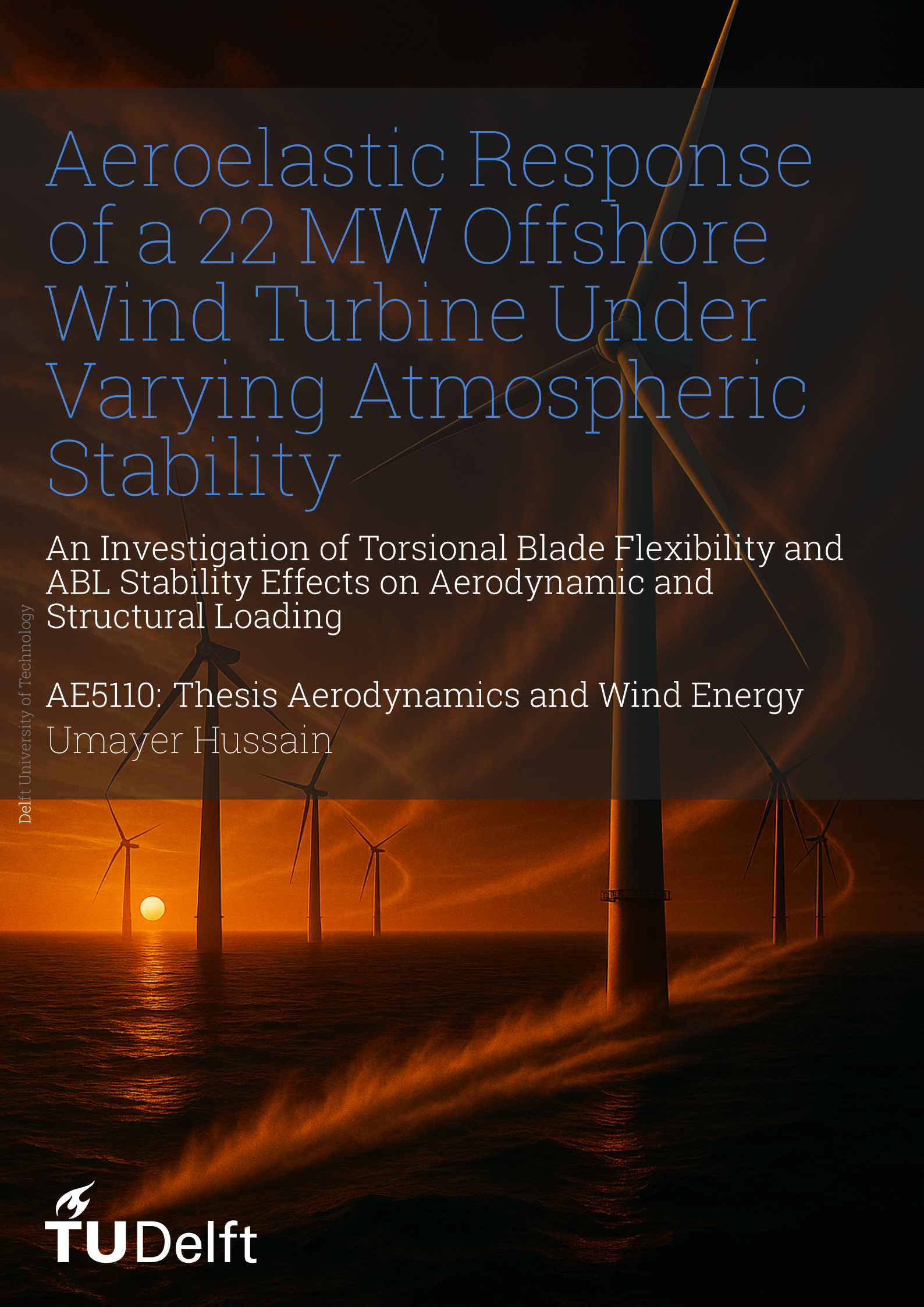


The background of the slide is a photograph of several offshore wind turbines in the ocean. The scene is captured during sunset or sunrise, with a warm orange and yellow glow from the low sun reflecting on the water and illuminating the sky. The wind turbines are silhouetted against the bright sky, with one turbine in the foreground being particularly prominent. The overall mood is serene and technological.

