Optimization of wind turbine loads for maximum power output and low fatigue loading

Optimering av lastprofiler hos vindturbiner för maximal kraftutbyte och låg utmattningslast

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Denna studie handlar om en analys av aerodynamiska laster hos en 1.5 MW landbaserad vindturbin. Målet handlar om specificering av stigningsvinkeln där kraftutbytet maximeras medan utmattningslaster hållas inom rimliga nivåer. Tretton hastighetsprofiler studerats (3 m/s till 27 m/s) för att kunna se samband mellan kraftutbytet och utmattningslaster. Vindhastighetsprofilerna simulerades med TurbSim, och de resulterande profilerna används som input för att analysera lasterna vid bladroten. Simuleringsverktyget FAST utnyttjas för olika stigningsvinklar (7,5 till 17 grader). Resultaten visar avvägningen mellan kraftutbyte och utmattningslast som funktion av stigningsvinkeln. Högre stigningsvinklar resulterar i ökat kraftutbytet, och oönskade utmattningslaster inträffar vid 16-17 grader. Skillnaden i kraftutbytet mellan lägsta och högsta stigningsvinklar kan vara så hög som 30%.
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Summary

In this thesis the aerodynamic loads for maximum power output at acceptable fatigue loads on a 1.5MW onshore wind turbine are examined. The objective mainly is to investigate pitch angles where optimal value of maximum power output at an acceptable level of fatigue loading can be achieved while studying the source of fatigue loading and the constraints of increasing the coefficient of performance of wind turbine power output.

A total of thirteen hub height mean wind speed profiles, at the same turbulence level, ranging from cut-in wind speed of 3m/s to cut-out wind speed of 27m/s at 2m/s incremental are simulated. The reference wind speed is set at the hub height. For reference wind set below the hub height, the logarithm wind profile is used to determine the hub height mean wind speed, and then the power law follows to determine the mean speed at other height. The speeds are determined on a meshed grid point to examine the change of wind speed and direction in time and space or turbulence which is mainly due to the shape and hostile of the terrains. Wind profile simulation is performed by TurbSim simulation code, and the resulting profile is used as input to analyze the loads at the blade root.

The loads are analyzed for the wind speed above the rated wind speed, 11m/s to 27m/s, where the blades are pitched to obtain an even power output. After performing several runs to investigate the relationship of wind speed to power output and fatigue loading, the wind speed, where the load should be analyzed, is narrowed to 21m/s which is close to the cut-out wind speed. The loads at the blade root are examined using the free simulation code, FAST, for different pitch angles ranging from 7.5 degrees to 17 degrees for each hub height mean wind speeds mentioned above. For examination of the loads at the selected locations the blade root is segmented to twelve equal points located 15 degrees away to each other. The points are located in angle between 0 and 180 degrees according to Load Rose approach.

The loads at the blade root are FAST output and they are used as input for post-processor MLife to analyze the fatigue load. The fatigue loads are examined in terms of damage equivalent loads of the bending moment out of plane. It is observed that pitching a blade angle has a significant effect on the power output and fatigue load, the power output increases and with undesirable fatigue load while pitching the blade angle to capture as maximum power output as possible. On the other hand, attempting to decrease the fatigue load affects the power output as well, that indicates minimizing the fatigue load cannot be achieved without affecting the power output.

Output power and fatigue load relation for different pitch angle ranging from 7.5 to 17 degrees of the selected wind speed 21m/s shows that while pitching the blade the power output increases with undesirable fatigue load. In general, it can be said that expected results are achieved at pitch angle ranging from 15 to 17 degrees. However, the fatigues loads may be not are in acceptable level, hence, it will not be appropriate to conclude that these pitch angles are the optimal angles where the maximum power output and minimum fatigue load can be achieved. Furthermore, looking at only the fatigue loads the minimum fatigue load is achieved at pitch angle of 7.5 at a sacrifice of 0.6MW of the maximum output power, 1.92MW, which is significant compared to the maximum output power that can be achieved.

Background

Wind energy is a renewable source, how much is used today will not affect the supply in the future. It is available freely. Due to increasing pollution level and growing environmental concerns production of energy from clean and renewable energy sources has become significant. Wind energy is one of the clean and environmental friendly energy sources. However it is said environmental friendly or have little impact on the environment there are still some concerns regarding the environment, like noise. Noise produced due to the interaction between the rotor blades and the flowing wind over it is the big issue in the wind industry.
Global wind energy trend
The wind energy worldwide is growing in an alarming way, Figure 1 shows the growth. The 3.75 Giga watt installed capacity in 2000 has increased to 63.5 GW by 2015 that shows how production of energy from the wind source is growing.

Figure 1: Global wind energy trend [1]

Wind energy in Europe
In Europe the wind energy production is also increasing as shown in Figure 2; the 3.2GW wind power in 2000 grew to 12.8GW in 2015. By 2020 the energy production from renewable source will cover 20% of all the energy demand. 34% of all electricity consumption should be from renewable sources of which wind energy accounts 15 to 18% of all electricity consumption. According to European Wind Energy Associations by 2030 wind power is expected to cover a quarter of EU power demand.

Figure 2: Wind power in Europe [2]
Introduction
The power production of wind turbine is mainly the interaction between the rotor and wind flowing over the blade. During operation the flowing wind over the rotating blade creates an aerodynamic force which decomposes to the lift and drag forces and these forces are acting perpendicular and parallel to the direction of wind flow, respectively. The aerodynamic force generated by the mean wind determines the major aspects of the wind turbine performance that is the mean power output and the loads (fatigue and extreme loads). Fatigue loads are which threaten to damage the turbine as a result of accumulated over time of several years of operation; while extreme loads are loads that occurs once while the turbine is in power production operation, like extreme gusts, and the components in the system needs to be able to withstand it by the time it is happening. During design of wind turbine components are designed to withstand fatigue loads, ultimate/extreme loads, or both loads as a combination [3]. Many modern wind turbines have achieved a reduction in fatigue loads by pitching (pitch control mechanism) individual blades [3]. Different sources such as aerodynamics, gravity, dynamic interactions and mechanical control can contribute to fatigue of wind turbine blades [4]. Fatigue reduction techniques for wind turbines can either be active or passive where the former involves controlling of the pitch angle, yaw angle, and thermal cycles are among many [5].

The core work of this thesis project is to investigate the maximum power output at a minimum acceptable fatigue loading on critical load carrying components of wind turbine. The optimization scenario is multiobjective inherently, and is defined in relation with the trade-off between maximum power output and reduction of fatigue load. It particularly focuses on pitch controlled horizontal axis wind turbines to optimize the wind turbine loads. As aerodynamic loads are considered the sources of fatigue, active fatigue reduction shall be implemented. We consider a dynamic wind model for a three-bladed horizontal axis direct drive wind turbine.

Motivation
Now days, aerodynamic load optimization of wind turbine blade has become the concern area of wind energy, as wind turbines are becoming big in size therefore reducing the blade loads minimizes the fatigue load on the mechanical components of the system. In fact, wind turbines are designed to perform for possible maximum power capture and given some safety factor that gives window for the wind turbine to perform for wind speeds higher than the rated speed. The power optimization or power boost termed as in the wind energy industry is performed above the rated wind speed at which the wind turbine power output reaches its maximum at this region of the power curve that consists high wind speeds. Optimization or power boosting is performed by sacrifice the life of the wind turbine given as a safety margin. Therefore, by changing the angle of attack or pitching the blade the power can be optimized for the wind speeds above the rated power. Having this in mind a range of pitch angles examined for maximum power for a given hub height mean wind speeds. These wind speeds are of course above the rated wind speed. The maximization of the power capture is examined simultaneously with low fatigue loading. Solving the scenario stated will definitely give a good knowledge of wind power production and fatigue analysis.
Objective
The main objective of this work is to investigate maximum power output at a minimum acceptable fatigue loading on critical load carrying components of active wind turbine. In the meantime, it also addresses possible techniques like blade pitch profiles to achieve the main objective of the thesis.

Scope
The scope of the thesis work is to obtain the best optimal solution for the given scenario.

Method of Analysis and Approach
The scenario is planned to be conducted in different steps.

1- Literature review: in this phase related works are to be studied so as to capture information and the state of art of the work that helps to formulate the model.
2- Model and problem formulation: to formulate the model the first step is to study the behavior of the aerodynamic loads and their contribution for power generation and impact on the fatigue loads of the wind turbine blade.
3- Analysis: the model formulated will be used to carry out the analysis. In this part the model validation will also be conducted. Simulation of the loads and torque is carried out. Multiobjective analysis approach will be followed to solve the trade-off and optimal solution.
4- Optimization: the values obtained will be used to investigate an optimal solution of the task.

The problem defined is to investigate the optimal solution of power output against the fatigue load by pitching wind turbine blade. The mean wind speed at hub height is simulated at turbulence intensity level of ‘A’. The pitch angle is ranging from 7.5 to 17 degrees at 2 degrees of incremental. The fatigue loading is analyzed at the blade root. The fatigue analysis is performed using simulation codes from National Renewable Energy Laboratory (NREL). First the wind profile is simulated using TurbSim, then FAST is used for simulation of loads at a selected location of the blade roots or nodes, finally FAST output is fed to MLife to analyze fatigue loading and Microsoft Excel is used to present the MLife output.

Literature review
In wind power production system the most important factor that influence the generation of energy and fatigue load, and reliability of a wind turbine system is the aerodynamic load on the wind turbine blade. Thus, optimization of the aerodynamic load, and fatigue load analysis of wind turbine blades has become a focus area of the system.

In Ref. [6] a static wind model for three bladed horizontal axis pitch controlled wind turbine is considered to investigate the sacrifice of the power output. The finding is a pitch profile which optimizes the maximum power production which simultaneously minimizes the fatigue loads on the wind turbine blade. For fatigue load minimization general pitching approach based on convex optimization is used. The study has mainly focused on finding pitch profile, ranging from 0 to 2π/3, minimizing the fatigue load and see how much power is sacrificed in the process. The model in this paper has two areas: wind model and turbine model. In this section it considers torque and force functions in order to find expression for each model. Under wind model vertical wind shear,
horizontal wind shear and tower shadow is expressed as a fatigue load, and in turbine model the tangential and axial forces acting on the blades are defined, and having using these values the torque and thrust forces are expressed that are responsible for power generation and bending. Two problems are defined: power maximization and fatigue load minimization, and used sequential convex programming (SCP), the method finds local solutions, local minima and maxima, iteratively. Using multiple initial pitch profiles as input for the SCP they found good trade-off curve, see figure below.

