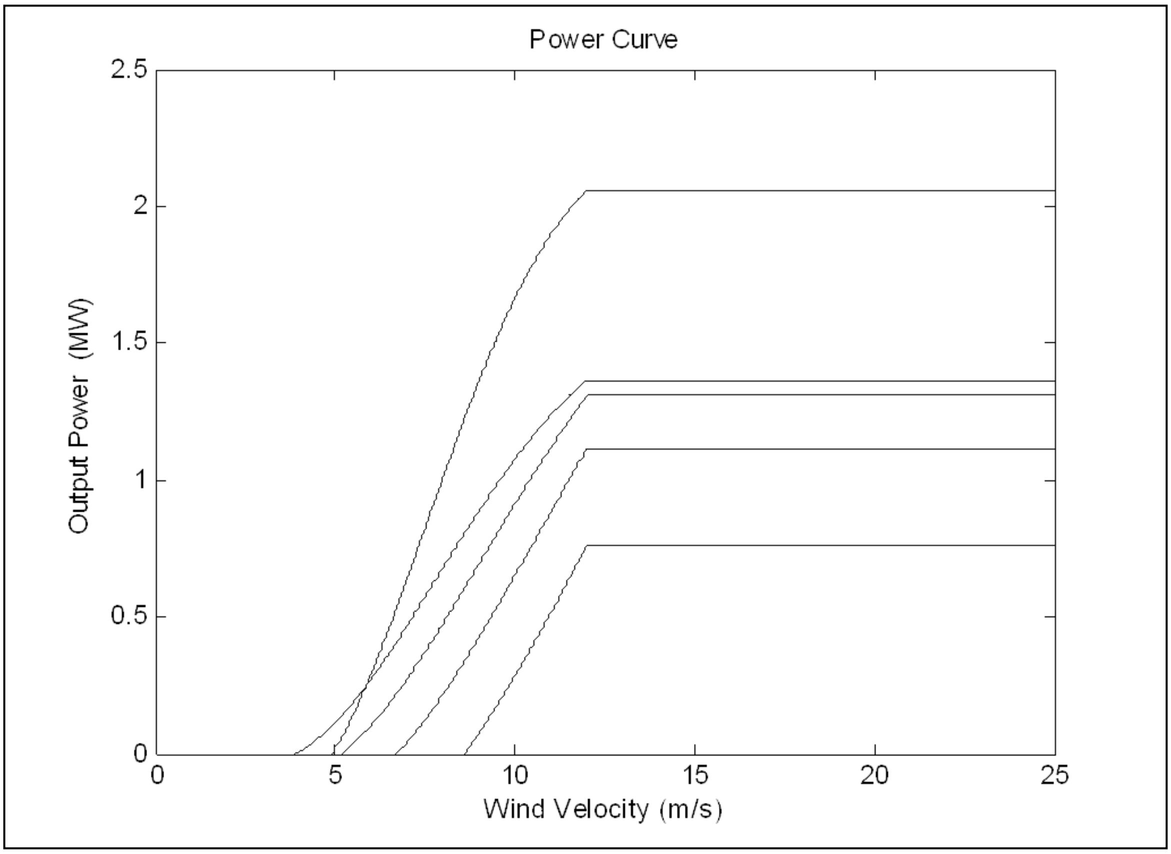


Figure 4.3: Effect of the pitch angle on the output power

4.1.1 Individual Pitch Control Concept

With great development of wind power technology and increase of wind turbine unit capacity, rotor diameter, nacelle weight and tower height of wind turbine increase rapidly. Dynamic load caused by wind turbulence, tower shadow, and rotor unbalance affects large scale wind turbine more and more distinctly, which is an essential factor must be considered.

Now, most of turbines use pitch to control power captured by the rotor. Blade derived and controlled by a servo system according to demand come from main controller according to different operating conditions. A lot of advanced intelligent control algorithms had been used in pitch control.

Even intelligent control algorithms applied, the traditional collective pitch control strategies move the three blades synchronal. However, aerodynamic force on three blades is different, so the rotor of the wind turbine endures unbalanced load all the time. The adjustment of pitch angle has an obvious influence on dynamic load. Dynamic load especially blade root load must be considered during pitch control algorithm design of large scale wind turbine.

At present, electrical servo system and hydraulic servo system are used to drive blade in most of turbine pitch system. Three blades can be controlled independently with three motors or cylinders, which make it possible to decrease the rotor unbalanced load by controlling pitch angle independently. In order to reduce dynamic load of blade root, the following requirements must be satisfied:

1) Try to keep the maximum wind energy using efficiency limited in the permitted range;
2) Try to reduce unbalance load caused by wind rotor itself, wind shear and wind turbulence;
3) Try to keep the power output steadily.

In recent years, many experts begin to study on individual pitch control and load reduction pitch control algorithm. It is an efficient way to realize individual pitch control according to rotor azimuth. Otherwise it can effectively reduce fatigue load caused by wind shear and tower shadow, but no using for reducing dynamic load caused by wind turbulence and other unbalance.

4.1.2 Running a Pitch Controlled Turbine at Variable Speed

There are a number of advantages of being able to run a wind turbine at variable speed. One good reason for that is to be able to run a turbine partially at variable speed is the fact that pitch-control (controlling the torque in order not to overload the gearbox and generator by pitching the wind turbine blades) is a mechanical process. This means that the reaction time for the pitch mechanism becomes an important factor in turbine design.

'In a variable slip generator, however, one may start increasing its slip once it is close to the rated power of the turbine. The control strategy is to run the generator at half of its maximum slip when the turbine is operating near the rated power. When a wind gust occurs, the control mechanism signals to increase the generator slip to allow the rotor to run a bit faster, while the pitch mechanism begins to cope with the situation by pitching the blades more out of the wind. Once the pitch mechanism has done its work, the slip is decreased again. In case the wind suddenly drops, the process is applied in reverse[3].

4.2 Load cases in wind energy converter

Wind turbine rotor bears different types of load as indicated below and shown in figure 4.4 as well. The wind turbine loads acting on the blades have more significant in comparison with loads acting on downstream components.

1. Aerodynamic Loads:

These loads occur due to wind. If the wind is in steady state then the wing bears continuous load but in case of gust or hurricane it bears transient loading.

2. Gravitational Loads:

Since blades are having huge weight for example in our case 5000 kg, that's why gravity factor also play role but is not of major concerns. Anyhow, in our design this load is also considered.

3. Centrifugal Loads:

Centrifugal force causes a pull on the blade and should also be considered.

Altogether, these loads cause fatigue and vibration in blades and hence the blade can have shorter life. In another way, the loads can be categorized in the following way as well.

1. Steady Loads:

Steady state time independent loading caused by aerodynamic and centrifugal loads at constant speed of rotor. During yaw motion of turbine, gyroscopic effect causes loading during each rotation of blade.

2. Cyclic Loads:

Cyclic loading caused by gravity and spatial non uniformity of air are due to increasing wind speed with increasing height. Examples are vertical wind shear, cross wind, tower shadow, tower dam, gravity forces and gyroscopic forces.

3. Non-Cyclic Loads:

In addition to above indicated loading, Transient and non cycling loading also occurs due to varying behavior of air.

4.3 Load sensors

It is indicated that trustworthy sensor are very important in Individual Pitch Control of wind turbine to get accurate value of asymmetrical loads on the blade. The values of these measured loads are fed into the appropriate control algorithm to take corresponding action of pitch angle control of individual blade as shown in figure 4.5. It is very important to measure stress especially in offshore wind turbines to get an idea of structural properties of wind turbine tower and jacket in worst cases.

Normally wind turbine structures are made up of steel and here cost matters very much. If proper analysis is not done then a big amount of money can be lost without any positive future improvement. That's why continuous data is obtained using optical strain gages that how structure is behaving under different load conditions.

Although electrical strain gage technology is quite mature in this field, optical strain gages have many important advantages over old technique. The Optical strain gages is only one cable transmits data from many different operating points and can work in harsh environment.

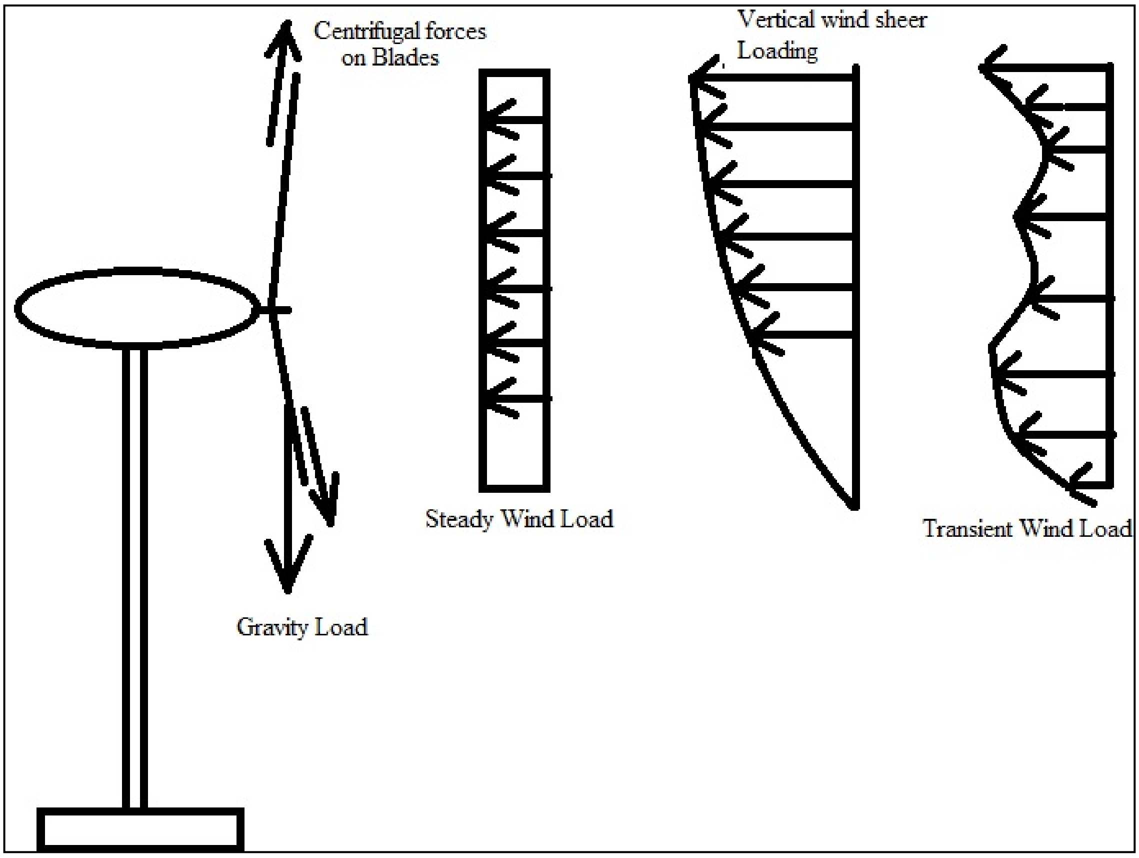


Figure 4.4: Types of load affect the blade[2]

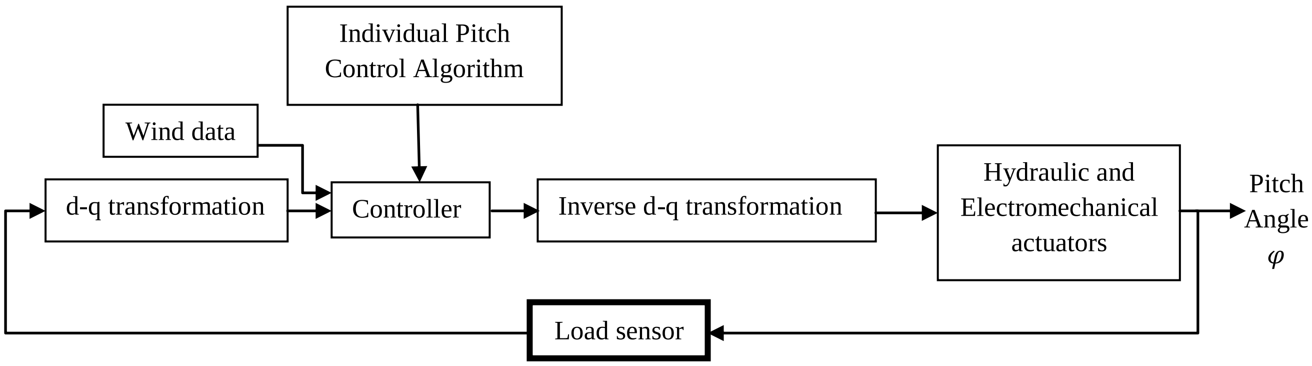


Figure 4.5: Individual Pitch Control - basic concept

The technical articles written under different test bench experiments from university people and modern technologies indicates the importance of "Structural Health Monitoring System", so called SHM Systems. Precisely defining, The SHM system informs about the condition of the blade indicating that blade requires overhauling or for example this specific part of the blade will damage within this period. So a good SHM system gives clear information at correct time, neither long time ago nor after the damage occurs. So four optical strain gages at the root of the blade is used to feedback the system with the stress and strain as shown in figure 4.2.