Aeroelastic Response of a 22 MW Offshore Wind Turbine Under Varying Atmospheric Stability

An Investigation of Torsional Blade Flexibility and
ABL Stability Effects on Aerodynamic and
Structural Loading

AE5110: Thesis Aerodynamics and Wind Energy
Umayer Hussain

Aeroelastic Response of a 22 MW Offshore Wind Turbine Under Varying Atmospheric Stability

An Investigation of Torsional Blade Flexibility
and ABL Stability Effects on Aerodynamic and
Structural Loading

by

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to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Tuesday July 7 2026 at 13:30.

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Cover: Offshore wind farm in sunset generated by LLM tool

Preface

Before I write my life story, I first want to thank the people that made this happen, the people who helped me get where I am now. My deepest gratitude goes to my supervisors, Wei Yu and Nirav Dangi. Thank you so much for your guidance, support, patience, and understanding. This thesis for my Master in Aerospace Engineering was incredibly challenging; if I had known the great challenge my thesis imposed, I would have certainly not combined this with my full-time job. It was a long road, but I am deeply thankful for your constant support. I would also like to give my thanks and appreciation to the Thesis Committee Delphine De Tavernier and Michiel Zaayer. Thank you for your time in reviewing my thesis.

My life during my time at TU Delft was full of joy, craziness, and laughter but also sadness, pain, and regrets. I met so many wonderful people and created memories that I will always take with me. Some are gone, and I never saw them again; some stayed and became close friends, and some of those friends became deeply entangled in my personal life. For me, student life felt honestly like a different world, a world that I had to balance with my family life. One was a world where I was surrounded by positivity and dreams; the other world was full of constant hardships and the harsh reality. I stayed in Rotterdam with my family, and there was no reason for me to move to Delft since the distance was so close. Yet I felt so constricted and was pushed to take responsibilities that I wasn't supposed to have at all. Moving to Delft and living by myself was one of the best decisions I ever made. It sounds so ridiculous that this change made me grow so much, but if I didn't do this, I would never have had the exposure to campus life or even have found my wife, Pamily. And to my surprise, my family grew with me. I remembered when my sister Jahin visited me in my fancy studio behind the library, where she said that distance brings people closer. And I think she was right. I did notice a change in my parents, and we did grow closer together. I just now hope that after all this is over, I can move on from this world and focus on my world where I came from.

To my world, Papa and Mama, thank you for always believing in me and for all your support and love. To Jahin and Nora, thank you for being my number one supporters, playing pool, and sharing late night ice creams. To my wife, Pamily, thank you for withstanding the difficult times we had. I am truly thankful that you were there for me.

Umayr Hussain
Delft, June 2026

Abstract

The continued upscaling of offshore wind turbines toward the 20 MW class introduces significant aeroelastic and atmospheric challenges not fully captured by conventional structural models and simplified inflow assumptions. As rotor blades grow increasingly long and slender, torsional flexibility and bend-twist coupling become non-negligible factors in determining the aerodynamic and structural response of the rotor. Simultaneously, the atmospheric boundary layer is thermally stratified, giving rise to distinct stability classes that impose fundamentally different inflow characteristics on the turbine.

This thesis investigates the influence of torsional degrees of freedom and atmospheric boundary layer stability on the aerodynamic performance and structural loading of the IEA 22 MW reference wind turbine. The torsional degree of freedom is assessed by comparing the ElastoDyn and BeamDyn structural solvers in OpenFAST across below-rated, rated, and above-rated operating conditions under neutral ABL inflow. The influence of atmospheric stability is evaluated by comparing unstable, neutral, and stable precursor inflow conditions across the same operating points using BeamDyn as the structural solver.