![Figure 3: Trade-off curves with different starting constants pitch profiles](#)

The figure shows the convergence of all the pitch profiles to \( p_{\text{t.o.}}(\theta) \)

According to the paper, they achieved to minimize fatigue load by scarifying 7% of the maximum attainable power output. In ref [7] minimum cost of energy is investigated by determining the fatigue and extreme loads and annual energy production. During the study life time equivalent fatigue loads are calculated based on time domain aeroelastic calculations and Rainflow counting is used, moreover, it address how multiobjective optimization are conflicting each other. In Ref. [4], the mechanical frame work of the wind turbine which must meet the requirement wind power system optimization is discussed. In ref. [8], variable speed horizontal axis wind turbine is chosen and the operation regions discussed. In this reference the dynamic model of variable speed which incorporates aerodynamic characteristics and aerodynamic power capture by the rotor is also shown and it elaborates the dependency of the power capture in the tip speed ratio and angle of attack. Furthermore, it states the region where maximization of power extraction is. In Ref. [9] discusses the aerodynamics of the wind turbine which includes design of airfoil, optimization mechanism of the system, and control and safety systems. This reference gives the state of art of the wind turbine and over view of the system. In Ref. [3], the aerodynamic model is described and their dependency on the pitch angle and tip speed ratio. In Ref. [10] fatigue load optimization of wind turbine blade is studied considering different type loads acting on the blade which are developed due to the change in wind speed. The wind speed is ranging from cut-in to cut-out. In the study they considered blade length, twist angle and chord length as optimizing parameters of the fatigue loading; accordingly the study found out that the twist angle is very sensitive than the other two parameters stated to the fatigue life of the blade and it increases exponentially. The paper treated the wind turbine blade as a cantilever to find out various stresses acting on it, which are developed due to various static force and moments. The static forces considered are thrust, tangential forces and gravity force. Finite
Element Analysis software (ANSYS) is used to find out the stresses acting on the turbine blade. In Ref [11] the unsteady aerodynamic load due to turbulent wind of NREL 1.5-MW HAWT blade is studied. The study is to minimize the fluctuation of the bending moment of the blade. In the study FAST simulation code is used to consider the turbulent wind as the wind input. In Ref. [12] multiobjective formulation, and the use of genetic algorithm and its advantage regarding solving multiobjective problems is stated well. In addition different type of multiobjective genetic algorithm is discussed in reference to their advantage and disadvantages.

Based on the available information and state of the art of wind turbine blade, this thesis work will formulate an optimization solution for wind turbine blade load which investigate maximum power output while simultaneously minimizing fatigue loading to an acceptable level by changing wind speed.

**HAWT Analysis Tools**

Wind turbines those are used for production of electricity by converting kinetic energy to mechanical energy then to electrical energy should be designed and simulated to be able to be cost effective, this should be done before costly prototypes are built and ready for commercial. IEC came up with minimum design requirements standards considering above mentioned problems. Today, there are many numerical tools and the corresponding wind turbine models are also developed.

The different numerical aero elastic models/codes that are few to mention are listed below

- FAST simulation code from National Renewable Energy Laboratory of USA (NREL)
- HAWC2 from Technical University of Denmark (DTU). Riso National Laboratory for sustainable energy

For this study FAST code is selected as it is an open and free for any user. A test case from the available sample distributed with FAST archive (Test 13) is used for this study.

**Problem definition and model**

Generation of wind energy mainly due to the aerodynamic load that act on the wind turbine blade and hence, the blades are subjected to aerodynamic loads which are resulted from the flow of air passes over the blades. The wind flow is unsteady in nature due to the turbulent nature (that is, a continual change of wind speed and direction in space and time) of the wind. In addition to the natural phenomenon of wind, other reasons can also affect the wind steadiness, for example the deviation of flowing air to the rotor from the axisymmetric condition like due to yaw misalignment.

The inflow is the main source of large fatigue loads on the turbine which intensity is directly related to the mean wind speed at hub height and the hub height itself above the ground level. Naturally, the turbulence intensity decreases as we go further up above the ground level.

Optimization of performance of wind turbine can be on wind turbine blade design stage and during operation that is altering the angle of attack by using pitch angle to adjust the torque and the wind speed depending on the power curve region.

The aerodynamic power captured by the wind turbine due to flow of air to the rotor is nonlinear. The expression is given below [13, 8, 14]. The following equation is used as a model for the study.
\[ P = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v_\infty^3 \]  

Where \( \rho \) is density of air, \( R \) is rotor radius, \( v_\infty \) is the free stream wind speed, and \( C_p \) refers to the efficiency and particularly called coefficient of performance of the rotor blade which depends on the tip speed ratio \( \lambda \), and the angle of attack that is also influenced by the pitch angle \( \beta \). The tip speed ration \( \lambda \) is given as follows \([13, 8]\).

\[ \lambda = \frac{V_{tip}}{V_{wind}} = \frac{\omega R}{v_\infty} \]  

Where \( \omega \) is rotor angular speed.

During analysis density of air over the swept area of the rotor, and angular velocity of the rotor are assumed constant. Moreover, the rotor radius is also assumed fixed.

Hence, during operation the efficiency of power capture is a function of the wind turbine blade pitch angle and turbine blade tip speed ratio. A rotating blade experiences apparent wind velocity which intensity actually depends on the mean true wind speed. The lift force is perpendicular to the apparent wind velocity and the tangential component of the force supports blade rotation and drag force opposes it that are called lift and drag, respectively. The lift force increases with the angle of attack along with that the undesirable drag force also increases. When these two forces lift and drag ratio is maximum a wind turbine can give a maximum performance and is called optimum angle of attack. Airfoil cross sections are aligned in a way to operate at this optimum angle of attack which is governed by pitch controller.

The equation of power further follows the relationship with the aerodynamic torque developed by angular velocity, and is given by

\[ P = T \omega \]  

\[ T = \frac{1}{2} \rho \pi R^3 v_\infty^2 C_T(\lambda, \beta) \]  

\[ F = \frac{1}{2} \rho \pi R^2 v_\infty^2 C_F(\lambda, \beta) \]  

Where \( T \) is aerodynamic torque, \( F \) is aerodynamic thrust, \( C_T \) and \( C_F \) are torque and thrust coefficients, respectively; and the coefficients are functions of tip speed ratio and pitch angle \([3]\).
The desire of this project is to obtain maximum even power output at an acceptable low level of fatigue loading. The power output is proportional to the mean aerodynamic torque. In addition, it investigates low fatigue loading referring the values attained at a search of maximum power output.

Since the fatigue of the wind turbine blade mainly affected by the wind property, here the mean wind speed at hub height is considered while investigating the optimal loads and low fatigue loads on the wind turbines blades. The mean wind speed at the hub height seen by a rotor blade is unsteady due to the turbulent nature of the wind and is simulated using turbulent wind simulator TurbSim. The mean wind speed ranges from cut-in to cut-out in 2 m/s increments (in this particular case the cut-in to cut-out ranges from 3m/s to 27m/s, therefore there will be 13 different cases to be examined), they are the reference mean values over the entire Analysis Time length of the simulation of the u-component wind speed. The simulated result (the .bts file) is used as input for aeroelastic simulator FAST, and then, finally, the output of the load is used to estimate the fatigue load at different locations/DOFs.

Using the Excel to help find the optimal load at a range of given pitch angle is conducted for each case, that is, the estimation of fatigue load is done for a mean wind speed of ranging from 3m/s to 27m/s at incremental of 2m/s.

**Multiobjective optimization model formulation**

Wind turbine operation is a multiobjective optimization task involving conflicting requirements and influencing each other. One objective of improvement often reduces the performance of other. Such as maximizing performance (power output) and minimizing load (fatigue load to acceptable level). In fact, it is impossible to obtain an optimal solution to make all targets achieve optimal at the same time; that is why there is a trade off between maximizing power output and minimizing the fatigue load on the wind turbine blades.

Therefore, the two main objective functions of this project work are:

1. Maximize the power output
2. Minimize the fatigue loading to acceptable level

These objective functions are subjected to constraints. Constraints are those variables which relates with the given problem but nothing to do with the objective functions. As many constraints as can be stated for each given objective functions based on the problem definition, for example, limitation of the pitch rate which is governed by the pitch motor, and limitation on the maximum rotor speed which is controlled and shut down by safety device if it exceeds the maximum threshold speed of the power production system.

Often, in real engineering problem applications multi-objective optimization problems do have multiple objectives and more than one constraint to be satisfied [12].

Given \( m \) and \( n \) dimensional decision variable vector \( x \): find a vector \( x \) that satisfy a given set of objective functions. The solution \( x \) is generally restricted by a series of constraints. The constraints can be expressed in equality, inequality and bounding variables (bounds on the decision variables). Hence, the maximization minimization multi-objective decision problem is defined as follows:

\[
\text{Maximize } f_m(x), \quad m = 1,2,\ldots,M; \\
\text{Minimize } f_n(x), \quad n = 1,2,\ldots,N;
\]
Subjected to \[ g_i(x) \leq 0, \quad i = 1,2,...,I; \]
\[ g_j(x) = 0, \quad j = 1,2,...,J; \]
\[ g_k(x) \geq 0, \quad k = 1,2,...,K; \]
\[ x_L \leq x_a \leq x_U, \quad a = 1,2,...,b; \]

Mechanical power extraction from wind turbine blade

Wind turbine power production depends on the interaction between the rotor blade and the wind; therefore, the power output and loads are determined by the aerodynamic forces generated by the wind [16]. The wind turbine mechanical power extraction generated can be expressed as referring equation (1)

\[ P_m = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v_{\infty}^3 \]

The maximum theoretical value of coefficient of performance, \( C_p \), which is a nonlinear function of both tip speed ratio and pitch angle, is approximately 0.59, and its particular value is between 0.4 and 0.45 [14, 17]. A small change in pitch angle can affect the power output dramatically; hence, it is necessary to have pitch angle regulation in order to adjust the speed of the rotor to maintain the tip speed ratio constant. That will increase the value of the coefficient of performance in turn which improves the efficiency of the turbine and increase power output [18].

![Figure 5: Power coefficient as a function of tip-speed ratio and pitch angle [18]](image)

The blade pitch angle, \( \beta \), that the coefficient of performance is a function for constrained with some mechanical limits and lies between \( \beta_{\min} \) and \( \beta_{\max} \) and tip-speed ratio should be satisfied the bounding condition \( \lambda \in (0, \infty) \) [19]. The parameters \( C_{p_{\max}}, \lambda_{opt} \) and \( \beta \) at which \( C_{p_{\max}} \) occurs are determined by examining a \( C_p, \lambda \) and \( \beta \) surface which is usually determined through simulation. The simulation can be using an aerodynamics codes to generate values for this surface as shown on Figure 4 above.

Blade tip speed ratio

As defined in equation 2, the tip speed ratio is a function of rotor blade velocity and relative wind velocity. The coefficient of performance or efficiency the turbine is directly proportional to the tip...
speed ration; hence, it can be increased with higher tip speed ratio. However, increasing the tip speed ratio constrained by the aerodynamic and centrifugal stress. A wind turbine blade designed in consideration of high tip speed ratio develops minimum torque at low blade rotation that in turn makes the cut-in speed to be higher [17].