4.4 Fos4x Company[25]

It is a German company comes as a result of a research at the Technical University of Munich. It has a technically superior approach to the evaluation of Fiber Bragg-grating sensors.

Nowadays, fiber optic measurement techniques can be used as part of a control loop in commercial applications. It offers solutions for condition monitoring and regulation of lightweight structures. In this way, Fos4x company helps the clients to exploit maximum limits are of light-weight structures, and to increase the efficiency of their machines and equipment. These sensors provide information on temperatures and mechanical conditions. This information is then used in the measuring instrument and then , it can be deduced automatically the operating instructions from it.

More than 21,000 wind turbines in Germany and their numbers will increase. To increase the efficiency of wind turbines on the future, fiber optic sensors will measure the stresses in the blades by the wind. With the sensors, we will find out how and where the material is loaded or damage the blades increases. For Fos4x Company, resource efficiency is the key to further growth of our company.

The problem, now-a-day, we are finding is that it is very difficult to implement sensors on such long blades. So, this thesis aims to calculate the stress and strain values mathematically using a simple model of the wind turbine blades.

CHAPTER 5
MATHEMATICAL MODEL

The basic element considered for mathematical model is beam element. It is a mathematical construct used to model beam-type structures. The beam is a common structure used in engineering. The structural beam element can be defined as horizontal of tilted member having load transverse to its longitudinal axis. It can be fixed, supported and/or free on its one and/or both ends. There are countless examples of beams like the wing of airplane which is an example of cantilever beam. In this thesis, it is used half cylinder model to represent the blades. This simple model enables me to calculate the measurable quantities including stress and strain.

5.1 The half cylinder model

Consider a half cylinder with outer chord length c_2, and inner chord length c_1 as shown in figure 5.1. The length of the half cylinder is R whereas its cross-section area is A. Axis configuration is shown in figure 5.2.

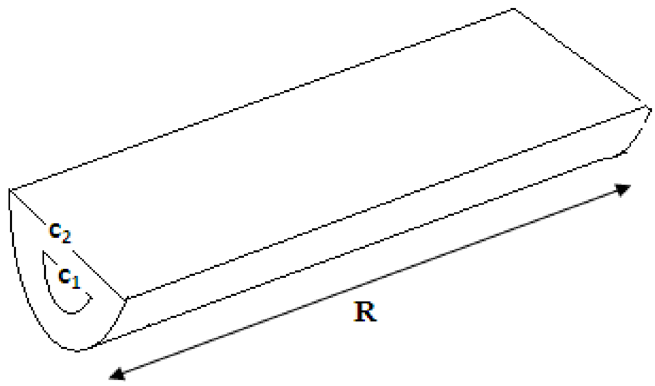


Figure 5.1: The half cylinder model of the blade

5.2 Rotation matrix between frames

The blade rotates around z- axis by the angle θ in the xyz frame. It also rotates around x'-axis by the pitch angle φ in the $x'y'z'$ frame as shown in figure 5.2. Finding the total forces and moments acts on the blade needs getting a transformation matrix between these two frames. Figure 5.3 explains how yz- plane rotates.

$$\boldsymbol{a_y} = \cos\varphi\, \boldsymbol{a_{y'}} + \sin\varphi\, \boldsymbol{a_{z'}} \tag{5.1}$$

$$\boldsymbol{a_z} = -\sin\varphi\, \boldsymbol{a_{y'}} + \cos\varphi\, \boldsymbol{a_{z'}} \tag{5.2}$$

$$\boldsymbol{a}_{x'} = \cos\theta\, \boldsymbol{a}_x + \sin\theta\, \boldsymbol{a}_y \tag{5.3}$$

$$= \cos\theta\, \boldsymbol{a}_x + \sin\theta\, (\cos\varphi\, \boldsymbol{a}_{y'} + \sin\varphi\, \boldsymbol{a}_{z'}) \tag{5.4}$$

$$= \cos\theta\, \boldsymbol{a}_x + \sin\theta \cos\varphi\, \boldsymbol{a}_{y'} + \sin\theta\ \sin\varphi\, \boldsymbol{a}_{z'} \tag{5.5}$$

$$= \cos\theta\, (\boldsymbol{a}_x + \tan\theta \cos\varphi\, \boldsymbol{a}_{y'} + \tan\theta\ \sin\varphi\, \boldsymbol{a}_{z'}) \tag{5.6}$$

$$\sec\theta\, \boldsymbol{a}_{x'} = \boldsymbol{a}_x + \tan\theta \cos\varphi\, \boldsymbol{a}_{y'} + \tan\theta\ \sin\varphi\, \boldsymbol{a}_{z'} \tag{5.7}$$

$$\boldsymbol{a}_x = \sec\theta\, \boldsymbol{a}_{x'} - \tan\theta \cos\varphi\, \boldsymbol{a}_{y'} - \tan\theta\ \sin\varphi\, \boldsymbol{a}_{z'} \tag{5.8}$$

Where $\boldsymbol{a}_x, \boldsymbol{a}_y$ and $\boldsymbol{a}_z$ are unit vectors in xyz frame and $\boldsymbol{a}_{x'}, \boldsymbol{a}_{y'}$ and $\boldsymbol{a}_{z'}$ are the unit vectors in $x'y'z'$ frame.

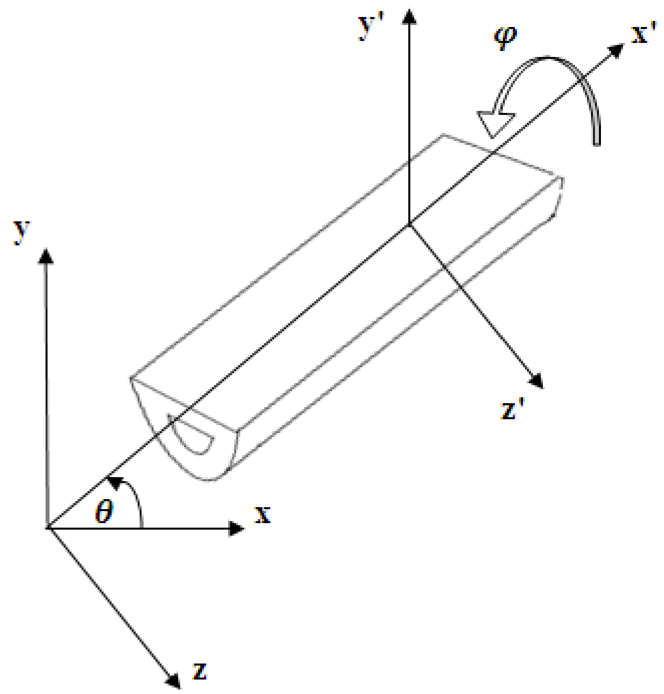


Figure 5.2 : Axis configuration of the model

Combining equations 5.1, 5.2 and 5.8 in a matrix, we get :

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \sec\theta & -\tan\theta\cos\Phi & -\tan\theta\sin\Phi \\ 0 & \cos\Phi & \sin\Phi \\ 0 & -\sin\Phi & \cos\Phi \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \tag{5.9}$$

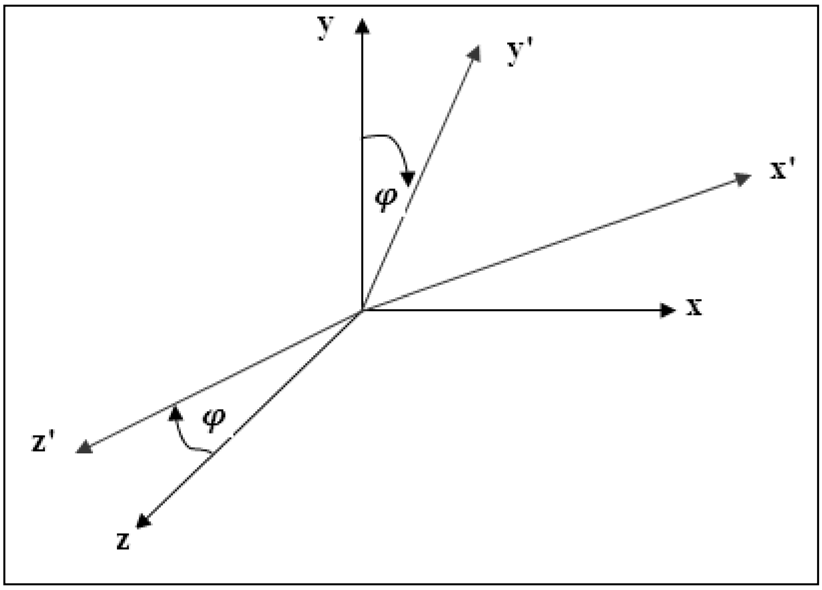


Figure 5.3: yz- plane rotation

5.3 Forces and moments

5.3.1 Thrust and torque

As shown in the last section of chapter 3; the wind flow against the rotor blades is translated to two normal forces which are lift and drag forces as shown in equations 3.22 and 3.23. In the following, normal and tangential forces in $x'y'z'$ with axis configuration shown in figure 5.1 is derived.

$$F_L = \frac{1}{2} \rho \, c_L \, u^2 \, A \, \boldsymbol{a_\theta} \tag{5.10}$$

Taking the cross section of one foil :

$$dA = dA_2 - dA_1 = 0.5 \, [\, (2 \, \pi \, c_2 \, dr) - (2 \, \pi \, c_1 \, dr \,)] \tag{5.11}$$

Then the force acts on one foil is:

$$dF_L = \frac{1}{2} \rho \, c_L \, u^2 \, . \, \frac{1}{2} \, \pi \, (c_2 - c_1) \, dr \, \boldsymbol{a_\theta} \tag{5.12}$$

by converting the cylindrical coordinates to the Cartesian :

$$\boldsymbol{a_\theta} = - \sin\theta \, \boldsymbol{a_x} + \cos\theta \, \boldsymbol{a_y} \tag{5.13}$$

Then:

$$dF_L = \frac{1}{4} \rho \, c_L \, u^2 \, \pi \, (c_2 - c_1) \, dr \, (- \sin\theta \, \boldsymbol{a_x} + \cos\theta \, \boldsymbol{a_y}) \tag{5.14}$$

By transforming dF_L to $x'y'z'$ frame, we got:

$$dF_L = \frac{1}{4}\rho\, c_L\, u^2\, \pi\left(c_2 - c_1\right)dr\, (-\, sin\, \theta\, (sec\theta\, \boldsymbol{a}_{x'} - \, tan\, \theta\, cos\, \Phi\, \boldsymbol{a}_{y'} - \, tan\, \theta\, sin\, \Phi\, \boldsymbol{a}_{z'}) + cos\, \theta\, (cos\, \Phi\, \boldsymbol{a}_{y'} + \, sin\, \Phi\, \boldsymbol{a}_{z'})) \quad (5.15)$$

$$= \frac{1}{4}\rho\, c_L\, u^2\, \pi\left(c_2 - c_1\right) dr\, ((-\, sin\, \theta\, sec\theta\, \boldsymbol{a}_{x'} + \, sin\, \theta\, tan\, \theta\, cos\, \Phi\, \boldsymbol{a}_{y'} + sin\, \theta\, tan\, \theta\, \, sin\Phi\, \boldsymbol{a}_{z'}) + \, (cos\, \theta\, cos\, \Phi\, \boldsymbol{a}_{y'} + \, cos\, \theta\, sin\, \Phi\, \boldsymbol{a}_{z'})) \quad (5.16)$$

$$= \frac{1}{4}\rho\, c_L\, u^2\, \pi\left(c_2 - c_1\right) dr\, ((-\, sin\, \theta\, sec\theta\, \boldsymbol{a}_{x'} + \, (sin\, \theta\, tan\, \theta\, cos\, \Phi + cos\, \theta\, cos\, \Phi)\, \boldsymbol{a}_{y'} + \, (sin\, \theta\, tan\, \theta\, sin\, \Phi + \, cos\, \theta\, sin\, \Phi)\boldsymbol{a}_{z'})\,) \quad (5.17)$$

Applying the same steps on the drag force; we get:

$$F_D = \frac{1}{2}\rho\, c_D u^2\, A\, (-\boldsymbol{a}_z) \quad (5.18)$$

$$dF_D = \frac{1}{2}\rho\, c_D\, u^2 * \frac{1}{2}\, \pi\, (c_2 - c_1)\, dr\, (-\boldsymbol{a}_z) \quad (5.19)$$

$$dF_D = \frac{1}{4}\rho\, c_D\, u^2\, \pi\, (c_2 - c_1)\, dr\, (-\boldsymbol{a}_z) \quad (5.20)$$

$$dF_D = \frac{1}{4}\rho\, c_D\, u^2\, \pi\, (c_2 - c_1)\, dr\, (-\, cos\, \Phi\, \boldsymbol{a}_{z'} + sin\, \Phi\, \boldsymbol{a}_{y'}) \quad (5.21)$$

From equations 5.17 and 5.21, It is found that the lift and drag forces have components in x', y' and z' directions. The axis configuration shown in figure 5.1, shows that x' axis represent the axial direction of the blade, y' the tangential direction and z' the normal one.