**Numerical method**

**Blade element momentum method**

As discussed above, the aerodynamic load on the blade influences the lifetime and reliability of a wind turbine system. It depends on the operating environment, which is mainly the wind condition. Therefore, the source for fatigue load, in this paper, is considered from aerodynamic force (normal and tangential forces) applied to the blade.

The aerodynamic load on the wind turbine blades are calculated applying the blade element momentum (BEM) theory method. The BEM method is widely and most commonly used method in design calculations for the use in aeroelastic codes, as the aerodynamic methods has to be efficient and time saving [20]. The aeroelastic code used in this thesis work is FAST (Fatigue, Aerodynamics, Structures, and turbulence) Code, which enables to obtain stress acting on the wind turbine blade. FAST Code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two and three bladed horizontal axis wind turbine and it has an aerodynamics software library called AeroDyn subroutine which is used by the designers of horizontal axis wind turbine blades [21, 11].

Blade element momentum theory (BEM) combines momentum theory and blade-element theory, which is used to analyze the aerodynamic performance of a wind turbine, and also used to outline the governing equations for aerodynamic design and power prediction of a horizontal axis wind turbine blade [16]. The performance parameters of a HAWT blade are power coefficient $C_p$, thrust coefficient $C_T$, and tip-speed ratio $\lambda$ see equation 2. $C_p$ and $C_T$ are dimensionless and can be given as follows:

$$C_p = \frac{2P}{\rho \pi R^2 v_{\infty}^3}$$  \hspace{1cm} (6)

$$C_F = \frac{2F}{\rho \pi R^2 v_{\infty}^2}$$  \hspace{1cm} (7)

**Aerodynamics of horizontal axis wind turbines**

The aerodynamic performance of wind turbine can be analyzed using BEM theory, and in model formulation of BEM model two assumptions are made

1- The blades are divided into a number of elements which are independent of one another, i.e, there is no radial dependency and what happens at one element won’t influence the others or can’t be felt by neighboring elements.

2- The force from the blades on the flow is constant throughout the entire element. The rotor can have an infinite number of blades.
Prandtl’s tip loss correction is used to correct the second assumption that enables the method to compute a rotor with a finite number of blades. In BEM model it is possible to calculate the steady loads, rotational speed and pitch angle [9]. Moreover, the code also able to consider a non-uniform inflow conditions like the wind shear and yaw error. The wake from the upstream turbine influences the inflow to the rotor area partially [22]. Even though the BEM model predicts the load distribution across a wide range of yaw angle well and it is originally dedicated to axisymmetric flow of wind turbine, wind turbines are usually subjected to run at yaw angle. The yaw angle is relative to the inflow, considering this skewness Pitt and Peters made a correction which improves the flapwise loading. The Pitt and Peters skewness correction model which is employed to BEM theory to correct skewed wake is given as follows [23, 24]:

\[
a_{skew} = a \left( 1 + \frac{15\pi r}{32 R} \tan \frac{x}{2} \cos \varphi \right)
\]  

Where \(a\) is induction factor, \(a_{skew}\) is Pitt and Peters skew correction, and \(\varphi\) is azimuth angle. \(R\) is rotor plane and \(r\) is control volume radius are shown on the Figure 5 below.

**Blade element theory**

The blade is divided into \(N\) sections considering the assumption stated above, and then blade element analysis can be applied.

![Figure 6: Control volume shaped as an annular element to be used in the BEM model and actuator disk model [9, 16]](image-url)
Having the final result of induction factor, corrected one, aerodynamic parameters and attack angle for each blade element can be found by iteration algorithm; however, in this project work as I am going to use FAST simulation code the algorithm shall be implemented on the software.
The main objective of BEM model is to find the axial induction factors which are depicted on the Figure 7 above. The induction factors are of the blade segments and the model predictions are accurate, then these predictions allow analyzing and predicting the aerodynamic performance of the wind turbine rotor [22].

**Simulation method**

The numerical optimization algorithm process together with calculation tools and simulation code is shown in the Figure 8 below.

![Figure 8: System of mode of Optimization; numerical algorithm with Calculation models and simulation](image)

**Genetic algorithm**

In this project work the objective function is optimization of aerodynamic loads for maximum power output and acceptable low level fatigue loading. For example the mean wind speed at hub height and rotor speed of each turbine are the variables of the objective function. As the governing parameters are conflicting to each other it is often difficult to find an analytical solution to the stated scenario. Therefore, genetic algorithm is best method that can lead to realistic optimal solution point of the objective function, and it is used to find the optimal pitch angle of the wind turbine blade to be able to maximize the aerodynamic power output at acceptable low level of the fatigue loading.

**General consideration of IEC standards**

International Electrotechnical Commission (IEC) states the minimum design requirements that should be fulfilled. IEC 64100-1 3rd edition 2005 is the latest version of the international standards of on-shore wind turbine. Here in after IEC 64100-1 refers the latest version of on-shore wind turbine design requirements standards that is IEC 64100-1 3rd edition 2005.

In IEC 64100-1 three standard wind turbine classes are defined according to their environmental parameter which is wind, and these standards are characterized assuming different wind condition and to be able to cover many sites. The classification of the wind turbine class is according to their reference wind speed $V_{ref}$, basic parameter, averaged over 10 min. The reference wind speed is at hub height and the corresponding annual average wind speed $V_{ave}$ is equal to $0.2 \times V_{ref}$. The parameters are summarized at table.

| Table 1: Parameters for wind turbine classes [25] |
Wind profile and Turbulence

The continuous change of wind velocity and direction in space and time is natural; hence, in engineering application categorizing the wind situation is vital. Commonly the turbulence intensity and the longitudinal mean wind speed $\bar{u}$ are used to categorization of wind profiles. The wind profile is mainly affected by the shape and hostility of the terrains, which is the main problem in wind energy and categorized as special and topographic issues, shown on Figure 9.

![Figure 10: Wind profile on different terrains](image)

Considering the turbulent inflow is important for modelling the wind turbine's aerodynamic loads, especially because of the close relationship between fatigue damage on a wind turbine and the turbulence characteristics of the inflowing wind field. The turbulence intensity is considered for the time interval of 10 min, which is the relative magnitude of wind speed fluctuation relative to the longitudinal mean wind speed $\bar{u}$.

![Figure 11: Process of the models](image)

Wind spectra

Wind spectra are the wind speed patterns in the field, and it is determined using data taken at different wind speeds and wind directions. There are different spectral models available for choice in TurbSim simulation (IEC models, the Riso smooth-terrain model, and several NREL site-specific models (NWTCUP, GP_LLJ, WF_UPW, WF_07D, and WF_14D). TurbSim uses a modified version of the Sandia method—the basic approach of the Sandia method is to simulate wind-speed time series at

<table>
<thead>
<tr>
<th>Wind turbine class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{ref}$ (m/s)</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td>$V_{ave}$ (m/s)</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td></td>
<td></td>
<td></td>
<td>Specified</td>
</tr>
<tr>
<td>characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A $I_{ref}$ (−) (High)</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B $I_{ref}$ (−) (Medium)</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C $I_{ref}$ (−) (Low)</td>
<td>0.12</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
several points in a plane perpendicular to the mean wind direction and to propagate the time series in the mean wind direction at the mean wind speed [26].

**TurbSim**
It is full field turbulent wind simulator [27]. It uses a statistical model, having a random probability distribution or pattern that may be analyzed statistically but may not be predicted precisely, to numerically simulate time series of three component wind speed vectors, longitudinal $u$, transverse $v$, and vertical $w$ [27]. The wind speed vectors are at points in a two dimensional rectangular grid that is fixed in space. The grid is oriented vertically in Z and Y coordinate as shown in Figure 11below.

![Figure 12: Coordinates of a TurbSim wind field. [27]](image)

**Turbine data for TurbSim simulator**
The wind turbine data is from sample model provided with FAST archive, which is named ‘WP 1.5MW’ and the specifications are given below.

**Table 2: Baseline turbine specifications of ‘Test#13’ from FAST [21]**

<table>
<thead>
<tr>
<th>Test name</th>
<th>Turbine name</th>
<th>No. blades (-)</th>
<th>Rotor diameter (m)</th>
<th>Rated power (KW)</th>
<th>Rated wind speed (m/s)</th>
<th>Cut-in wind speed (m/s)</th>
<th>Cut-out wind speed (m/s)</th>
<th>Hub height (m)</th>
<th>Chord average length (m)</th>
<th>Test description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 13</td>
<td>WP 1.5MW</td>
<td>3</td>
<td>70</td>
<td>1500</td>
<td>11</td>
<td>3</td>
<td>27.6</td>
<td>84.37</td>
<td>1.93</td>
<td>Flexible, variable speed &amp; pitch control turbulence</td>
</tr>
</tbody>
</table>

Wind turbulence dependence on many factors; amongst, hub height from ground level has a significant effect on the turbulence intensity and the roughness.
Hub Height (HH) = Tower height + tower to shaft + over hang * shift tillt angle

\[ HH = 82.39 + 1.69 + 3.3 \times \tan 5 = 84.369 \]

**Turbsim simulation function**

The flow chart in figure below shows the overall simulation processes in the TurbSim turbulence wind simulator. In the flow chart below: the processes influenced by input parameters are indicated by blue lines, and the black line indicates the process that takes place internally and the variables are also internal and can’t be influenced by the user unless edited/changed the source code.

![Turbsim simulation flow chart](image)

Figure 13: Overview of the TurbSim simulation method [21]

Turbsim as simulation software starts by reading in all the input from the input file, and then it checks the turbulence model specified under meteorological boundary condition. This project follows the IEC standard, and uses the Kaimal model in Turbsim. This model assumes neutral atmospheric stability and the corresponding Richardson’s number is zero (RICH_NO = 0).

The next thing it does is find the correct sigma (standard deviation) for each component for the given spectral model (i.e IEC model) and turbulence model (i.e, IECKAI). Using the IEC standard (IEC 61400-1 3\textsuperscript{rd} 2005), the turbulence type (IEC_WindType) is NTM (Normal turbulence model).

The velocity spectra, \( S \), for each component, \( K = u, v, w \) are given by

\[
\sigma^2 = \int_0^\infty S(f) df \quad (9)
\]

The velocity spectra, \( S \), for each component, \( K = u, v, w \) are given by

\[
S_K(f) = \frac{4\sigma_k^2 L_K/\bar{u}_{hub}}{(1 + 6 f L_K/\bar{u}_{hub})^{5/3}} \quad (10)
\]
Where: $f$ is the cyclic frequency and $L_K$ is an integral scale parameter. The IEC 61400-1 standard defines the integral scale parameter to be

$$L_K = \begin{cases} 8.10 \Lambda_U, & K = u \\ 2.70 \Lambda_U, & K = v \\ 0.66 \Lambda_U, & K = w \end{cases}$$

(11)

Where the turbulence scale parameter, $\Lambda_U$, is

$$\Lambda_U = \begin{cases} 0.7 \times \min (30m, \text{HubHt}), \text{Edition 2} \\ 0.7 \times \min (60m, \text{HubHt}), \text{Edition 3} \end{cases}$$

The $\min$ function in above equation indicates the minimum of the two variables in the bracket.

The standard deviation and their relationships of the three velocity components are indicated below

$$\sigma_v = 0.8 \sigma_u$$

$$\sigma_w = 0.5 \sigma_u$$

Turbsim then opens the .sum file and writes the parameters given as input with the standard deviations. After this, Turbsim generates the random phase for each grid point, for each wind component and for each analysis frequency, and then goes ahead with calculating the spectral and transfer function matrices. This involves calling a function which computes the coherence between two points in the grid for all the points.

After this, an Inverse Fast Fourier Transform (IFFT) is performed to obtain the wind speeds of zero mean time series (that is the error from the model should have a zero mean or a mean that is not significantly different from zero at all the grid point). After the IFFT, Turbsim checks if a parameter is set to scale all the wind speeds to meet the target standard deviations (turbulence intensity) and mean wind speed, and performs the scaling if the parameter is set. The scale IEC turbulence (ScaleIEC) parameter is a switch to tell how to scale the time-domain velocity output of the IEC spectral models. At the end it writes the output files and calculates the mean wind speed across the whole grid and the turbulence intensity from the simulated data.

Note: Turbsim generates a random phase for each grid point, each wind component, and analysis frequency. So, changing any of those values leads to obtain different random phases, which then result in different time series.

**Grid size**

NumGrid_Z and NumGrid_Y determine the number of points simulated. The height of the points will determine their mean wind speed, but each individual point on the NumGrid_Y x NumGrid_Z grid will have different random phases, so they will get different time series at each point (i.e., the instantaneous wind speeds will be different).

The grid height and width parameters are denoted in TurbSim as GridHeight and GridWidth, respectively. They should be 10% greater than rotor diameter. Hence, in this case the grid size should be 80m which is greater than 1.1*70.
The grid density is determined by TurbSim’s number of grid points in the Z-coordinate (NumGrid_Z), Y-coordinate (NumGrid_Y), and simulation time step (TimeStep) inputs. Those input give the number of points in each direction; the time step/time determines the X direction.

The number of grid points and time step determines the TurbSim’s memory requirements, as the number of grid point increases the simulation time also increases.

The required wind data is at full field size, in the input file under RunTime options full field (FF) time series data in TurbSim/AeroDyn form or BLADED/AeroDyn for should be True.

The instantaneous wind speed at each grid point is stored temporarily and the binary files are written at the end of the simulation as a TurbSim output (either in .wnd or .bts file, depending on the output parameter set ‘True’).

Reference wind speed and height (URef and RefHt)

To generate (calculate) the mean hub height velocity \( \bar{u}_{hub} \) TurbSim uses the input reference height and reference mean wind speed at the reference height, and the velocities at other heights are calculated using the mean velocity at hub height \( \bar{u}_{hub} \); and the hub height as the reference point using the corresponding wind profile type chosen under ‘Meteorological Boundary Conditions’ in TurbSim input files. In this project the power law wind profile is used since the project follows the IEC model. The power-law mean velocity profile uses the power law exponent (PLExp) input parameter set in the input file to calculate the average wind speed at the height. The power-law equation is stated below.

\[
\bar{u}(z) = \bar{u}(z_{ref}) \left( \frac{z}{z_{ref}} \right)^{PLExp}
\]

Where \( \bar{u}(z) \) is the mean wind speed at \( z \), \( z_{ref} \) is a reference height above ground where the mean speed \( \bar{u}(z_{ref}) \) is known.

However the IEC wind profile uses the power-law wind profile for the wind speeds at height on the rotor disk, it uses logarithmic profile for heights not on the rotor disk.

For example, if the reference wind speed is specified at a reference height below the rotor disk, the logarithmic profile is used to calculate the hub height mean wind speed, and then the power-law is used to calculate the wind speed across the rotor disk.

Input file summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Turbulence model</th>
<th>IEC Kaimal</th>
<th>Turbulence intensity corresponding to the standard IEC categories of turbulence characteristic. ‘A’ the most turbulent</th>
<th>IEC turbulence category (%)</th>
<th>A</th>
<th>Turbulence intensity corresponding to the standard IEC categories of turbulence characteristic. ‘A’ the most turbulent</th>
<th>IEC wind type (IEC turbulence type)</th>
<th>Normal (NTM)</th>
<th>Normal turbulence model — indicates which IEC wind model will be used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Description</td>
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<tr>
<td>Time step (s)</td>
<td>0.05</td>
<td>Time step of analysis time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of analysis time series (s)</td>
<td>600</td>
<td>Length of analysis time series ‘based on 10 minute average speed’</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Usable time (s)</td>
<td>120</td>
<td>Usable length of output time series</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Number of grid (Z) (NumGrid_Z)</td>
<td>15</td>
<td>The number of vertical grid points should be set so there is sufficient</td>
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<td>vertical grid resolution. A typical value is an odd integer that is close</td>
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<td>to the GridHeight divided by the mean chord of the turbine’s blades.</td>
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<tr>
<td>Number of grid (Y) (NumGrid_Y)</td>
<td>15</td>
<td>The number of lateral grid points should be set so there is sufficient</td>
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<td>lateral grid resolution. A typical value is an odd integer that is close</td>
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<td>to the GridWidth divided by the mean chord of the turbine’s blades.</td>
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<tr>
<td>Grid height (GridHeight) (m)</td>
<td>80</td>
<td>The grid height (in meters) typically is 10% larger than the</td>
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<td>turbine rotor diameter. It must be larger for turbines that have</td>
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<td>significant displacements.</td>
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<tr>
<td>Grid width (GridWidth) (m)</td>
<td>80</td>
<td>The grid width (in meters) typically is the same as GridHeight. Grid width</td>
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<td>should be greater or equal to</td>
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<td></td>
<td>2*(rotor radius + shaft length)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height of reference wind speed (RefHt) (m)</td>
<td>84.369</td>
<td>The reference height is the height where the input wind speed is defined</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>(Specifies the height of the corresponding reference wind speed) (URef).</td>
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<tr>
<td></td>
<td></td>
<td>TurbSim uses this reference height and wind speed with the wind profile</td>
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<td>type to calculate the HH mean wind speed. It is typically the same as hub</td>
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<td></td>
<td></td>
<td>height (HubHt)</td>
<td></td>
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</tr>
<tr>
<td>Mean wind speed at the reference height (URef) (m/s)</td>
<td>3 – 27</td>
<td>Is the mean stream wise wind speed at the reference height (RefHt). It</td>
<td></td>
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<td></td>
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<td>typically ranges from cut-in to cut-out in 2 m/s increments. It is the</td>
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<td>mean value over the entire Analysis Time length of the simulation of the u-</td>
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<td></td>
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<td>component wind speed</td>
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</tr>
</tbody>
</table>

### Wind data

### Output

TurbSim simulation result output can be either in full field or at hub height depending on the parameter enabled and disabled. The full field can also be either in binary or human readable format. The binary format is the file that is used by FAST and provides information for the AeroDyn module. The FF wind speed size has a grid specified in the input. In this case, the size is a 15 by 15 matrix, and the wind speed and turbulence is simulated at each grid points. Sample TurbSim full field output is shown in the Figure 13 below.
The other output is at the hub height and these values are used to predict the power output and fatigue load of the wind turbine. The wind speed is the mean value of the full field wind speed for each time step. The horizontal wind speed is a vectorial sum of the wind speed in the x direction which is denoted as U and y direction which is denoted as V. The output is compatible with AeroDyn. The wind speed and direction at the hub height is shown in the Figure 14 below. In this project the full field wind speed is fed to FAST as input in the inflow wind parameter.
Figure 15: Sample TurbSim output of wind speed and direction

The turbulence intensity and the mean wind speed for the size of the turbine blade diameter are investigated, and the relation among them is shown in the Figure 15. The turbulence intensity decreases as we go above the ground level and the mean wind speed relation is directly proportional to the height above the ground level. The measurement of the height is from the lowest point of the turbine blade tip to the highest point of the turbine blade.

Figure 16: Sample TurbSim output Turbulence intensity and mean wind speed at different height above the ground (for mean wind speed 21m/s)

For this particular simulation the result is depicted below

- Mean standard deviation across all grid points for u component velocity is 3.5 m/s
- The mean wind speed interpolated at hub height point is 20.6 m/s
- The U-comp (X) mean wind speed at different height is the cos component of the mean wind speed at angle of 10 degrees.
- The mean turbulence intensity (TI) is 15.76 %
- Horizontal mean flow angle is 10 degrees
- Vertical mean flow angle is 5 degrees

| Table 4: Hub-Height simulated turbulence statistical summary for reference mean wind speed 21m/s |
|---------------------------------|-------|-------|-------|-------|-------|
| Type of Wind                    | Min (m/s) | Mean (m/s) | Max (m/s) | Sigma (m/s) | TI (%) |
| Longitudinal (u)               | 11.96    | 21.00    | 33.29    | 3.305      | 15.73  |
| Lateral (v)                    | -10.53   | 0.00     | 8.53     | 2.681      | 12.76  |
| Vertical (w)                   | -5.82    | 0.00     | 6.08     | 1.658      | 7.89   |
| U component                    | 11.24    | 20.6     | 33.56    | 3.247      | 15.76  |
| V component                    | -6.84    | 3.63     | 12.36    | 2.727      | 13.273 |
| W component                    | -4.00    | 1.83     | 8.18     | 1.697      | 8.239  |
| Horizontal (U&V)               | 12.43    | 21.09    | 33.73    | 3.279      | 15.548 |
| Total                          | 12.43    | 21.24    | 33.82    | 3.295      | 15.515 |

**Aerodynamic Load analysis**

The loads, force and moment, on the specific location of the blade and tower are analyzed with respect to a coordinate system they are oriented; these locations are can be flagged according to the point of interest called degree of freedom, and hence, they are used to specify the input and output parameter.

**Coordinate axis**

To simulate the loads acting on the wind turbine system particularly on the blade establishing a coordinate axis is the best practice. In this study the blade coordinate axis and the loads at the blade root is simulated. The origin of the blade coordinate system is at the center of the blade root as shown in the Figure 16 below. The orientations of the axes are:-

1. The x-axis makes perpendicular to the z-axis aligning towards the downwind direction.
2. The z-axis aligns with the pitch axis and starts at the blade root pointing towards the blade tip.
3. The y-axis creates the right hand cartesian coordinta system
Figure 17: Blade coordinate system [28]

In the Figure 16 shown above the momentum and forces acting at the blade root are denoted as RM and RF with their respective coordinate axis, respectively.