So, taking x' components of dF_L gives the axial force :

$$\boldsymbol{dF_{axial}} = \frac{1}{4}\rho\, c_L\, u^2\, \pi\, (c_2 - c_1)\, dr\, (-\, sin\, \theta\, sec\, \theta\,)\boldsymbol{a}_{x'} \quad (5.22)$$

$$= -\frac{1}{4}\rho\, c_L\, u^2\, \pi\, (c_2 - c_1)\, dr\, (tan\, \theta\,)\, \boldsymbol{a}_{x'} \quad (5.23)$$

$$= dF_{x'}$$

Taking y' components of $dF_L$and dF_D gives the tangential force of the blade:

$$\boldsymbol{dF_{tangential}} = \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, dr\, (c_L(sin\, \theta\, tan\, \theta\, cos\, \Phi + \, cos\, \theta\, cos\, \Phi) + c_D sin\, \Phi)\, \boldsymbol{a}_{y'} \quad (5.24)$$

$$= \frac{1}{4}\rho\, u^2\, \pi\left(c_2 - c_1\right)dr\, (c_L \sec\theta \cos\Phi + \, c_D \sin\Phi)\, \boldsymbol{a}_{y'} \quad (5.25)$$

$$= dF_{y'}$$

Taking z' components of dF_L and dF_D gives the normal force of the blade:

$$\boldsymbol{dF_{normal}} = \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, dr\, (c_L\, (sin\,\theta\, tan\,\theta\, sin\,\Phi + cos\,\theta\, sin\,\Phi) - c_D\, cos\,\Phi)\, \boldsymbol{a_{z\prime}} \tag{5.26}$$

$$= \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, dr\, (c_L\, sec\,\theta\, sin\,\Phi - c_D\, cos\,\Phi)\, \boldsymbol{a_{z\prime}} \tag{5.27}$$

$$= dF_{z\prime}$$

The aerodynamic loading on the blade can be calculated through different methods like blade element momentum theory. Integrating $\boldsymbol{dF_{axial}}$, $\boldsymbol{dF_{tangential}}$ **and** $\boldsymbol{dF_{normal}}$ over the total length of the blade R produces the overall forces on the blade in each direction.

$$\boldsymbol{F_{axial}} = F_x = \int_0^R -\frac{1}{4}\rho\, c_L\, u^2\, \pi\, (c_2 - c_1)(tan\,\theta)\, dr$$

$$= -\frac{1}{4}\rho\, c_L\, u^2\, \pi\, (c_2 - c_1)(tan\,\theta)\, R \tag{5.28}$$

$$\boldsymbol{F_{tangential}} = F_y = \int_0^R \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)(c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi) dr$$

$$= \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, (c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi)\, R \tag{5.29}$$

$$\boldsymbol{F_{normal}} = F_z = \int_0^R \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)(c_L\, sec\,\theta\, cos\,\Phi - c_D\, sin\,\Phi) dr$$

$$= \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, (c_L\, sec\,\theta\, cos\,\Phi - c_D\, sin\,\Phi)\, R \tag{5.30}$$

From equations 5.29 and 5.30, moments in edgewise and flapewise directions respectively can be calculated. Integrating the tangential forces over the blade length produces the rotor torque. But integrating the normal forces produces the rotor thrust.

$$\boldsymbol{Torque} = \int_0^R r\, \boldsymbol{a_{x'}}\, X\, dF_{y\prime} \tag{5.31}$$

$$= \int_0^R r\, \boldsymbol{a_{x'}} X\, (\frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1) dr\, (c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi))\, \boldsymbol{a_{y\prime}}$$

$$= \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, (c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi) \int_0^R r\, dr\, (\boldsymbol{a_{x'}} X\, \boldsymbol{a_{y\prime}})$$

$$= \frac{1}{4}\rho\, u^2\, \pi\, (c_2 - c_1)\, (c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi)\, \frac{R^2}{2}\, \boldsymbol{a_{z'}}$$

$$= \frac{1}{8}\rho\, u^2\, \pi\, (c_2 - c_1)\, (c_L\, sec\,\theta\, cos\,\Phi + c_D\, sin\,\Phi)\, R^2\, \boldsymbol{a_{z'}} \tag{5.32}$$

$$= M_z$$

$$\boldsymbol{Thrust} = \int_0^R r\, \boldsymbol{a}_{x'} X\, dF_{z'} \quad (5.33)$$

$$= \int_0^R r\, \boldsymbol{a}_{x'} X \left(\frac{1}{4}\, \rho\, u^2\ \pi\, (c_2 - c_1)\, dr\, (c_L\ \sec\theta \sin\Phi - c_D \cos\Phi) \right) \boldsymbol{a}_{z'}$$

$$= \frac{1}{4}\, \rho\, u^2\, \pi\, (c_2 - c_1)\ (c_L\ \sec\theta \sin\Phi - c_D \cos\Phi) \int_0^R r\, dr\, (\boldsymbol{a}_{x'} X\, \boldsymbol{a}_{z'})$$

$$= \frac{1}{4}\, \rho\, u^2\ \pi\, (c_2 - c_1)\ (c_L\ \sec\theta \sin\Phi - c_D \cos\Phi)\ \frac{R^2}{2}\ (-\boldsymbol{a}_{y'})$$

$$= \frac{-1}{8}\, \rho\, u^2\ \pi\, (c_2 - c_1)\ (c_L\ \sec\theta \sin\Phi - c_D \cos\Phi)\, R^2\, \boldsymbol{a}_{y'} \quad (5.34)$$

$$= M_y$$

Note that F_{axial} produce zero moment since $\boldsymbol{a}_{x'}$ is in the same direction with $\boldsymbol{a}_r$, so :
$\boldsymbol{a}_r\ X\ \boldsymbol{a}_{x'} = 0$

5.3.2 Gravitational force and moment

As the blade has a high, the downward gravitational force has an effect on it. As the blade rotates the gravitational will be in $(-\boldsymbol{a}_y)$ direction at a distance equals one third of the total length of the blade which is the center of gravity (G) as shown in figure 5.4.

$$\boldsymbol{F}_{gravitational} = m\,.\,g\ (-\boldsymbol{a}_y) \quad (5.35)$$

Where m is the mass of the blade and g is the gravity acceleration. Transforming it to the *x'y'z'* frame results in :

$$\boldsymbol{F}_{gravitational} = -\,m\,.\,g\,.\cos\theta\ \left(\cos\varphi\, \boldsymbol{a}_{y'} + \sin\varphi\, \boldsymbol{a}_{z'}\right) \quad (5.36)$$

And the gravitational moment is :

$$\boldsymbol{Moment}_{\ gravitational} = r\, \boldsymbol{a}_{x'}\ \mathrm{X}\ F_{gravitational}$$

$$= r\, \boldsymbol{a}_{x'} \mathrm{X} \left(-\,m\,.\,g \cos\theta\ \left(\cos\varphi\, \boldsymbol{a}_{y'} + \sin\varphi\, \boldsymbol{a}_{z'}\right)\right)$$

$$= -\,m\ g\ G \cos\theta\ \left(\cos\varphi\, \boldsymbol{a}_{z'} - \sin\varphi\, \boldsymbol{a}_{y'}\right) \quad (5.37)$$

5.4 Stress and strain

From rotor thrust and rotor torque, the static load which is the stress and strain can be calculated. Stress is a measure of the internal forces acting within a deformable body. Normal stress is the force per unit area applied in a direction perpendicular to the surface of an object.

Strain is the change in dimensions per unit original dimensions. In engineering, it is expressed as the ratio of total deformation to the initial dimension of the material body in which the forces are being applied.

$$strain = \Delta l / L \tag{5.38}$$

For example, if your stretch a 100 cm long wire by 5 cm, strain = 5/100 = 0.05.

Stress and strain exert on the blade of wind turbine are related with the forces and moments affect the blade. They relate to each other according to the mathematical relations in table 5.1.

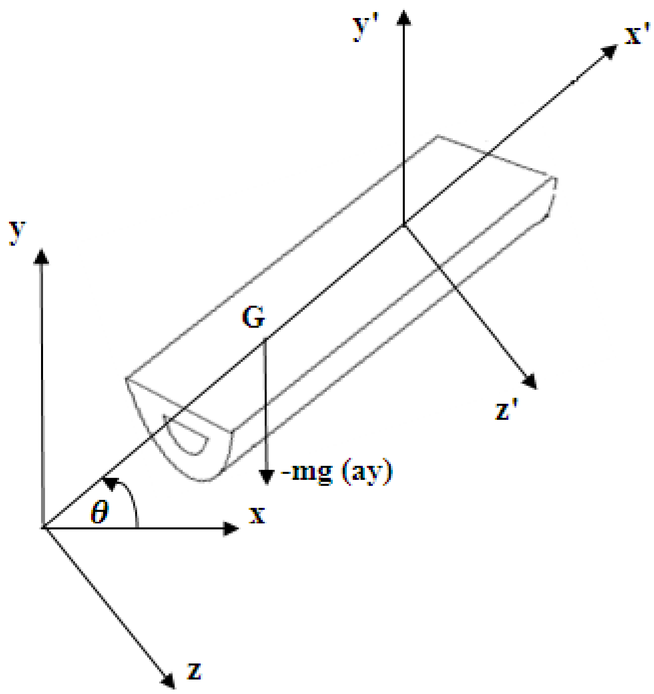


Figure 5.4 : Gravitational force

5.5 Calculations of stress and strain at point X

In this section, a sensor at the position X is exist. Figure 5.5 shows a cross section of the wind turbine blade modeled as a hollow half cylinder and the position of the sensor X is showed also. The following calculation of stress and strain are related to that sensor for the first blade.

Some declarations:

Blade length: $R = 30\ m$
Mass of blade: $m = 5000\ kg$
Air density: $\rho = 1.225$
Speed: $u = 12.3\ m/sec$
Chord$_1$: $c_1 = 1.048 * 2 = 2.096\ m$
Chord$_2$: $c_2 = 1.15 * 2 = 2.3\ m$

Cross area: A = 0.5 $*$ π *($c_2{}^2$ - $c_1{}^2$) / 4 = 0.352 m^2
Rotation speed: f = 0.2 Hz
Angular rotation speed: w = $2\pi f$ = $2\pi *$ 0.2 = 1.2566 rad/sec
Rotation angle (at time = 3 sec) : θ = 2 π f t = 2 π $*$ 0.2 $*$ 10 $*$ $\frac{180}{\pi} = 216$ °
Gravity center : G = 10 m
Gravity acceleration: g = 9.8 m/s^2
Pitch angle : φ = desired pitch angle

Table 5.1 : Stresses and strains in the structural models

Type	***Stress***	***Strain***
Normal	$\sigma_{xx} = \frac{N}{A}$ σ_{yy}= 0 σ_{zz} =0 $\tau_{xy} = 0$ $\tau_{yz} = 0$ $\tau_{xz} = 0$	$\varepsilon_{xx} = \frac{\sigma_{xx}}{E}$ $\varepsilon_{yy} = -\nu\frac{\sigma_{xx}}{E}$ $\varepsilon_{zz} = -\nu\frac{\sigma_{xx}}{E}$ $\gamma_{xy} = 0$ $\gamma_{yz} = 0$ $\gamma_{xz} = 0$
Shear	$\tau_{x\theta} = \frac{T\rho}{J}$ $\sigma_{xx} = 0$ σ_{yy}= 0 σ_{zz} =0 $\tau_{yz} = 0$	$\gamma_{x\theta} = \frac{\tau_{x\theta}}{G}$ $\varepsilon_{xx} = 0$ $\varepsilon_{yy} = 0$ $\varepsilon_{zz} = 0$ $\gamma_{yz} = 0$
Symmetric bending about z – axis	$\sigma_{xx} = -\frac{M_z\, y}{I_{zz}}$ $\tau_{xs} = -\frac{V_y Q_z}{I_{zz}\, t}$ σ_{yy}= 0 σ_{zz} =0 $\tau_{yz} = 0$	$\varepsilon_{xx} = \frac{\sigma_{xx}}{E}$ $\varepsilon_{yy} = -\nu\frac{\sigma_{xx}}{E}$ $\varepsilon_{zz} = -\nu\frac{\sigma_{xx}}{E}$ $\gamma_{xs} = \frac{\tau_{xs}}{G}$ $\gamma_{yz} = 0$
Symmetric bending about y – axis	$\sigma_{xx} = -\frac{M_y\, z}{I_{yy}}$ $\tau_{xs} = -\frac{V_z Q_y}{I_{yy}\, t}$ σ_{yy}= 0 σ_{zz} =0 $\tau_{yz} = 0$	$\varepsilon_{xx} = \frac{\sigma_{xx}}{E}$ $\varepsilon_{yy} = -\nu\frac{\sigma_{xx}}{E}$ $\varepsilon_{zz} = -\nu\frac{\sigma_{xx}}{E}$ $\gamma_{xs} = \frac{\tau_{xs}}{G}$ $\gamma_{yz} = 0$