**FAST (Fatigue, Analysis, Structures and Turbulence)**

The FAST analysis code is a wide-ranging aeroelastic simulator used for predicting loads (both extreme and fatigue) of horizontal axis wind turbines, HAWT, of either two bladed or three bladed. FAST code is used for validation of proposed chattering torque control and proportional integral pitch control considering variable speed variable pitch horizontal axis wind turbine power generation which is operating at high speed [29]. In FAST fatigue is often computed in terms of loads instead of the usual method which is in terms of stress. FAST contains subroutines Aerodynamic model, AeroDyn, which is a time-domain wind turbine aerodynamic module coupled with FAST can also be run as a standalone code. But, when coupled with FAST it is a library which supplies the aerodynamics algorithms for the rotor and able to analyze the unsteady aerodynamic loads on the blades.

The FAST simulation mode is the time-marching of the nonlinear equation and during simulation wind turbine loads and response to inflow wind conditions is determined in time, and the output of the aerodynamic loads is in the form of time-series data; in addition to these, loads and deflections of the structural members of the wind turbine are the outputs of the simulation. These outputs are used to predict both the extreme and fatigue loads of the horizontal-axis wind turbines. In this project work the aerodynamic loads output is used to examine fatigue.

FAST uses primary input file to describe the wind turbine operating parameters and basic geometry which are often not user defined if preloaded sample example is used, and the output of the simulation are time series data of the desired parameters [21, 30].
Blade Input Files
The input files are distributed in tabular form which has several columns which contains airfoil identifier for a blade, twist angle, chord length, geometry of the blade, and unconnected nodal points.

The three bladed HAWT modeled, in FAST, with 24 degree of freedoms (DOFs). The blade has different DOF that are important to investigate the loads at each nodal point, and these DOFs and blade flapwise tip motion, tip displacement, and blade edgewise tip displacement are the DOFs and features are most applicable for this study. Otherwise, any combination of the available DOFs and features can be enabled for the wind turbine analyzed for.

Blade Loads
During operation the wind turbine blade is subjected to different source of loading: the aerodynamic load, gravitational, centrifugal, gyroscopic, and operational [17]. The magnitude of the loads depends on the operational condition. If the wind turbine is designed to capture high power output then optimal rotor shape is maintained and the turbine size will also increases, which in turn increases the mass of the blade. Therefore, both, the aerodynamic loads, gravitational and centrifugal forces are inevitable. However, operational and gyroscopic loads can be controlled or reduced by manipulating some system parameters. Hence, aerodynamic, gravitational, and centrifugal loads are the focus area of this project.

Edgewise bending
The edgewise bending moment fluctuates sinusoidal. The bending moment increases as the blade rotates from its lowest point to highest point, and when the blade reaches the horizontal position the moment becomes maximum, then it starts decreasing as it rotates upward from its horizontal position, and again the moment starts decreasing until it reaches its horizontal position.
Flapwise bending

The aerodynamic loads that rotate the blade result a flapwise bending moment. See Figure 19 below.

The blade length is denoted by L and the radius where most tensile and compression stresses are located at a distance r from the blade root. The w or UDL express the ultimate load the material should sustain.
FAST

ElastoDyn
It is a fundamental part of FAST simulation code, and it is a callable structural-dynamic model of HAWT with separate input files and source code. ElastoDyn includes models of rotor, drivetrain, nacelle, tower, and platform.

![Figure 21: ElastoDyn inputs, states, parameters, and outputs](image)

ElastoDyn module of FAST implements the blade bending degree of freedoms DOFs specifically for each blade, not rotor modes. Hence, enabling or disabling the EdgeDOF in ElastoDyn source code will enable or disable, respectively, the edgewise bending mode of each blade.

Aerodynamics module (AeroDyn)
It is a time-domain aerodynamic module of wind turbine. During calculation of aerodynamic the principles of actuator lines is applied, which is the three dimensional flow around a body is approximated by local two dimension flow at cross sections. The lift forces, drag forces, and pitching moments lumped at a node used to approximate the shear stress and pressure distribution. Wind data calculated by inflow module and structural data calculated by structural-dynamics model (ElastoDyn) are passed to AeroDyn as an input, and then it calculates the aerodynamic loads on each node of the blade and tower. The AeroDyn again return the analyzed results back to FAST as part of aero-elastic calculation. The AeroDyn consists of submodules: rotor induction/wake, blade airfoil aerodynamics, tower influence on the wind local to the blade nodes, and tower drag. The most important of the aerodynamics model (AeroDyn) is the wake model it includes. This model has two model approaches, the blade element momentum theory (BEM) model, and the generalized dynamic wake theory (GDW) model [30]. The BEM model is used for in this project work.

Airfoil
The aerodynamics of the blade airfoil can be steady or unsteady, where the steady model accounts for static airfoil data that includes tables containing the lift and drag force coefficient, and pitching moment versus angle of attach; and they are used to calculate loads on the nodes appropriately under idling or parked conditions. The static airfoil data is always used in the BEM iteration [31]. Unsteady model accounts for time dependent flow and it is more appropriate for wind turbine having an angle of attack ranging from small to moderate under normal operation. The dependent airfoil parameters may be extracted from static airfoil data, and it is applied after the BEM iteration and after skewed-wake correction [31].
Primary input file
The input file dedicates the model specification. The input and output file are specified particularly for AeroDyn model—the input file defines the modeling options, environmental conditions, airfoils, and in addition.

In FAST, to calculate the mean values of angular or rotor seed of the blade and pitch angle as a function of wind speed, for a given wind turbine with a given control system, a series of FAST simulations at a different wind speeds should be ran. Doing so, the pitch and torque control should be enabled.

Output Files
FAST calculates loads as a lumped forces or moments at the required cross section. For example, in this study the blade root is chosen as a target area of moment calculation.

The output of the simulation code depends on the input file and the settings, and it generates as many output files based on the input files and the settings also. According to the choice of type of output and analysis the primary output file contains column for each parameters that is required in the primary input file.

According to the setting in FAST hereafter the output at the blade root discussed. The output at blade root are edgewise moment of blade 2 (RootMxb2) and flapwise moment of blade 2 (RootMyb2) are enabled to be able to feed them to fatigue analysis simulator MLife. The blade edgewise moment is caused by edgewise forces whereas the flapwise moment is caused by flapwise forces. The unit is kN.m for both. The output for both cases is for the total runtime of 650s and at a time step of 0.05 second and at different pitch angle of ranging from 7.5 to 17 degrees. According to IEC 61400-1 recommendation the first 50 second should be neglected due to the instability or extreme vibration of the simulation which never happens in real life.
Influence of Pitching wind turbine blade

The pitch angle provides the wind turbine to capture the maximum possible wind energy by changing the position of the angle of attack. Doing so has an impact on the blade loads which result to the tradeoff between the fatigue load and power output. The following figure illustrates how the bending moment at the blade root changes together with the pitch angle. The figure is from sample output of FAST. The pitch angle for this project ranges from 7.5 degree initial angle to 17 degree final pitch angle at 2 degrees of incremental.
**Fatigue failure**

Fatigue failure is an inevitable source to failure in material that occurs over a period of time of the material design life; fatigue load case damage the structural components through many repeated small loading and unloading happenings that are accumulated in the time history of the fatigue loads. The individual partial damage happening throughout the life of the blade for much individual load cycle accumulated to cause the structural component to fail. The Conisholm wind turbine, Figure 23, is one example of fatigue failure of the mechanical component of wind turbine. The failure was due to bolt fatigue on the nacelle that caused a loss of 1 million pound.

![Figure 24: Conisholme wind turbine -one of the blades flew away due to bolt failure](image)

The impact of aerodynamic loads due to the spectral load distribution on fatigue load can be described using the concept of damage equivalent load. According to Miner’s rule stated in IEC 61400 1 (Annex G) accumulated damage value due to fluctuating loads over the design lifetime of the turbine should be less than or equal to 1, if it exceeds this value then the limit state is reached [25].

**Minimization of fatigue load**

Many researches have been done to minimize the impact of fatigue failure on the mechanical components of the wind turbine. Pitching wind turbine blade has shown a remarkable result on the reduction of fatigue load. The blades can be pitched individual or cumulative. Region 3 of the power curve is where the pitching is important, shown on Figure 24.
Design Load Case (DLC)
The general consideration of the DLCs of wind turbine is as proposed by the IEC 61400-1 (3rd ed 2005). The DLC proposed by IEC are under consideration of the state of the wind turbine and external conditions such as wind and electrical power network. Design situations and load cases for wind turbine are described in IEC 61400-1 which predefines 22 load cases for different wind conditions. These design load cases combines 17 ultimate load and 5 fatigue analysis (refer Table 2 page 35 of IEC 61400-1 [25]). The investigation the loads are for normal operation of the turbine under power production. Thus, for the given wind turbine of this project from IEC 61400-1 the design situation lies on power production at a wind condition of NTM (Normal turbulence model) the wind speed ranging from cut-in to cut-out.

Power production
The wind turbine is simulated from cut-in to cut-out wind speed at the hub height with the help of aeroelastic simulation model. The setting of the turbulence is normal turbulence model (NTM) according to IEC 61400-1. The design load cases (DLC) 1.1 and 1.2 under normal operation of the wind turbine and under consideration of atmospheric turbulence represents the requirements for loads throughout its life time (NTM) [25]. The NTM is based on IEC Kaimal model.

Ultimate/Extreme load case and analysis
Ultimate load of the design is not in scope the scope of the project. Ultimate load is the maximum load that the turbine can experience during its design life, that is, an occasional happening of single loading and unloading that may cause a structural component to fail reaching the limit state. Such load depends on how intense the wind condition, for example an extreme coherent gust that changes the direction and is too quick that the yaw system to act accordingly, can create large partial
damage or destroy the blade rotor with one load cycle [37]. Moreover, it can be used to define the strength of the components, as stated in IEC 61400-1 [25]. However, the ultimate loads (extreme value distribution) are more important and needed when examining of the design against failure in ultimate load.

The best estimation of ultimate loads of a material that can withstand is approximated by using a finite element method (FEM). However, the simulation is expensive and not a focus area of this study, hence, it is no important to undergo a FAM simulation to define the ultimate load. In this study the failure of the turbine shall be investigated against the fatigue load, hence, the ultimate load of the design is not considered; however, it is estimated based on the time series data of FAST simulated result. The ultimate load bases on the absolute maximum of all the time series of the blade root bending moment and multiply it by some scaling factor. The statement is equated as follows:

\[ L_{Ult} = X \times \text{MAX}(\text{time series}_\text{ABS}) \]

where: \( X \) is the scaling factor \((1 \text{ to } \infty)\)

Multiplying the absolute maximum value of the time series with some range of scaling factor provides verification that the DEL results is approaching the asymptotic limit.

Fatigue load analysis

The Miner’s cumulative damage rule is a linear method of fatigue load analysis. The fatigue life of a turbine that experiences varying load can be estimated based on the stress strain (S-N) curve. The cumulative damage occur from fluctuating loads on turbine is a summation of damage from each cycle. The expression is stated below.

\[ D = \sum_i \frac{1}{N(S_i)} \]  

(12) [25]

Where: \( D \) is the total damage sustained by the turbine, \( N \) is measured value of the number of cycle to failure of the material at a stress level \( S_i \), and \( S_i \) is the load range or stress for the \( i^{th} \) cycle. During operation, the wind turbine faces different wind conditions that will have many cycles of varying sizes. Hence, the life of wind turbine must be estimated using a load spectrum.

The number of cycles the wind turbine experience during its operational period (usually 20 years) can exceed \( 10^6 \). The fatigue analysis corresponding DLC 1.2 of IEC 61400-1 is conducted which applies Rainflow counting method. The fatigue loads are calculated for an equivalent frequency of 1 Hz from the 10 min simulation load result of the FAST.

MLife

MLife is a MATLAB-based tool created to post-process one or more time series statistical information that able to calculate damage equivalent loads (DELS). The statistical information are fatigue estimates results from wind turbine tests, and aero-elastic, dynamic simulations like FAST, and then MLife perform a fatigue analysis that follows a rainflow cycle counting method, and generates the variable amplitude load ranges found in the time series data in the form of a rain flow cycle [32, 33]. In MLife there are settings that should be done in order to obtain the required output, for example, enabling DoLife will produce lifetime related calculations. There are three design load case (DLC) grouping in MLife [33]:
- Normal operation DLC
- Idling or parked DLC
- Catch-all for discrete events occurring over the design lifetime.

During lifetime calculations the fatigue cycle that relates to the input time series are scaled out over the design lifetime depending on DLC grouping set in the input file.

Program outline

1- Process all the input data files, one at a time
   a. Read a time-series file into memory
   b. Compute the statistics for this time series
   c. Extract the local maxima and minima (peaks) from the time-series
   d. Filter the peak (optional)
2- Compute the aggregate statistics across all data files
3- Determine the fatigue cycle for each time-series using rainflow counting. Each cycle is characterized by,
   a. The cycle’s mean load and range
   b. The adjusted load range when using a fixed or zero mean
   c. The weight of the cycle, which allows partial cycle to be counted as a fraction of a complete cycle. Complete cycles have a count of one
4- Compute the short-term damage-rates and damage-equivalent load (DEL) of each time-series.
5- Sum the damage contribution of each time-series to determine short-term aggregate damage-rates and DELs.
6- Extrapolate the damage contribution of each time-series across the design lifetime to determine the lifetime damage
7- Determine the lifetime DEL
8- Compute the time until failure.

**Damage equivalent load (DEL)**
The damage equivalent load involves a constant load range that fluctuates at a mean load of the load spectrum

FAST outputs, which are loads, for each specified or enabled degree of freedom (DOF) are used directly in MLife; hence, MLife processes the loads to calculate the DEL. During setting up the simulator, the ultimate load (L_Ult) at the cross section of interest (the blade root) is needed; often, they are unavailable or not given due to their importance to the calculation. However, it should be specified to some value greater than the maximum load (can be the magnitude of the vector sum of the two orthogonal loads) or run the simulation for different L_Ult until find the approximate L_Ult for 20 years that satisfies the condition that the damage fraction should be in the range between 0.75 and 1. The ultimate load corresponds with the channel chosen in the setting – for moment channel the ultimate load is a moment at the cross section; for a force channel the ultimate load is a force. In the analysis, since the load at the cross section is the moment the L_Ult (ultimate load) is a moment. In this analysis the latter is applied.
Load Rose
A load rose calculates loads at different orientation as many orientation as it is specified around the cross section of the blade root. In this particular case 12 sectors are set, which are oriented at every 15 degrees between 0 and 180 degree.

The usual way of measuring bending loads on any beam is by using two pairs of strain gage that are placed 90 degrees to each other. However, it is not necessarily the beam (in this case blade) is bent perfectly in the direction of one of the strain gages; it can be at some angle between the gages. Therefore, there will be an error of measuring since they are measuring the bending moment at two places and only in those two directions.

The fatigue damage of the blade can be determined by taking the magnitude of the bending moment at the blade root measured by the two strain gages; however, this practice is not reasonable due to the reason mentioned above. Moreover, it is unlikely that either orientation represents the most heavily loaded orientation.

For fatigue loads estimation it is necessary to calculate the DEL at multiple orientations around the blade root. Since, during the analysis performing rainfall cycle counting together with DEL is important, and the rainfall cycle count would be affected if the load orientation changes with each cycle, hence, the result will be inaccurate and would be deceiving. Therefore, the load rose method is advisable and best practice to implement in the simulation process.

Estimation of Damage Equivalent Load
MLife, a MatLab application, is used to be able to analyze damage equivalent load at the blade root of the turbine. The DEL of load spectrum cycles about a fixed mean load and constant load range, and at a constant frequency. Therefore, during analysis of the DEL the frequency of the load spectra should be set a fixed value, and the Whöler exponent, m, and the simulation time should be the same for all load cases. Once these parameters are set equal for all load spectrum, the only thing that varies because of the different load spectra is the damage equivalent load. In this study, however, the influence of pitching also considered in the load spectra. The following equation explains the dependency of the DEL on simulation time, Whöler exponent m, and frequency.

\[
D_j^{ST} = \sum_i n_j^{STeq} \frac{n_i}{N_j^{eq}}
\]

\[
n_j^{STeq} = f_j^{eq} T_j
\]

\[
N_j^{eq} = \frac{L_{ult} - |L_{MF}|}{\left(\frac{1}{2} \frac{D_{j}^{STF}}{m}\right)^m}
\]

Where \(D_j^{ST}\) is the short term damage estimation for the time series \(j\) of the load spectrum, \(f_j^{eq}\) is the specified frequency of the DEL, \(T_j\) is the simulation time, \(n_j^{STeq}\) is the total equivalent number of cycles count for fatigue failure for time-series \(j\).

In the setting of the MLife the load mean is set to zero, as result the life equivalent load about a zero mean load can be expressed as follows,
\[ \text{DEL}^{ST0}_j = \left( \frac{\sum_{i \in \{n_{ji}, (L_{ji}^{RO})^m\}}^{\text{Seq}}}{\text{Seq}_j} \right) \]  

(19) [32]

Where \( \text{DEL}^{ST0}_j \) is the design equivalent load about a zero fixed mean value of the time series \( j \), and \( L_{ji}^{RO} \) is the load range that is adjusted about the zero fixed mean.

**Result**

In this chapter, the loads at the blade root, the power output, and the fatigue loading as a result of changing the pitch angle at a fixed mean wind speed is presented. The fatigue loading is estimated by damage equivalent load (DEL). The results for different pitch angle are shown in the figures below.

For the hub height mean wind speed ranging from 11m/s to 27 m/s at 2 m/s incremental six runs changing the pitch angle from start angle of 7.5 degrees to 17 degrees at 2 degrees of incremental are conducted for each wind profile, and the mean value of the load at the blade root and the power output are calculated for each of six different scenarios. Pitch angles used for demonstration of the results are:

- Pitch angle 7.5,
- Pitch angle 9,
- Pitch angle 11,
- Pitch angle 13,
- Pitch angle 15 and,
- Pitch angle 17

However, here the six different scenarios for the mean hub height wind speed are discussed. The mean wind speed chosen for discussion is 21 m/s which is close to the cut-out speed. This is because of the reason that the blade experiences high aerodynamic loads at high wind speed.

**Bending moment**

Figure 255 to 30 shows the bending moment at the blade root for the different scenarios. The result is obtained from simulation of FAST. The bending moment that the result discusses about is the flapwise bending moment which mainly affected by the aerodynamic load from the flow of wind over the turbine blade. The results are of 2 minutes of truncated full time step of 10 minutes. The full time step result is found in the appendix.
Figure 26: Flapwise bending moment at the blade root at the pitch angle 7.5 degree and mean wind speed 21m/s

Figure 27: Flapwise bending moment at the blade root at the pitch angle 9 degrees and mean wind speed 21m/s

Figure 28: Flapwise bending moment at the blade root at the pitch angle 11 degrees and mean wind speed 21m/s
Figure 29: Flapwise bending moment at the blade root at the pitch angle 13 degrees and mean wind speed 21m/s

Figure 30: Flapwise bending moment at the blade root at the pitch angle 15 degrees and mean wind speed 21m/s

Figure 31: Flapwise bending moment at the blade root at the pitch angle 17 degrees and mean wind speed 21m/s
Power output

The power output of the wind turbine at different pitch angle for a given mean wind speed is shown in the Figure 31 to Figure 36. For comparison reason it is given with respect to the mean wind speed at the hub height, 21m/s.

Figure 32: Power output at hub height mean wind speed 21m/s and pitch angle 7.5 degrees

Figure 33: Power output at hub height mean wind speed 21m/s and pitch angle 9 degrees
Figure 34: Power output at hub height mean wind speed 21m/s and pitch angle 11 degrees

Figure 35: Power output at hub height mean wind speed 21m/s and pitch angle 13 degrees

Figure 36: Power output at hub height mean wind speed 21m/s and pitch angle 15 degrees
The mean power output at the different pitch angle is shown in the Figure 37 below. The mean value of the mean wind hub height wind speed, 21m/s, is for the whole time step.

As shown on the figure 37 above the power output drops dramatically pitching from angle 17 to 19, hence, omitting the angles above 17 is appropriate. The rest of the results, therefore, focus the angles from 7.5 to 17.

**DELS (Damage Equivalent Loads)**

The DELs result that is obtained from MLife is presented in the Figure 38 below.
Discussion

The power output and the damage equivalent load will be presented to see the optimal result that meets the required conditions, that is, maximum power output at acceptable low level fatigue loading due to pitching the blade. The power output is calculated only for one hub height mean wind speed, 21m/s, and the DEL is analyzed at the blade root of the wind turbine. There are six pitch cases for different thirteen wind profiles ranging from 3m/s to 27m/s at 2 m/s incremental. Each of the wind profiles are analyzed for the six pitch cases:

- Pitch angle of 7.5 degree
- Pitch angle of 9 degree
- Pitch angle of 11 degree
- Pitch angle of 13 degree
- Pitch angle of 15 degree
- Pitch angle of 17 degree

The wind profile coordinate axis used in the TurbSim is shown in Figure 11 and the calculated sample output of TurbSim is presented in the Figure 13 to Figure 15. The fluctuation of wind direction causes turbulence in the wind flow it is seen in Figure 14. The fluctuation of the values are between negative and positive –where negative values indicate the wind is blowing in a downward direction and the positive values indicate the wind is blowing in the upward direction. Further, the relationship between height and turbulence is shown in Figure 15, here the mean turbulence intensity and the mean wind speed result shows the expected relation with respect to the simulation height above the ground. Both the mean TI and the mean wind speed have an inverse relation with respect to the height. For the mean wind speed 21m/s the resulting mean TI (%) is 16.23 causing a mean standard deviation of 3.5m/s this means that the wind speed can vary ±3.5m/s of the mean wind speed (21m/s). The full result can be found in the Appendix B. The thirteen wind profiles are simulated at different seed range for the randomness of the wind profile, however the turbulence characteristic is set the same for all wind conditions. The wind profiles are integrated over the grid width and height.
at each grid points, defined in section Grid size and Reference wind speed and height (URef and RefHt). The sample output values are tabulated and found in Appendix.