Where :

N : normal force, A : area, σ : normal stress, τ : shear stress, ε : strain
γ : shear strain, ν : poisson ratio, E : young modulus of Elasticity
G : modulus of rigidity, M : bending moment, Q : shear force
I : moment of inertia, V : moment of area, t : thickness, T : shear moment
J : polar moment of area, ρ : density of the material

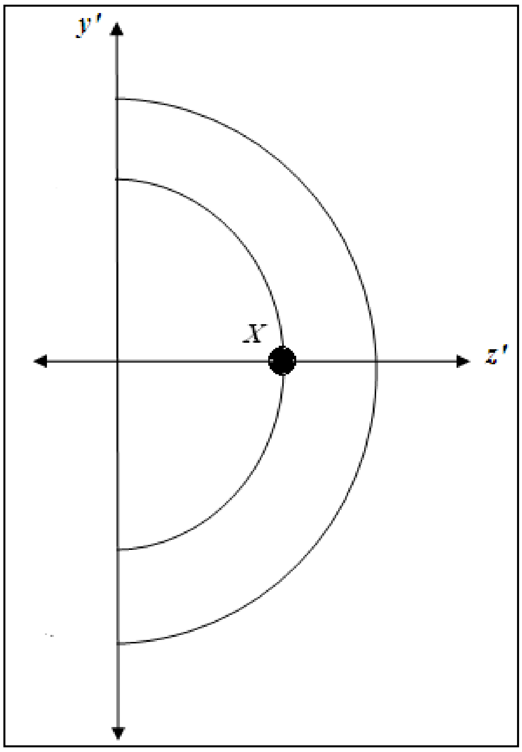


Figure 5.5: A cross section area shows the position of the sensor X

<u>Calculation of the desired pitch angle and maximum received power:</u>

It will be calculated under the condition of maximizing the power coefficient c_p which is defined according equation 3.20:

$$c_p(\lambda, \varphi) = c_1 \left(c_2 \frac{1}{\beta} - c_3\varphi - c_4\varphi^x - c_5 \right) e^{-c_6 \frac{1}{\beta}}, \beta = \frac{1}{1/(\lambda+0.08\,\varphi) - 0.035/(1+\varphi^3)}$$

Recalling equation (4.4) :_ $\lambda_R = \frac{\omega R}{u} = 3.065$

Considering the values :_ $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21$ (x is not used because $c_4 = 0$).

Thus : $\beta = \frac{1}{\frac{1}{3.065+0.08\,\varphi} - \frac{0.035}{1+\varphi^3}}$, and $c_p(\varphi) = 0.5 \left(116 \frac{1}{\beta} - 0.4\,\varphi - 5 \right) e^{-21 \frac{1}{\beta}}$

And according to equation (4.5) : $P_R = c_p(\lambda(u), \varphi) * P = c_p(\lambda(u), \varphi) . \frac{1}{2} A\rho u^3$

Differentiation of $P_R(\varphi)$ with respect to φ, and equating it with zero gives the value of the desired pitch angle which is :

$$\varphi = -99.7109\,^{o}$$

Then $P_{R_{max}} = 1.6261(10^5)\ Watt$

Calculating the gravity moment:

Gravity moment in z-direction:

$$G\_M\_z = -G * g * m * \cos\theta * \cos\varphi$$
$$= -10 * 9.8 * 5000 * \cos(216) * \cos(-99.7109)$$
$$= -66866.614\, N.m = -66.867\, kN.m$$

Gravity moment in y-direction:

$$G\_M\_y = G * g * m * \cos\theta * \sin\varphi$$
$$= 10 * 9.8 * 5000 * \cos(216) * \sin(-99.7109)$$
$$= 390738.21\, N.m = 390.738\, kN.m$$

Airfoil coefficients :
angle of attack : $\alpha = 10^{o}$

Considering the airfoil of type '$NACA63(4) - 221$' shown in figure 5.6. Its characteristics are as follows in table 5.2[26]:

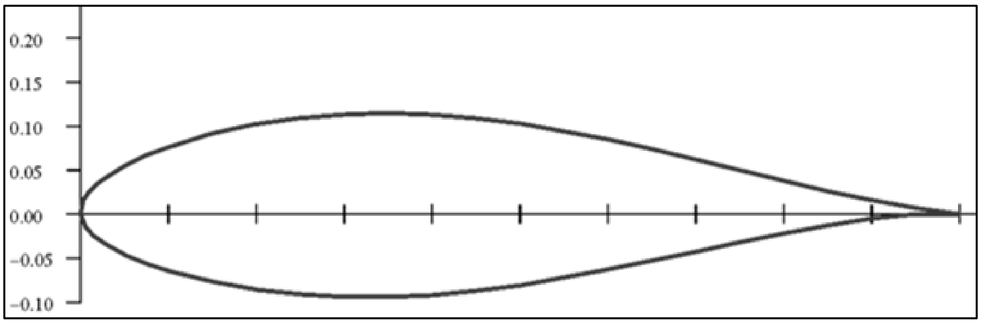


Figure 5.6: $Naca\ 63 - 221$ airfoil

Table 5.2 : Naca 63-221 airfoil characteristics[26]

Thickness	21.0 %
Camber	1.2 %
Trailing edge angle	12.7 %
Lower flatness	7.5 %
Leading edge radius	3.1 %
Stall angle	-0.5

Zero lift angle: $\alpha_{zl} = -1.5$
Max C_L: $c_{Lmax} = 1.439$
Max C_L angle: $angle\ of\ c_{L_{max}} = 14.5$

Drag coefficient: c_D = 0.04
Lift coefficient: $c_L = \frac{c_{Lmax}}{angle\ of\ c_{Lmax}} * (\alpha + \alpha_{zl}) = \frac{1.439}{14.5} * (10 - 1.5) = 0.844$

Centrifugenal force :

$F_x = \omega * m * R^2 = 1.2566 * 5000 * 30^2 = 5654866.776\,N = 5.655\,MN$

Tangential forces in y- direction:

$F_y = 0.25 * \rho * u^2 * \pi * (c_2 - c_1) * R * (c_L * sec\,\theta * cos\,\varphi + c_D * sin\,\varphi)$
$= 0.25 * 1.225 * 12.3^2 * \pi * (2.3 - 2.096) * 30 * (0.844 * sec\,(216)$
$* cos\,(-99.7109) + 0.04 * sin\,(-99.7109)) = 121.635\,N$

Normal forces in z- direction:

$F_z = 0.25 * \rho * u^2 * \pi * (c_2 - c_1) * R * (c_L * sec\,\theta * sin\,\varphi - c_D * cos\,\varphi)$
$= 0.25 * 1.225 * 12.3^2 * \pi * (2.3 - 2.096) * 30 * (0.844 * sec\,(216) *$
$sin\,(-99.7109) - 0.04 * cos\,(-99.7109)) = 922.03\,N$

Bending moments :

$Torque\_y = \frac{-1}{8} * \rho * u^2 * \pi * (c_2 - c_1) * R^2 * (c_L * \sec\theta * \sin\varphi - c_D * \cos\varphi)$
$= \left(-\frac{1}{8}\right) * 1.225 * 12.3^2 * \pi * (2.3 - 2.096) * 30^2 * (0.844 * \sec(216) *$
$\sin(-99.7109) - 0.04 * \cos(-99.7109))$
$= 1.1850 * 10^4\,N.m$

$Thrust\_z = \frac{1}{8} * \rho * u^2 * \pi * (c_2 - c_1) * R^2 * (c_L * \sec\theta * \cos\varphi + c_D * \sin\varphi)$
$= \left(\frac{1}{8}\right) * 1.225 * 12.3^2 * \pi * (2.3 - 2.096) * 30^2 * (0.844 * \sec(216) *$
$\cos(-99.7109) + 0.04 * \sin(-99.7109))$
$= -1.0324 * 10^4\,N.m$

Total moments :

$moment\_y = Torque\_y + G\_M\_y = 1.1850 * 104 + 390738.21$
$= 4.0259 * 10^5\,N.m$

$moment\_z = Thrust\_z + G\_M\_z = -1.0324 * 104 + (-66866.614)$
$= -7.7191 * 10^4\,N.m$

Stresses:
1. axial stress

Poisson ratio: $\nu = 0.28$

Young modulus of elasticity in x- direction : $E_x = 37 * 10^9 \ Pa$
Young modulus of elasticity in y- direction : $E_y = 9 * 10^9 \ Pa$
Young modulus of elasticity in z- direction : $E_z = 9 * 10^9 \ Pa$

Axial normal stress : $\sigma_{xx1} = \frac{F_x}{A} = 5.655 * (10^6) / 0.352 = 16.07 \ MPa$

2. Symmetric bending about z-axis stress

$yDistance = 0$

Moment of inertia about z- axis :

$$I_{zz} = 0.5 * (\frac{\pi}{2}) * ((\frac{c_2}{2})^4 - (\frac{c_1}{2})^4)$$

$$= 0.5 * (\frac{\pi}{2}) * ((\frac{2.3}{2})^4 - (\frac{2.096}{2})^4) = 0.543 \ m^4$$

Normal stress due to bending about z- axis:
$\sigma_{xx2} = -moment\_z * yDistance / I_{zz} = 0$
Thickness : $t = 2 * (c_2 - c_1) = 2 * (2.3 - 2.096) = 0.408 \ m$

Moment of area: $V_y = F_y * R = 121.635 * 30 = 3649.1 \ N.m = 3.6491 \ kN.m$
Shear force: $Q_z = 0.5 * (\frac{2}{3}) * (((\frac{c_2}{2})^3 - (\frac{c_1}{2})^3)) = 0.1233 \ N$
modulus of rigidity : $G = 3.5 * 10^9$

Shear stress due to bending about z- axis:
$\tau_{xs1} = -V_y * Q_z / (I_{zz} * t)$
= - 3649.1 * 0.1233 / (0.543 * 0.408) = - 2031 Pa = -2.031 KPa

Symmetric bending about y-axis

$$zDistance = \frac{c_1}{2} = 2.096 / 2 = 1.048 \ m$$

Moment of inertia about y- axis :

$$I_{yy} = 0.5 * (\frac{\pi}{2}) * ((\frac{c_2}{2})^4 - (\frac{c_1}{2})^4)$$

$$= 0.5 * (\frac{\pi}{2}) * ((\frac{2.3}{2})^4 - (\frac{2.096}{2})^4) = 0.543 \ m^4$$

Normal stress due to bending about y- axis:

$\sigma_{xx3} = -moment_y * \; zDistance \; / \; I_{yy}$

$= -4.0259 * (10^5) * 1.048 / 0.543 = -0.777 \; MPa$

Thickness : $t = 2 * (c_2 - c_1) = 2 * (2.3 - 2.096) = 0.408 \; m$

Moment of area: $V_z = F_z * R = 922.03 * 30 = 27660.9 \; N.m = 27.661 \; kN.m$
Shear force: $Q_y = 0$
Shear stress due to bending about y- axis: $\tau_{xs2} = -V_z * Q_y / (I_{yy} * t) = 0$

<u>Stress</u>
Using the superposition method:

Total normal stress: $\sigma_{xx} = \sigma_{xx1} + \sigma_{xx2} + \sigma_{xx3} = 16.07 + 0 + -0.777 = 15.293 \; MPa$

Total shear stress: $\tau_{xs} = \tau_{xs1} + \tau_{xs2} = -2.031 \; KPa + 0 = -2.031 \; KPa$

<u>Strain:</u>

$\varepsilon_{xx} = \frac{\sigma_{xx}}{Ex} = (15.293 * 10^6) / (37 * 10^9) = 4.1 * (10^{-4})$

Comparing with results in [2] , ε_{xx} = 0.55 mm/m.(error : 21%)

$\varepsilon_{yy} = -\nu \frac{\sigma_{xx}}{Ex} = -0.28 * (15.293 * 10^6) / (9 * 10^9) = -4.758 * (10^{-4})$

$\varepsilon_{zz} = -\nu \frac{\sigma_{xx}}{Ex} = -0.28 * (15.293 * 10^6) / (9 * 10^9) = -4.758 * (10^{-4})$

$\gamma_{x\theta} = \frac{\tau_{x\theta}}{G} = -2.031 / (3.5 * (10^9)) = -5.8 * (10^{-7})$

CHAPTER 6
SIMULATION AND RESULTS

In this chapter, a simulation using Matlab software program is developed. It aims to get the values of the stress and strain for any wind turbine. The inputs for program will be the wind speed and the characteristics of the blade as blade length, blade mass, centre of gravity.

6.1 Simulation using Matlab

The code consists of three main parts. The first one defines some variable which are considered as the inputs to the code as wind speed, rotation speed and the blade's profile name, length, mass and centre of gravity. The rotation angle and pitch angle of each blade is also defined.

The second part defines the forces and moments affects the three blades. The third part defines the stress and strain in terms of the forces and moments in the second part.

By this simulation, the stress and strain are plotted with respect to time, wind speed, pitch angle and attack angle.

6.2 Results

This section includes the results of the code has been built. The first blade is considered.

6.2.1 Stress and strain versus time

In this part the stress and strain are plotted with respect to time with fixing the other variables. The nominal value of wind speed is 12.3 m/s. The pitch angle value is selected to give the maximum power. The attack angle is 10 degree. Forces and moments exert on the blade are plotted as shown in figure 6.1 and figure 6.2, respectively. Stress and strain are plotted in figure 6.3.

6.2.2 Stress and strain versus wind speed

In this part the stress and strain are plotted with respect to wind speed with fixing the other variables. The value of time is fixed at 10 sec. The pitch angle value is selected to give the maximum power. The attack angle is 10 degree. Forces and moments exert on the blade are plotted as shown in figure 6.4 and figure 6.5, respectively. Stress and strain are plotted in figure 6.6.