The discussion mainly on the wind speed around the cut-out wind speed; as result 21m/s is chosen for the analysis purpose. All the results under Result section are of at the hub height mean wind speed. The coordinate axis at which the aerodynamic loads are analyzed is shown in Figure 16. These blade coordinates are oriented 3 dimensionally (in X, Y, and Z axis), which is important during analysis of the loads, due to aerodynamics, at the selected location.

The edgewise bending moment at the blade root takes a sinusoidal pattern as seen in Figure 21 that is what it should look like since the effect comes from a constant exertion of the gravitational force on the blade. Whereas, the flapwise bending moment, as shown in same figure, is a function of the turbulence (fluctuation) of the wind flow—it has a direct relation with the fluctuation of the wind flow. The flapwise bending, in small amount in bending moment, can be altered by pitching the blade angle. The influence of pitching blade, even at small wind speed, as shown in Figure 22 is very significant on the bending moment results. According to IEC 61400-1 the first fifty seconds of the simulation should be disregarded as this is causing a vibration at the start of the simulation as a result of the wind turbine experiences, that never happens in real life, an airflow wind speed change from 0m/s to an airflow flow of up to 12m/s within a fraction of seconds. This looks reasonable when looking at the figure which gives inconsistent and unreasonable result for the first few seconds up to 3 seconds of simulation time step. This figure gives a good understanding of the reason given by the IEC 61400-1. Hence, depending on this figure, it can be said that the simulation should have been performed for long time steps to get best results and be able to truncate the first fifty seconds of the simulation result. In fact, the result kept on the study to show the understanding of the reason given by IEC 64100-1, otherwise during simulations the time step used is 650 seconds, then the first 50 seconds are truncated; but this particular result was simulated only for 60 seconds.

The damage equivalent loads are calculated for at the location of interest of the blade root. The blade is investigated for fatigue load, and hence the ultimate load of is not the interest of this project it is simply specified as a vectorial sum of the two moment results obtain from FAST simulation. These two moments are oriented in X and Y direction at the coordinate axis. In fact, the ultimate load estimated based on the vector sum of the two moments (edgewise and flapwise bending) is tested to satisfy conditions that the damage equivalent should be for 20 years and the fraction should be in the range 0.75 and 1. Accordingly, the ultimate load is 96.2KN at each point along the blade root curvature. The blade root is assumed to be circle and is divided to 12 equal parts where the loads are analyzed, this is called load rose in MLife. Therefore, the DELs are calculated at these given points. See section Load Rose for detail.

As results show, Figure 25 to Figure 30, it seems that the bending moment has a direct relation with pitch angle. The bending moment herein after refers the flapwise bending moment only. The results of the bending moment shown in the Figure 25 to Figure 30 are of the different pitch angle, and the results seem reasonable according to why the pitching a wind turbine blade is implemented. Pitching blade either reduces or increases the loads on the blade. Pitching a blade angle basically is to change the angle of attack and hence the aerodynamic loads are controlled to the control either the torque or the rpm of the blade.
In the attempt to analyze the loads on the wind turbine blade mainly at the blade root, as the small wind speed naturally will not cause as heavy load as high wind speeds at the same turbulence intensity level, the analyses were done for wind speed 19 to 27m/s and 21m/s is preferred for the analysis. The power output at this particular wind speed pitching the blade to capture as much energy as possible is analyzed and seen that a small change in pitch angle makes a significant difference on the power output. The figures, Figure 31 to Figure 36, show how pitching significantly affects the power output. However, the change is not always necessarily true as it is seen in the figures under Power output section. For this particular study, the results of the power output show pitching the blade angle from 7.5 to 9 and until 15 degrees make a significant change on the power output; but, pitching from 15 to 17 degree does change the power output at small amount.

The fatigue load of the wind turbine blade is estimated in terms of the damage equivalent load at the selected location of the blade. It is based on the input of the bending moments at same locations. The design load case of this study is of standard operation condition, which is power production DLC 1.2. As it is known that increasing the lift force will simultaneously increases the undesirable drag force; this is true according to the result obtained, it can be investigated by looking at the results of power output, Figure 37, and the fatigue load result which is expressed in terms of damage equivalent load Figure 38. The damage equivalent loads express the loads that can damage the blade at the selected location for the given pitch angle. According to the results given in Figure 38, the load increases as pitching the blade from angle 7.5 degrees until angle 13 degrees, then after the load decreases until the pitch angle 17 degrees. The increase in the load is significant for the pitch angle from 7.5 degrees until 13 degrees then from 13 to 15 also it is very significant. However, pitching the blade from 15 degrees to 17 makes a little change on the load.

The minimum fatigue load can be achieved at the pitch angle 7.5; however, at this pitch angle the power output is at minimum level. The maximum power output is achieved at pitch angles 15 and 17 degrees; however, the fatigue loads at these angles are high.

To find the optimal results that satisfy the objective of this thesis project both the fatigue load and power output are analyzed based on the moments applied at the blade root which in turn is responsible for the torque and speed of the blade that determines the power output also.
Figure 40: Comparison of the fatigue load and power output of the different pitch angle of the wind speed 21m/s

Figure 40 show the fatigue load and the power output at the different pitch angle. As shown, the power output increases while pitching the blade from 7.5 degree to 17 degree of the pitch angle with the undesirable fatigue load, but not a significant change is seen from 15 degree angle to 17 degree both for the power output and fatigue load. Hence, from this graph the optimal point that satisfies the maximum power output and minimum fatigue load is at pitch angles 15 and 17 degrees. Therefore, for the given wind speeds and pitch angles it will possible to capture maximum power output.

Conclusion

In this thesis thirteen wind profiles, with different seeds and same turbulence level included, for different pitch angles ranging from 7.5 to 17 degrees have been tested on a 1.5MW onshore wind turbine. The pitch angle has been set ranging from 7.5 to 17 degrees at 2 degrees incremental to investigate its effect on the fatigue load and power output. The results seem reasonable according to the theories. However, to get a better results of fatigue load and power output more pitch angles recommended to be included, this is to mean that instead of expressing the range where maximum power output at low fatigue loading can be achieved it would be better to find the exact angles, otherwise the study has examined angles ranging from 0 to 90 degrees Moreover, the wind profiles should be run for analyzed for different turbulence intensities.

The expected result is achieved at the pitch angle ranging from 15 to 17 degrees. The power output result for the different pitch angle increases in a stair pattern.

Upon looking at the fatigue load, only, the minimum value can be achieved at:

- $\beta = 7.5$ scarifying 620KW of the maximum output power, 1.92MW that can be attained
A proposal for future work is to perform more the wind profiles for different turbulence intensity and different seeds for each profile. Moreover, the optimization should be done with the help of genetic algorithm of Matlab.

**Bibliography**


Appendices

Appendix A

MLife Input file text format

----- MLife version 1.0 Input File --------------------------
Test#13
----- Job Options -------------------------------------
True  EchoInp  Echo input to <rootname>.echo as this file is
being read.
True  StrNames Use channel names following a "$" instead of numbers when
specifying channels in this input file.
fals e  OutData  Output modified data array after
scaling and calculated channels. (currently unavailable)
"%6.2e"  RealFmt  Format for outputting floating-point values.
"%6.2e"  RootName  Root name for aggregate output files.
----- Input-Data Layout --------------------------------
5  TitleLine  The row with the file title on it (zero if no title is
available).
0  NamesLine  The row with the channel names on it (zero if no names are
available or are specified below).
0  UnitsLine  The row with the channel units on it (zero if no units are
available or are specified below).
9  FirstDataLine  The first row of data.
22  NumChans  The number of channels in each input file.
ChanTitle  ChanUnits  Scale  Offset  PSF_Type  NumCols rows of data follow. Title and
units strings must be 10 characters or less.
"Time"  "(sec)"  1.0  0.0  0
"Wind1VelX"  "(m/sec)"  1.0  0.0  0
"Wind1VelY"  "(m/sec)"  1.0  0.0  0
"Wind1VelZ"  "(m/sec)"  1.0  0.0  0
"BldPitch2"  "(deg)"  1.0  0.0  0
"IPDefl1"  "(m)"  1.0  0.0  0
"IPDefl2"  "(m)"  1.0  0.0  0
"TwstDefl1"  "(deg)"  1.0  0.0  0
"TwstDefl2"  "(deg)"  1.0  0.0  0
"TwstDefl3"  "(deg)"  1.0  0.0  0
"RootMxb2"  "(kN.m)"  1.0  0.0  0
"RootMyb2"  "(kN.m)"  1.0  0.0  0
"RootMzb2"  "(kN.m)"  1.0  0.0  0
"LSShtFys"  "(kN)"  1.0  0.0  0
"LSShtFzs"  "(kN)"  1.0  0.0  0
"LSSTipMys"  "(kN·m)"  1.0  0.0  0
"LSSTipMzs"  "(kN·m)"  1.0  0.0  0
"YawBrTdxp"  "(m)"  1.0  0.0  0
"YawBrTdy "  "(m)"  1.0  0.0  0
"YawBrTxm "  "(kN)"  1.0  0.0  0
"YawBrTym "  "(kN)"  1.0  0.0  0
"YawBrTzm "  "(kN)"  1.0  0.0  0
----- Calculated Channels ----------------------------------
0  NumCChan  The number calculated channels to generate.
1234567890  Seed  The integer seed for the random number generator (-
2,147,483,648 to 2,147,483,647)
Col_Title  Units  Equation  Put each field in quotes. Titles and units are limited to
10 characters. NumCChan rows of data follow.
----- Load Roses -----------------------------------------
1  NumRoses  The number of load roses to generate.
Rose Name  Units  Channel1  Channel2  nSectors
"RootMxyb2"  "(kN)"  $\text{RootMxb2}$  $\text{RootMyb2}$  12
----- Time and Wind Speed -------------------------------
$\text{Time}$  TimeChan  The channel containing time.
$\text{Wind1VelX}$  WSChan  The primary wind-speed channel (used for mean wind speed
and turbulence intensity, 0 for none)
----- Statistics and Extreme Events ------------------------
true  DoStats  Generate statistics of all the channels.
true  WrStatsXLS  Write the stats to an Excel file?
14  NumSFChans  Number of channels that will have summary statistics generated
for them.
$\text{RootMxb2}$  $\text{RootMyb2}$  $\text{RootMxyb2}$ 1S  $\text{RootMxyb2}$ 2S  $\text{RootMxyb2}$ 3S  $\text{RootMxyb2}$ 4S  $\text{RootMxyb2}$ 5S  $\text{RootMxyb2}$ 6S  $\text{RootMxyb2}$ 7S  $\text{RootMxyb2}$ 8S  $\text{RootMxyb2}$ 9S  $\text{RootMxyb2}$ 10S  $\text{RootMxyb2}$ 11S  $\text{RootMxyb2}$
----- Distributions --------------------------------------

false UserDistrib User defined distribution? true = load user-specified distribution, false = only use Weibull wind distribution

2.3 WeibullShape Weibull shape factor. If WeibullShape=2, enter the mean wind speed for WeibullScale.
6 WeibullScale Weibull scale factor. If WeibullShape<>2. Otherwise, enter the mean wind speed.
3 WSin Cut-in wind speed for the turbine.
27 WSout Cut-out wind speed for the turbine.
43 WSMaxBinSize Maximum wind speed value for the wind-speed bins.
2 WSMaxBinSize Maximum wind speed value for the wind-speed bins.
0 nDistribVars Number of independent variables in the user-specified distribution, ignored if UserDistrib = false

--- Fatigue ----------------------------------------------------------
15 nFatigueChannels The number of fatigue channels. Next six lines ignored if zero.