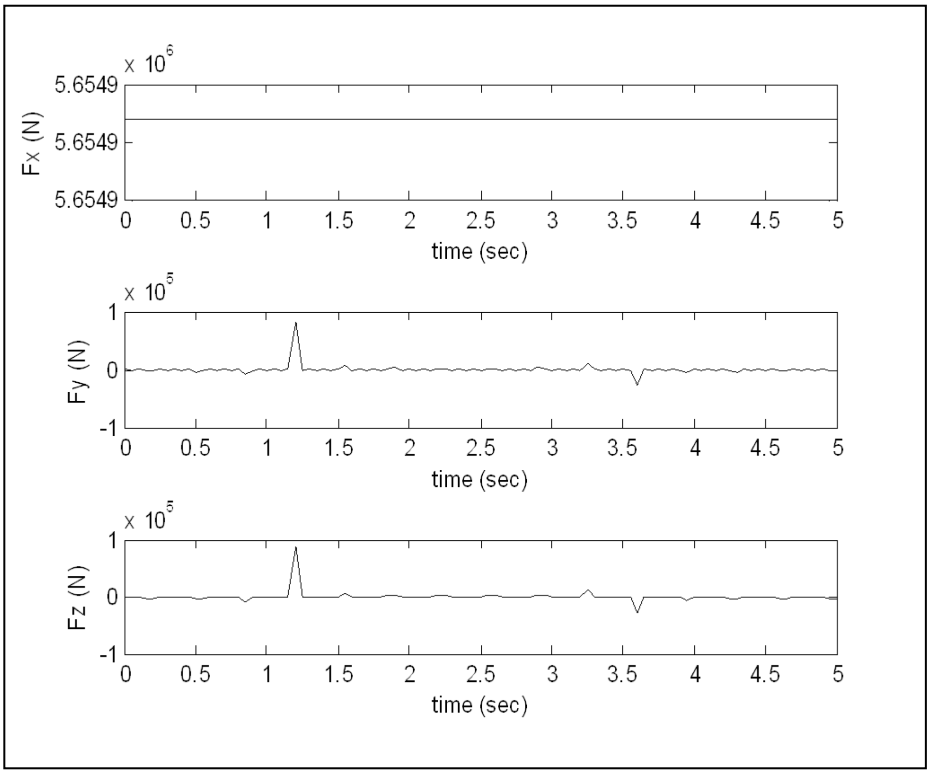


Figure 6.1 : Forces versus time

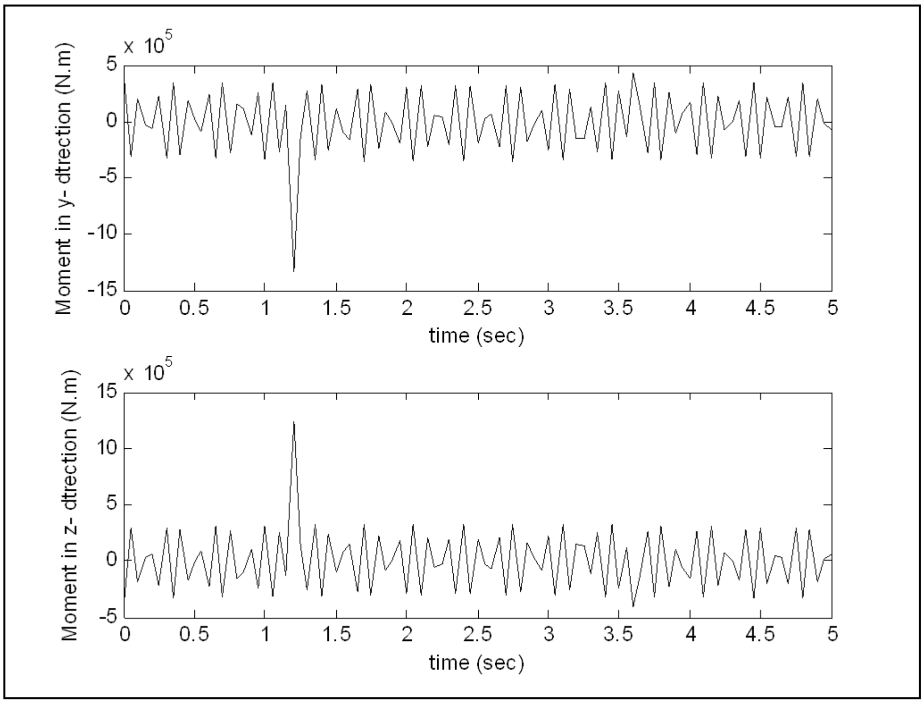


Figure 6.2 : Moments versus time

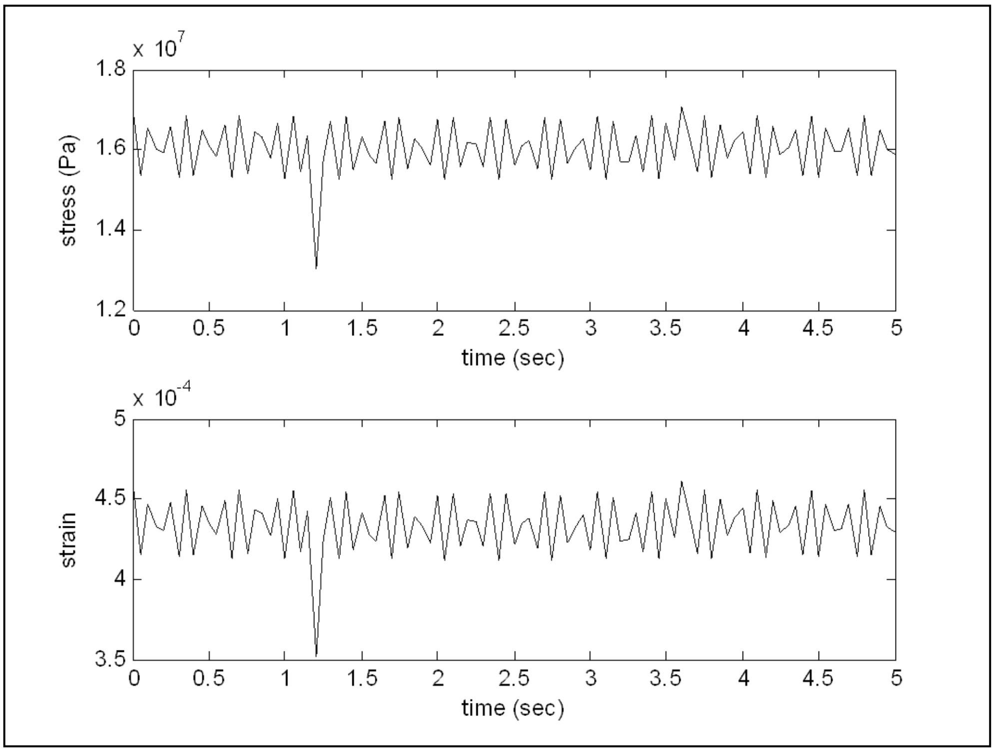


Figure 6.3 : Stress and strain versus time

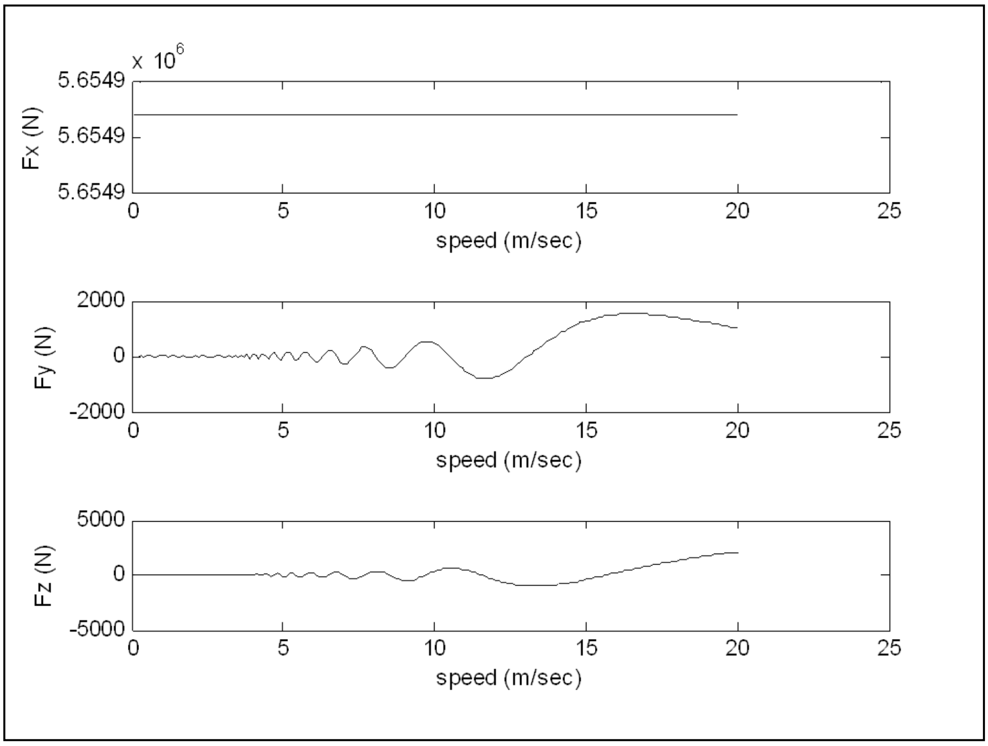


Figure 6.4 : Forces versus wind speed

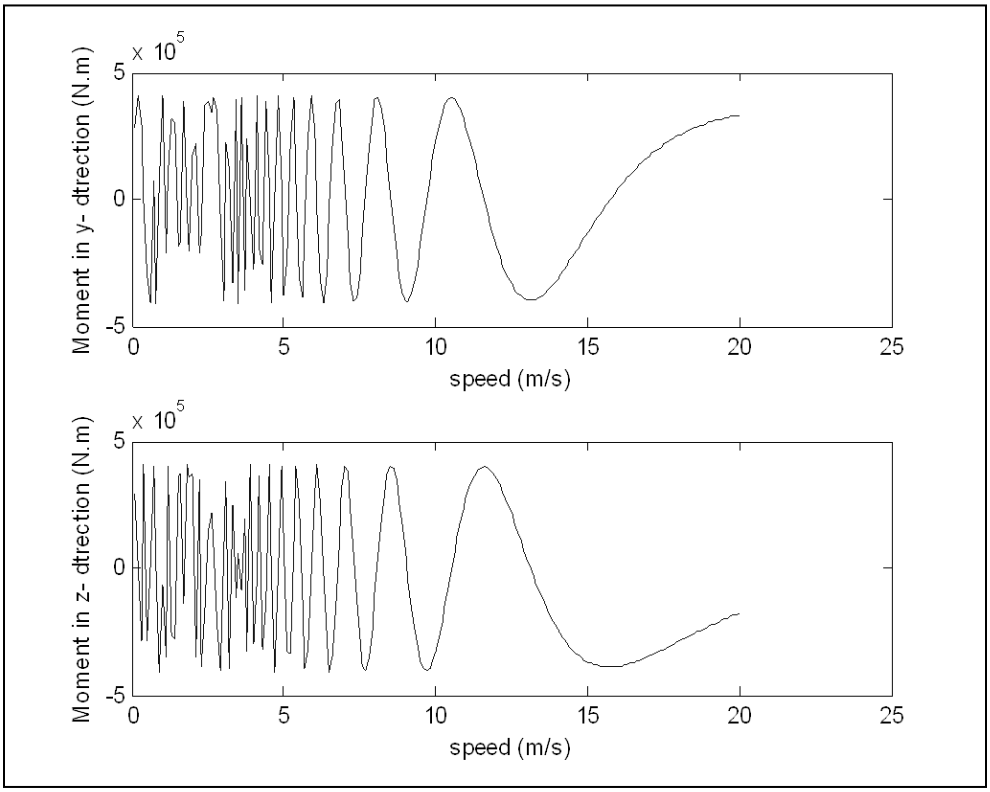


Figure 6.5 : Moments versus wind speed

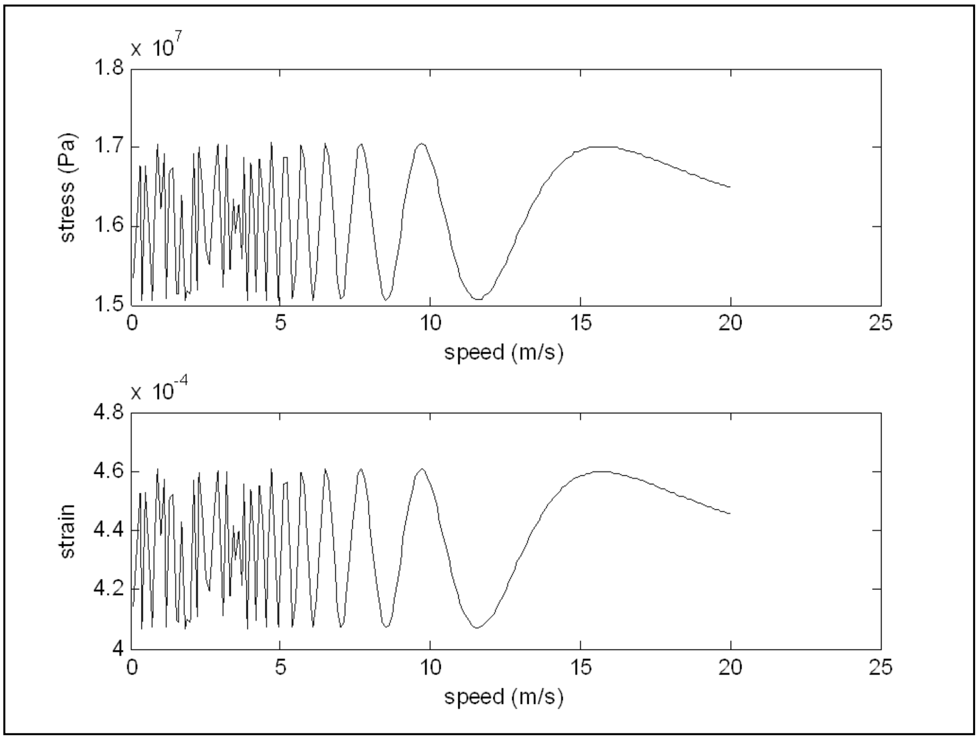


Figure 6.6 : Stress and strain versus wind speed

6.2.3 Stress and strain versus pitch angle

In this part the stress and strain are plotted with respect to the pitch angle with fixing the other variables. The nominal value of wind speed is 12.3 m/s. The time value is fixed at 10 sec. The attack angle is 10 degree. Forces and moments exert on the blade are plotted as shown in figure 6.7 and figure 6.8, respectively. Stress and strain are plotted in figure 6.9. Note that the relation is sinusoidal as expected from the theoretical equations.

6.2.4 Stress and strain versus attack angle

In this part the stress and strain are plotted with respect to the attack angle with fixing the other variables. The nominal value of wind speed is 12.3 m/s. The time value is fixed at 10 sec. The pitch angle value is selected to give the maximum power. Forces and moments exert on the blade are plotted as shown in figure 6.10 and figure 6.11, respectively. Stress and strain are plotted in figure 6.12.

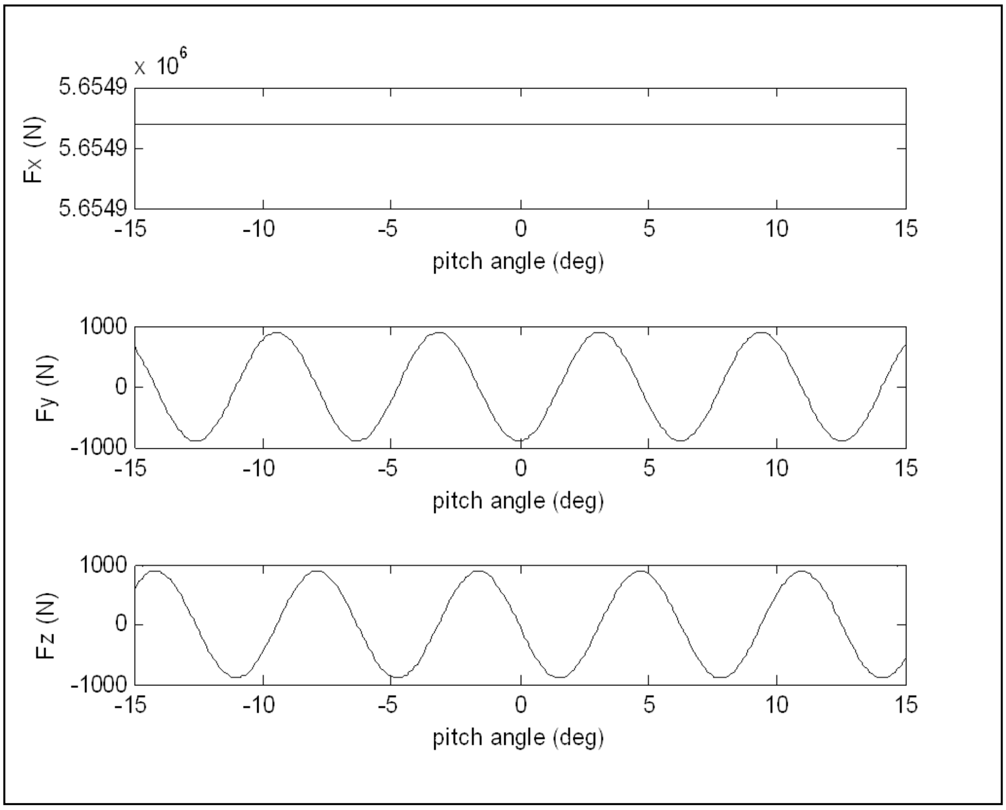


Figure 6.7: Forces versus pitch angle

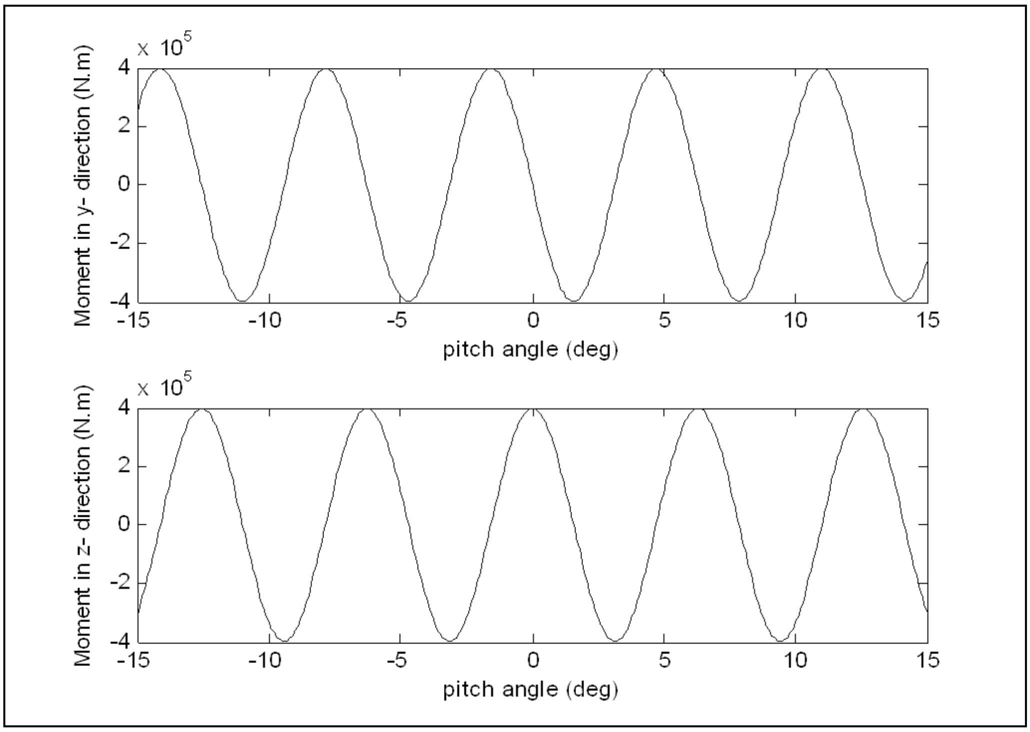


Figure 6.8 : Moments versus pitch angle

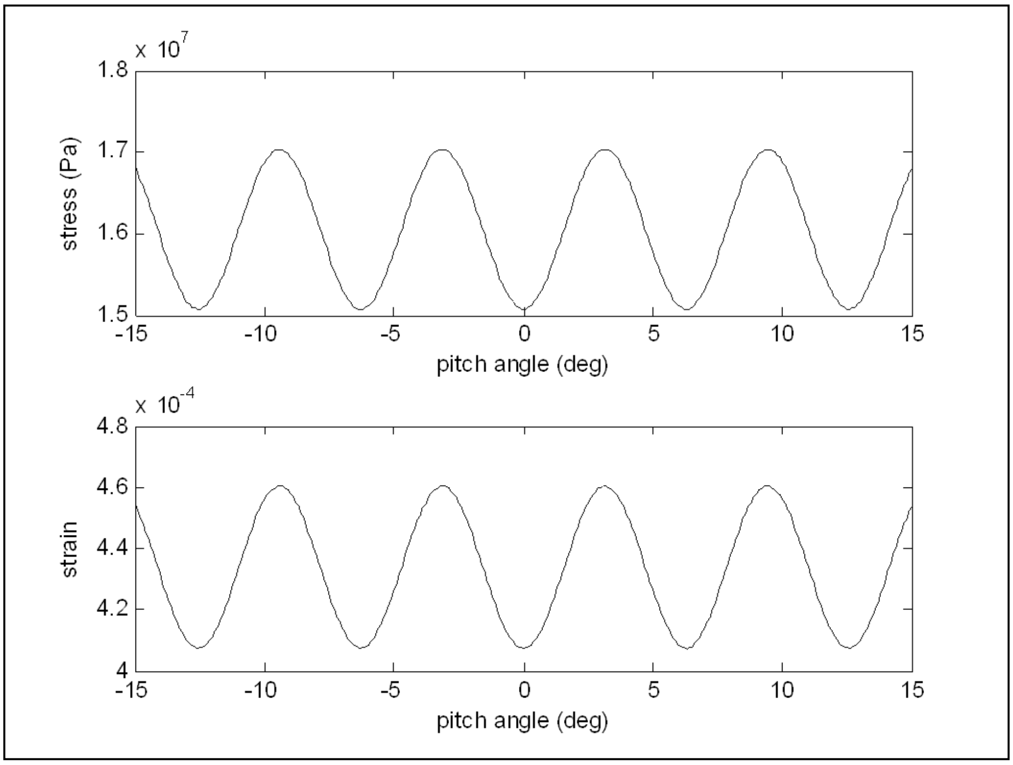


Figure 6.9 : Stress and strain versus pitch angle

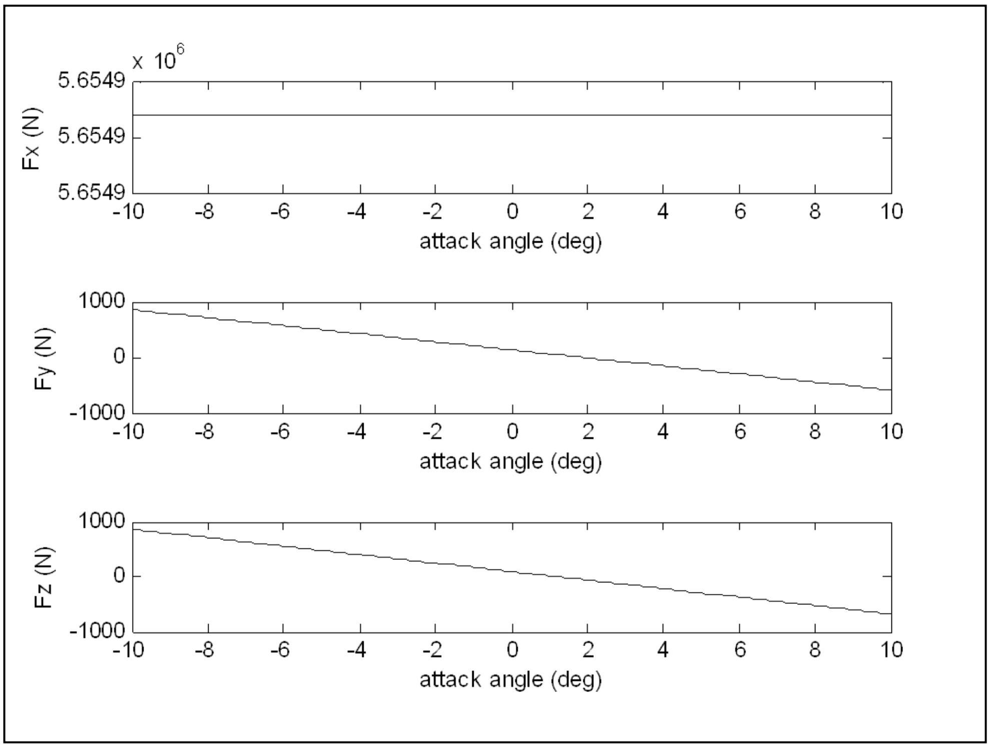


Figure 6.10 : Forces versus attack angle

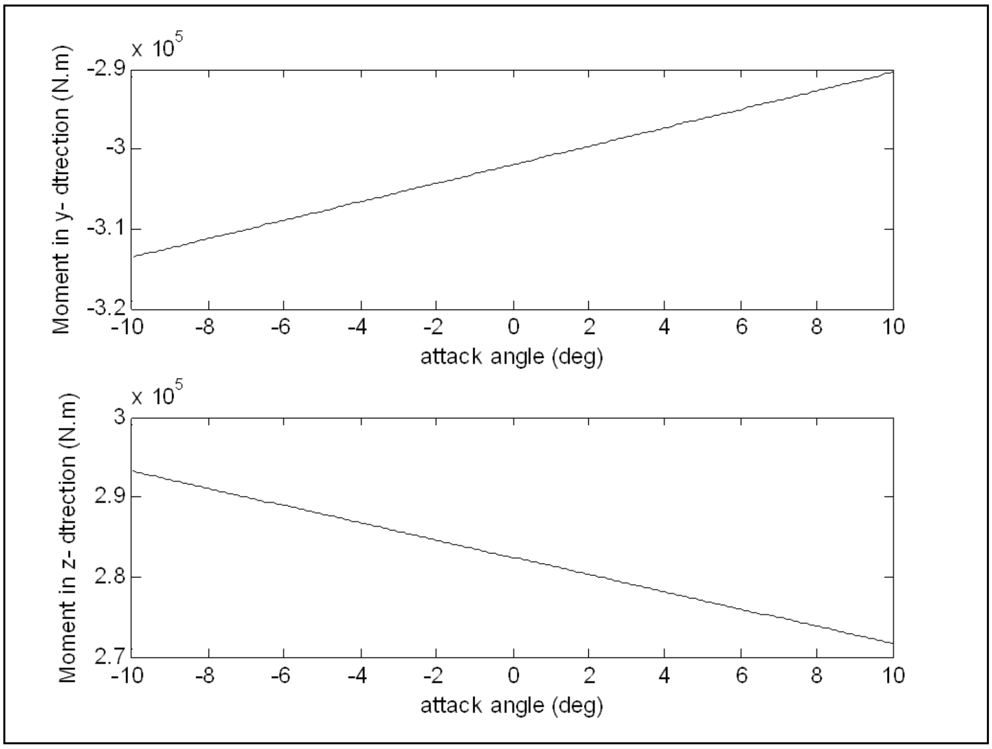


Figure 6.11 : Moments versus attack angle

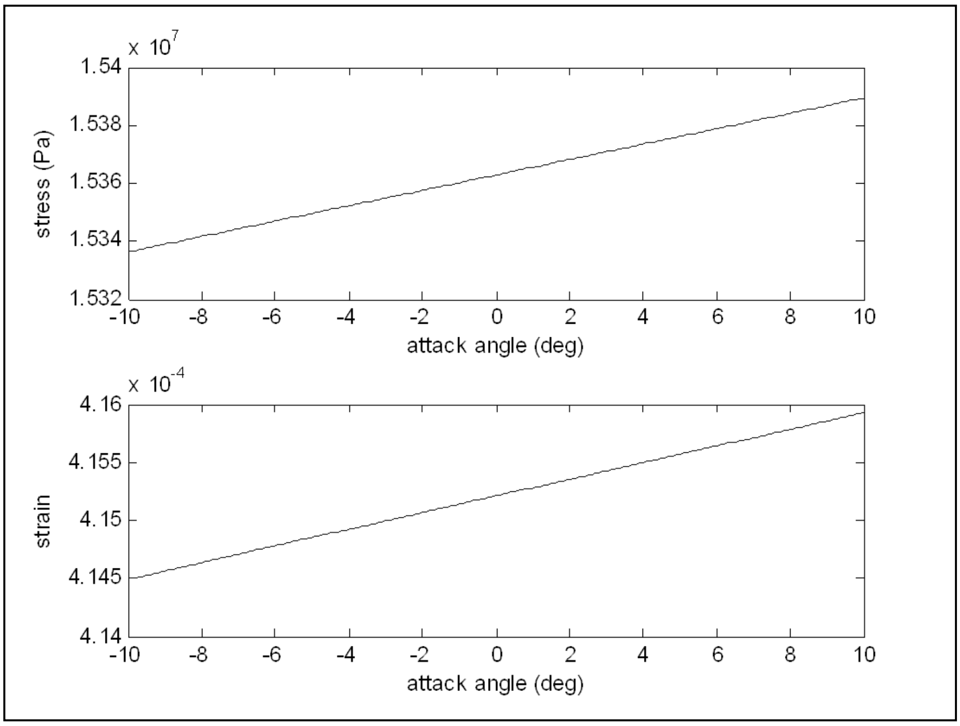


Figure 6.12 : Stress and strain versus attack angle

6.3 Analysis

The mean values of variables plotted in figures 6.1 – 6.3:

M_y = -0.7482 (10^4) N.m and M_z = 0.7712 (10^4) N.m

F_x = 5.6549 (10^6) N, F_y = 568.4700 N and F_z = 557.0406 N

σ_{xx} = 1.6038 (10^7) Pa

ε_{xx} = 0.4335 (10^{-3}) , ε_{yy} = -0.499 (10^{-3}) and ε_{zz} = -0.499 (10^{-3})

γ_{xs} = -0.3385 (10^{-5})

$P_{R_{max}}$ = 1.6261 (10^5) Watt

The mean values of variables plotted in figures 6.4 – 6.6:

M_y = 2.3462 (10^4) N.m and M_z = -7.2774 (10^4) N.m

F_x = 5.6549 (10^6) N, F_y = 0.3637 (10^3) N and F_z = 158.0863 N

σ_{xx} = 1.6236 (10^7) Pa

ε_{xx} = 0.4335 (10^{-3}) , ε_{yy} = -0.5051 (10^{-3}) and ε_{zz} = -0.5051 (10^{-3})

γ_{xs} = -0.0961 (10^{-5})

$P_{R_{max}}$ = 9.7932 (10^{4}) Watt

The mean values of variables plotted in figures 6.7 – 6.9:

M_y = 2.172 (10^{4}) N.m and M_z = 1.6166 (10^{4}) N.m

F_x = 5.6549 (10^{6}) N, F_y = -36.4052 N and F_z = -1.4484 N

σ_{xx} = 1.6018 (10^{7}) Pa

ε_{xx} = 0.4335 (10^{-3}) , ε_{yy} = -0.4983 (10^{-3}) and ε_{zz} = -0.4983 (10^{-3})

γ_{xs} = 0.8801 (10^{-8})

$P_{R_{max}}$ = 51.8883 Watt

The mean values of variables plotted in figures 6.10 – 6.12:

M_y = -3.0197 (10^{5}) N.m and M_z = 2.8248 (10^{5}) N.m

F_x = 5.6549 (10^{6}) N, F_y = 133.8739 N and F_z = 91.2509 N

σ_{xx} = 1.5363 (10^{7}) Pa

ε_{xx} = 0.4335 (10^{-3}) , ε_{yy} = -0.478 (10^{-3}) and ε_{zz} = -0.478 (10^{-3})

γ_{xs} = -0.0554 (10^{-5})

$P_{R_{max}}$ = 1.6261 (10^{5}) Watt

When comparing the previous result values with the calculation results in chapter 5;

M_y = 4.0259 (10^{5}) N.m and M_z = -7.7191 (10^{4}) N.m

F_x = 5.6549 (10^{6}) N, F_y = 121.635 N and F_z = 922.03 N

σ_{xx} = 1.5293 (10^{7}) Pa

ε_{xx} = 0.41 (10^{-3}) , ε_{yy} = -0.4758 (10^{-3}) and ε_{zz} = -0.4758 (10^{-3})

γ_{xs} = -5.8 (10^{-7})

$P_{R_{max}}$ = 1.6261 (10^{5}) Watt

it is found that they are convergent.

Considering my result ε_{xx} = 0.4335 mm/m. Comparing with results in [3] , ε_{xx} = 0.55 mm/m.(error : 21%). Comparing with ANSYS, ε_{xx} = 0.52 mm/m (error : 19.95%).

Thus by using a simpler model comparing with [3], an expected result to compute the values of stress and strain are found.

CHAPTER 7
CONCLUSION

This chapter conclude this thesis documentation. It introduces some recommendations for the future works in wind energy field. Steps are intended to be taken in the future is found in this chapter also.

7.1 Conclusion

More than 50 countries around the world have an organized set up in the field of wind power. Large progress in wind power has been witnessed in the countries of the European Union.

In the past few years[3], a new frontier for wind power development has also been established in the sea. With offshore wind parks beginning to make a contribution, the possibilities of using wind energy systems worldwide are likely to increase many times in the future. Establishing wind energy projects in the sea has opened up new demands, including the need for stronger foundations, long underwater cables and larger individual turbines, but offshore wind parks are expected to contribute an increasing proportion of global capacity.

Studies of different institutions around the world have confirmed that a lack of wind is not likely to be a limiting factor on global wind power development. With the expansion of the wind industry, large quantities of wind powered electricity will need to be integrated into the grid network. Because of the variability of the wind, control methods have to be established for dealing with variations in demand and supply. Their installation could help to handle this issue.

It has been estimated by the GWEC that wind power could supply one third of the world's electricity by 2050. This is a big challenge not only for the wind energy sector, but for the entire electricity supply system.

In this thesis, the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient is developed. The half cylinder simple model to represent the blades of the wind energy turbines is used. This model is used to make an analytical measurements of the moments generated by the wind and the gravity of each blade then the stress and strain exerts each blade.

Simulation results showed the values of the stress and strain affect the blade. They were compared by the real values measured by fiber Bragg grating sensors of Fos4x German Company and the results were agreeable.

7.2 Recommendation

In future researches, It is recommended to use our simple half cylinder model of the wind turbine blade to give a feedback information regarding the stress and strain values on the wind turbine blades.

7.3 Future Work

In the future, It is intended to go ahead and get the PHD degree in the wind energy field which is the hot field in the world up to this moment. It aims to get the maximum energy available in wind energy. I will plan to visit Fos4x company in Germany. Also, a study about how much the wind energy can be applied in Gaza Strip in intended to acheived and the amount of electrical power can be produced .