--- Input Files ------------------------------------------------------
1 FileFormat Format of input files. 1 = FAST ascii, 2 = FAST binary

<table>
<thead>
<tr>
<th>Name</th>
<th>NChannels</th>
<th>ChannelList</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;RootMxyb2&quot;</td>
<td>14</td>
<td>1 3 4 5 6 7 8 2 9 10 11 12 13 14</td>
</tr>
</tbody>
</table>

--- FileFormat Format of input files. 1 = FAST ascii, 2 = FAST binary
"test13_27mps.out"
0 1.1 1.3 1.5 1.7 (Weibull-Weighted Idling: NumIdleFiles, PSF1, PSF2, PSF3, PSF4)
0 1.2 1.3 1.4 1.6 (Discrete Events: NumDiscFiles, PSF1, PSF2, PSF3, PSF4)
NumFiles The number of input files to read.
**EOF** DO NOT REMOVE OR CHANGE. MUST COME JUST AFTER LAST LINE OF VALID INPUT.
Appendix B
This summary file was generated by TurbSim (v2.00.01a-bjj, 14-Oct-2014) on 22-Apr-2016 at 17:01:14.

Runtime Options:

4403040  Random seed #1
10003647  Random seed #2

  F  Output binary HH turbulence parameters?
  F  Output formatted turbulence parameters?
  T  Output AeroDyn HH files?
  T  Output AeroDyn FF files?
  F  Output BLADED FF files?
  F  Output tower data?
  T  Output formatted FF files?
  F  Output coherent turbulence time step file?
  T  Clockwise rotation when looking downwind?

0 - NONE  IEC turbulence models scaled to exact specified standard deviation
Turbine/Model Specifications:

15 Vertical grid-point matrix dimension
15 Horizontal grid-point matrix dimension
0.050 Time step [seconds]
650.000 Analysis time [seconds]
650.000 Usable output time [seconds]
84.300 Hub height [m]
80.000 Grid height [m]
80.000 Grid width [m]
5.000 Vertical flow angle [degrees]
10.000 Horizontal flow angle [degrees]

Meteorological Boundary Conditions:
IEC Kaimal spectral model

1. IEC standard: IEC 61400-1 Ed. 3: 2005

A. IEC turbulence characteristic

NTM IEC Normal Turbulence Model

N/A IEC Extreme Turbulence Model (ETM) "c" parameter [m/s]

IEC Wind profile type

84.300 Reference height [m]

21.000 Reference wind speed [m/s]

N/A Jet height [m]

0.200 Power law exponent

0.030 Surface roughness length [m]

Non-IEC Meteorological Boundary Conditions:

N/A Site latitude [degrees]

N/A Gradient Richardson number

N/A Friction or shear velocity [m/s]
N/A Mixing layer depth [m]
N/A Mean hub u'w' Reynolds stress
N/A Mean hub u'v' Reynolds stress
N/A Mean hub v'w' Reynolds stress

Spatial Coherence Models:

IEC  u-component coherence model
NONE  v-component coherence model
NONE  w-component coherence model

( 12.000, 0.353E-03) u-component coherence parameters
N/A  v-component coherence parameters
N/A  w-component coherence parameters

N/A Coherence exponent

You have requested that the following file(s) be generated:
Kaimal.hh (AeroDyn hub-height file)
Kaimal.bts (AeroDyn/TurbSim full-field wind file)
Kaimal.u (formatted full-field U-component file)
Kaimal.v (formatted full-field V-component file)
Kaimal.w (formatted full-field W-component file)

Turbulence Simulation Scaling Parameter Summary:

- Turbulence model used = IEC Kaimal
- Turbulence characteristic = A
- IEC turbulence type = Normal Turbulence Model
- IEC standard = IEC 61400-1 Ed. 3: 2005
- Mean wind speed at hub height = 21.000 m/s
- Expected value of turbulence intensity at 15 m/s = 16.000%
- Characteristic value of standard deviation = 3.416 m/s
- Turbulence scale = 42.000 m
u-component integral scale = 340.200 m

Coherency scale = 340.200 m

Characteristic value of hub turbulence intensity = 16.267%

Gradient Richardson number = 0.000

Wind profile type = Power law on rotor disk, logarithmic elsewhere

Power law exponent = 0.200

Mean shear across rotor disk = 0.053 (m/s)/m

Assumed rotor diameter = 80.000 m

Surface roughness length = 0.030 m

Nyquist frequency of turbulent wind field = 10.000 Hz

Number of time steps in the FFT = 13000

Number of time steps output = 13000

Number of points simulated = 225
Mean Flow Angles:

Vertical  =  5.0 degrees
Horizontal =  10.0 degrees

Mean Wind Speed Profile:

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Wind Speed (m/s)</th>
<th>Horizontal Angle (degrees)</th>
<th>Vertical Angle (degrees)</th>
<th>U-comp (X) (m/s)</th>
<th>V-comp (Y) (m/s)</th>
<th>W-comp (Z) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124.3</td>
<td>22.70</td>
<td>10.00</td>
<td>5.00</td>
<td>22.27</td>
<td>3.93</td>
<td>1.98</td>
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<tr>
<td>118.6</td>
<td>22.48</td>
<td>10.00</td>
<td>5.00</td>
<td>22.06</td>
<td>3.89</td>
<td>1.96</td>
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<td>112.9</td>
<td>22.26</td>
<td>10.00</td>
<td>5.00</td>
<td>21.84</td>
<td>3.85</td>
<td>1.94</td>
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<td>107.2</td>
<td>22.03</td>
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<td>5.00</td>
<td>21.61</td>
<td>3.81</td>
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<tr>
<td>101.4</td>
<td>21.79</td>
<td>10.00</td>
<td>5.00</td>
<td>21.38</td>
<td>3.77</td>
<td>1.90</td>
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<tr>
<td>95.7</td>
<td>21.54</td>
<td>10.00</td>
<td>5.00</td>
<td>21.13</td>
<td>3.73</td>
<td>1.88</td>
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<tr>
<td>90.0</td>
<td>21.28</td>
<td>10.00</td>
<td>5.00</td>
<td>20.87</td>
<td>3.68</td>
<td>1.85</td>
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<tr>
<td>84.3</td>
<td>21.00</td>
<td>10.00</td>
<td>5.00</td>
<td>20.60</td>
<td>3.63</td>
<td>1.83</td>
</tr>
<tr>
<td>Type of Wind</td>
<td>Min (m/s)</td>
<td>Mean (m/s)</td>
<td>Max (m/s)</td>
<td>Sigma (m/s)</td>
<td>TI (%)</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>-----------</td>
<td>------------</td>
<td>-----------</td>
<td>-------------</td>
<td>--------</td>
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</tr>
<tr>
<td>78.6</td>
<td>20.71</td>
<td>10.00</td>
<td>5.00</td>
<td>20.32</td>
<td>3.58</td>
<td></td>
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<tr>
<td>72.9</td>
<td>20.40</td>
<td>10.00</td>
<td>5.00</td>
<td>20.01</td>
<td>3.53</td>
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<tr>
<td>67.2</td>
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<td>10.00</td>
<td>5.00</td>
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</tr>
<tr>
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<td>5.00</td>
<td>19.34</td>
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</tr>
<tr>
<td>55.7</td>
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<tr>
<td>50.0</td>
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<td>5.00</td>
<td>18.56</td>
<td>3.27</td>
<td></td>
</tr>
<tr>
<td>44.3</td>
<td>18.46</td>
<td>10.00</td>
<td>5.00</td>
<td>18.11</td>
<td>3.19</td>
<td></td>
</tr>
</tbody>
</table>

Harvested Random Seeds after Generation of the Random Numbers:

1992320583 Harvested seed # 1
1629526362 Harvested seed # 2
<table>
<thead>
<tr>
<th></th>
<th>Min Reynolds</th>
<th>Mean Reynolds</th>
<th>Max Reynolds</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Stress (m/s)^2</td>
<td>Stress (m/s)^2</td>
<td>Stress (m/s)^2</td>
<td>Coefficient</td>
</tr>
<tr>
<td>u'w'</td>
<td>-70.995</td>
<td>0.407</td>
<td>35.612</td>
<td>0.074</td>
</tr>
<tr>
<td>u'v'</td>
<td>-58.922</td>
<td>0.462</td>
<td>48.080</td>
<td>0.052</td>
</tr>
<tr>
<td>v'w'</td>
<td>-31.205</td>
<td>0.576</td>
<td>32.553</td>
<td>0.130</td>
</tr>
</tbody>
</table>
Friction Velocity (Ustar) = 0.638 m/s

Maximum Instantaneous TKE = 94.496 (m/s)^2

Maximum Instantaneous CTKE = 39.101 (m/s)^2

Grid Point Variance Summary:

Y-coord -40.00 -34.29 -28.57 -22.86 -17.14 -11.43 -5.71 0.00 5.71 11.43 17.14 22.86 28.57 34.29 40.00

Height Standard deviation at grid points for the u component:

<table>
<thead>
<tr>
<th>Height</th>
<th>Standard deviation at grid points for the v component:</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.01</td>
<td>2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681 2.681</td>
</tr>
<tr>
<td>Height</td>
<td>Standard deviation at grid points for the w component:</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------</td>
</tr>
</tbody>
</table>
Mean standard deviation across all grid points:

- u component: 3.470 m/s
- v component: 2.681 m/s
- w component: 1.658 m/s

U-component (X) statistics from the interpolated hub point:

Mean = 20.6023 m/s

Ti = 15.7600 %
Appendix C
Flapwise Bending moment at blade root and mean Hub height mean wind speed

Time step
- Flapwise bending at Pitch angle 11 degrees
- Mean Wind speed at hub height

Flapwise Bending moment at blade root and mean Hub height mean wind speed

Time step
- Flapwise bending at Pitch angle 13 degrees
- Mean Wind speed at hub height
Appendix D

Power output at hubheight wind speed of 21m/s and pitch angle of 7.5 degrees

Power output at hubheight wind speed of 21m/s and pitch angle of 9 degrees