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APPENDIX A

MATLAB CODES

A.1 Code for plotting the Relationship between wind velocity and power of wind

```
clear all
clc

vc = 3 ;
vr = 12;
vf = 25;

step = 0.01;
v = step : step : 25;
P = zeros(1, length(v));
index = 1;

for v1 = step : step : vc
    P(index) = 0;
    index = index + 1;
end

for v2 = vc+step : step : vr
    r = 50;                                % in meters, inducates the
blade length
    A = pi * (r^2);
    Raw = 1.225;                              % Air Density, in kg/m³
    P(index) = 0.5 * A * (v2^3) * Raw ;    % Cubic relation
    index = index + 1;

end

Prated = P(index-1);

for v3 = vr+step : step : vf
    P(index) = Prated;
    index = index + 1;

end

plot(v,P/(10^6));
title ('Theoritical Power Curve')
xlabel('Wind Velocity (m/s)')
ylabel('Output Power  (MW)')
```

A.2 Code of Weibull distribution plot between wind velocity and probability

```
% Weibull Distribution

v = 0: 0.01 : 25;
a = 7;                  % scale parameter
b = 2;                  % shape parameter
P = wblpdf(v,a,b);      % weibull probability ditribution

plot(v,P)
title ('Weibull distribution Plot ')
xlabel('Wind Velocity (m/s)')
ylabel('Probability')
```

A.3 Code of an example of the relationship between the cp and λ

```
clear all
clc

lamda = 2:0.1:16;
c = [0.5 116 0.4 0 5 21];
x = 20;

for PitchAngle = 0 : 5 : 20;

ghama = 1./(1./(lamda+0.08*PitchAngle)-0.035/(1+(PitchAngle^3)));
Cp    =    c(1).*(c(2)./ghama-c(3).*PitchAngle-c(4).*(PitchAngle^x)-
c(5)).*(exp(-c(6)./ghama));
plot(lamda,Cp)
axis([2 16 0 0.45])
xlabel('Tip speed ratio')
ylabel('Power coefficient')
hold on

end
```

A.4 The code shows the effect of the pitch angle on the output power

```
% Power curve plot
clear all
clc

vc = 3 ;
vr = 12;
vf = 25;

step = 0.01;
```

```
v = step : step : 25;
P = zeros(1, length(v));
index = 1;
for PitchAngle = 0:5:20
   P = zeros(1, length(v));
   index = 1;

for v1 = step : step : vc
    P(index) = 0;
    index = index + 1;
end

for v2 = vc+step : step : vr
    R = 50;
    f = 0.2;
    w = 2*pi*f;                                 % in meters, inducates
the blade length
    A = pi * (R^2);
    Raw = 1.225;                               % Air Density, in kg/m³

    lamda = w*R/v2;
    c = [0.5 116 0.4 0 5 21];
    x = 20;

    ghama              =              1./(1./(lamda+0.08*PitchAngle)-
0.035/(1+(PitchAngle^3)));
    Cp   =   c(1).*(c(2)./ghama-c(3).*PitchAngle-c(4).*(PitchAngle^x)-
c(5)).*(exp(-c(6)./ghama));

    P(index) = 0.5 * A * (v2^3) * Raw * Cp;   % Cubic relation
    index = index + 1;

end

Prated = P(index-1);

for v3 = vr+step : step : vf
    P(index) = Prated;
    index = index + 1;

end

for h= 1: length(P)
    if P(h) < 0
        P(h) = 0;
    end
end

plot(v,P/(10^6));
```

```
title ('Power Curve')
xlabel('Wind Velocity (m/s)')
ylabel('Output Power  (MW)')
hold on
end
```

A.5 Main Code to find stress and strain

```
clear all
close all
clc
% -------------------------------------------------------------------
BladeProfilnumber  =   'NACA63(4)-221';
BladeLength  =   30;  %     Blade length in meters
BladeMass  =   5000;  %     The blade mass in kg
% -------------------------------------------------------------------
% Angular position of the blades
counter = 1;
 f = 0.2;          % speed Rotation
 w = 2 * pi * f;  % angular speed rotation
for t = 0:1:9     % to get readings for 10 different blade rotation
angles
RotationsAngle = w * t * 180 / pi;        % in degree
BladeRotationAngle(1) = RotationsAngle;
BladeRotationAngle(2) = RotationsAngle + 120;
BladeRotationAngle(3) = RotationsAngle + 240;
% -----------------------------------------------------------------

% Pitch angle of the three blades
PitchAngle(1) = DesiredPitchAngle;       % 90 ° is approximately the
feathered position, while still corrected for
                                         % the zero-lift angle must
be (approximately -1.5 °)
PitchAngle(2) = PitchAngle(1);
PitchAngle(3) = PitchAngle(1);
% ------------------------------------------------------------------

% Calculating the gravity moment
GravityCenter =  10;      % centre of gravity in meter
g = 9.8;                  % acceleration of gravity

% for blade 1
% graviy moment in z-direction
GravityMoment_z(1) = - GravityCenter* g * BladeMass *cos
(BladeRotationAngle(1))* cos (PitchAngle(1));
% gravity moment in y-directio
GravityMoment_y(1) = GravityCenter *g* BladeMass *cos
(BladeRotationAngle(1))* sin (PitchAngle(1));

% for blade 2
```

```
% graviy moment in z-direction
GravityMoment_z(2) = - GravityCenter*g * BladeMass *cos
(BladeRotationAngle(2))* cos (PitchAngle(2));
% gravity moment in y-direction
GravityMoment_y(2) = GravityCenter *g * BladeMass *cos
(BladeRotationAngle(2))* sin (PitchAngle(2));

% for blade 3
% graviy moment in z-direction
GravityMoment_z(3) = - GravityCenter * BladeMass *cos
(BladeRotationAngle(3))* cos (PitchAngle(3));
% gravity moment in y-direction
GravityMoment_y(3) = GravityCenter * BladeMass *cos
(BladeRotationAngle(3))* sin (PitchAngle(3));
% -------------------------------------------------------------------

% % airfoil coefficient
alpha = -20 + (20-(-20)).*rand(1,1);   % Random angle of attack in
the range [-20, 20]
alphavec (counter) = alpha;            % for plot
[c_L c_D] = Airfoil_coefficients(BladeProfilnumber, alpha);    % to
get Airofoil coefficients
% --------------------------------------------------------------------

AirDensity = 1.225;                    % Air density
speed = 12.3;                          % Nominal speed
speedvec(counter) = speed;             % for plot
chord1 = 1.048*2;                      % Inner diameter
chord2 = 1.15*2;                       % Outer diameter
ro = 0;                                % length of the cylindrical
portion in the root of the aerodynamic profile
R= BladeLength;                        % Rotor radius
A = 0.5 * pi *(chord2^2-chord1^2)/4;   % cross section area (hollow
half cylinder )

% axial force, centrifugenal force

Fx(1) = w * BladeMass * BladeLength^2;    % for blade 1
Fx(2) = w * BladeMass * BladeLength^2;    % for blade 2
Fx(3) = w * BladeMass * BladeLength^2;    % for blade 3

% Tangential forces in y- direcction
Fy(1) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(1)) * cos (PitchAngle(1))+ c_D *
sin (PitchAngle(1)));
Fy(2) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(2)) * cos (PitchAngle(2))+ c_D *
sin (PitchAngle(2)));
Fy(3) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(3)) * cos (PitchAngle(3))+ c_D *
sin (PitchAngle(3)));
```

```
% normal forces in z- direcction
Fz(1) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(1)) * sin (PitchAngle(1))- c_D *
cos (PitchAngle(1)));
Fz(2) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(2)) * sin (PitchAngle(2))- c_D *
cos (PitchAngle(2)));
Fz(3) = 0.25 * AirDensity *(speed^2) * pi * (chord2 - chord1) * (R -
ro) * (c_L * sec(BladeRotationAngle(3)) * sin (PitchAngle(3))- c_D *
cos (PitchAngle(3)));

% Bending moments
Factor = (-1/8)*AirDensity*(speed^2)*pi*(chord2-chord1)*(R^2-ro^2);
% taken as a factor to simplify the program1

% for blade 1
Torque_y(1) = Factor * (c_L * sec(BladeRotationAngle(1)) * sin
(PitchAngle(1))- c_D * cos (PitchAngle(1)) );
Thrust_z(1) = -1 * Factor * (c_L * sec(BladeRotationAngle(1)) * cos
(PitchAngle(1))+ c_D * sin (PitchAngle(1)) );

% for blade 2
Torque_y(2) = Factor * (c_L * sec(BladeRotationAngle(2)) * sin
(PitchAngle(2))- c_D * cos (PitchAngle(2)) );
Thrust_z(2) = -1 * Factor * (c_L * sec(BladeRotationAngle(2)) * cos
(PitchAngle(2))+ c_D * sin (PitchAngle(2)) );

% for blade 3
Torque_y(3) = Factor * (c_L * sec(BladeRotationAngle(3)) * sin
(PitchAngle(3))- c_D * cos (PitchAngle(3)) );
Thrust_z(3) = -1 * Factor * (c_L * sec(BladeRotationAngle(3)) * cos
(PitchAngle(3))+ c_D * sin (PitchAngle(3)) );

% Total moments for 3 blades
moment_y = (Torque_y + GravityMoment_y);
moment_z = (Thrust_z + GravityMoment_z);
% ------------------------------------------------------------------
% note: the following calculations for the sensor on y- axis
% stresses
% 1. axial stress
new = 0.28;                   % Poison ratio

E_Mx = 37 * (10^9);           % Young modulus of Elasticity in x-
direction
E_My = 9 * (10^9);            % Young modulus of Elasticity in y-
direction
E_Mz = 9 * (10^9);            % Young modulus of Elasticity in z-
direction

sigmaxx1 = Fx/A;              % axial normal stress
```

```
% 2. Symmetric bending about z-axis stress
yDistance = chord1 / 2;
Izz = 0.5 * (pi / 2)* (((chord2/2)^4)-((chord1/2)^4));  % Moment of
inertia about z- axis
sigmaxx2 = -moment_z * yDistance / Izz;                 % normal
stress due to bending about z- axis

t = 2* (chord2-chord1);                                 % thickness
Vy = Fy * R;
Qz = 0;                                                 % since the
sensor is on y- axis
G =  3.5 * (10^9);                                                %
modulus of rigidity, not sure about this value

tawxs1 = -Vy * Qz / (Izz * t);                          % shear
stress due to bending about z- axis

% Symmetric bending about y-axis
zDistance = 0;                                          % since the
sensor is on y- axis
Iyy = 0.5 * (pi / 2)* (((chord2/2)^4)-((chord1/2)^4));  % Moment of
inertia about y- axis

sigmaxx3 = -moment_y * zDistance / Iyy;                 % normal
stress due to bending about y- axis

t = 2* (chord2-chord1);                                 % thickness
Vz = Fz * R;
Qy = 0.5 * (2/3) * (((chord2/2)^3) - ((chord1/2)^3));

tawxs2 = -Vz * Qy / (Iyy * t);                          % normal
stress due to bending about y- axis

% strain
sigmaxx = sigmaxx1 + sigmaxx2 + sigmaxx3;             %
Superposition method
tawxs = tawxs1 + tawxs2;

absoxx(counter,:) = sigmaxx /E_Mx;
absoyy(counter,:) = -new*sigmaxx /E_My;
absozz(counter,:) = -new*sigmaxx /E_Mz;

ghamaxs(counter,:) = tawxs / G;

counter = counter+1;
end

% for print on the command window

absoxx = mean (absoxx)
```

```
absoyy = mean (absoyy)
absozz = mean (absozz)
ghamaxs = mean (ghamaxs)
______________________________________________________________

% This function computes the coefficient of lift C_A
%  the coefficient of drag c_W
%  from the alpha angle in deg for a given profile


function [c_L c_D] = Airfoil_coefficients(Profilnumber, alpha)

    switch Profilnumber
        case 'NACA63(4)-221'

%              The profile data are from
http://www.worldofkrauss.com/foils/1683
%       Assumption: only linear C_A running on alpha
%       Assumption: c_W constant over angle (only for about + -10 °)

            alpha_zl    = -1.5;            % Zero lift angle
            c_L         = 1.439/14.5.*(alpha+ alpha_zl);
            c_D         = 0.04;

        otherwise
            fprintf('Unknown Aerodynamic Profile\n')
    end
end
_____________________________________________________________

function Desired_Pitch_Angle = DesiredPitchAngle

syms F P g Cp

c = [0.5 116 0.4 0 5 21];
x = 10;

v = 3.32 + (8.2-3.32).*rand(1,1);
r = 50;
A = pi * (r^2);
Raw = 1.225;
R = 50;
f = 0.2;
w = 2*pi*f;
L = w*R/v;

g = 1./(1./(L+0.08*F)-0.035./(1+(F^3)));
Cp = c(1).*(c(2)./g-c(3).*F-c(4).*(F^x)-c(5)).*(exp(-c(6)./g));
P = 0.5 * Raw * A * (v^3)* Cp;
dP_dF = diff (P , F);
Y = solve(dP_dF , F);
```

```
Yd = double (Y);

Desired_Pitch_Angle = getmax(Yd,c,x,v,Raw,A,L);
_____________________________________________________________

function Fmax = getmax(Y,c,x,v,Raw,A,L)

s = size(Y);

k = 1;

for i = 1 : 1 : s
    j = isreal(Y(i));
    if j == 1;
        YY(k) = Y(i);   % real values of critical pitch angles
        Ff = YY(k);
        gf = 1./(1./(L+0.08*Ff)-0.035./(1+(Ff^3)));
        Cpf = c(1).*(c(2)./gf-c(3).*Ff-c(4).*(Ff^x)-c(5)).*(exp(-
c(6)./gf));
        Pf = 0.5 * Raw * A * (v^3)* Cpf;
        PP(k) = Pf;
        k = k +1;
    end
end

Pmax = max (PP);

for b = 1 : 1 : k-1
    if Pmax == PP(b)
       h= b;
    end
end

Fmax = YY(h);
```