ElastoDyn generally overestimates the axial aerodynamic load in the tip region across all operating conditions due to its rigid torsion assumption, though at below-rated conditions the two models show closer agreement along most of the blade span. The most pronounced difference is observed in mean rotor thrust at below-rated conditions, where BeamDyn yields a 7.0% lower mean thrust, driven by the nose-down torsional deformation reducing the local angle of attack. At rated and above-rated conditions, the mean thrust differences narrow, while BeamDyn consistently exhibits higher dynamic load variability.

The atmospheric stability analysis reveals that unstable conditions consistently produce the highest load variability. The fatigue analysis demonstrates that stable conditions do not always produce the lowest fatigue loading at rated wind speed, stable stratification produces the highest flapwise DEL at high Wöhler slopes despite having the lowest load variability. Unstable conditions produce the highest torsional DEL at above-rated conditions, approximately 10% higher than neutral. These findings demonstrate that both torsional structural modeling fidelity and atmospheric stability class have significant consequences for load and fatigue assessment of large offshore wind turbines.

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Nomenclature

Abbreviations

Abbreviation	Definition
ABL	Atmospheric Boundary Layer
AoA	Angle of Attack
BEM	Blade Element Momentum
CBL	Convective Boundary Layer
DEL	Damage Equivalent Load
DOF	Degrees of Freedom
DTU	Technical University of Denmark
GE	General Electric
HAWT	Horizontal-Axis Wind Turbine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LES	Large-Eddy Simulation
NREL	National Renewable Energy Laboratory
PBL	Planetary Boundary Layer
PDF	Probability Density Function
PSD	Power Spectral Density
ROSCO	Reference Open Source Controller
SBL	Stable Boundary Layer
TKE	Turbulent Kinetic Energy
UA	Unsteady Aerodynamics

Symbols

Symbol	Definition	Unit
a	Axial induction factor	[-]
c	Blade chord length	[m]
f	Frequency	[Hz]
f_c	Coriolis parameter	[rad/s]
F_n	Normal aerodynamic force per unit span	[N/m]
F_t	Tangential aerodynamic force per unit span	[N/m]
L	Obukhov length	[m]
m	Wöhler slope exponent	[-]
M_{flap}	Flapwise blade root bending moment	[kNm]
M_{tors}	Torsional blade root moment	[kNm]
M_{FA}	Tower base fore-aft bending moment	[kNm]
M_{SS}	Tower base side-side bending moment	[kNm]
n	Number of load cycles	[-]
r	Radial position along blade span	[m]
R	Blade radius	[m]
T	Rotor thrust	[kN]
TI	Turbulence intensity	[-]
U	Mean wind speed	[m/s]
U_∞	Freestream wind speed	[m/s]

Symbol	Definition	Unit
u_*	Friction velocity	[m/s]
z	Height above ground	[m]
z_0	Aerodynamic roughness length	[m]
α	Angle of attack	[deg]
α_s	Wind shear exponent	[-]
β	Blade pitch angle	[deg]
κ	Von Kármán constant	[-]
λ	Tip speed ratio	[-]
μ	Mean value	[-]
Ω	Rotor angular velocity	[rad/s]
ϕ	Inflow angle	[deg]
ψ	Azimuth angle	[deg]
ρ	Air density	[kg/m ³]
σ	Standard deviation	[-]

Introduction

1.1. Background & Motivation

To combat against the energy crisis that is happening globally, governments from different countries in the world are working together to implement energy policies. Making use of renewable energy sources is one of these policies. Wind energy is one of the renewable energy sources that displays prospect. The wind turbine field underwent a rapid increase of development in the past decade while simultaneously, the cost underwent a significant reduction making wind turbines more commercially feasible [43]. Over the years, the size of wind turbines are increased as the turbines became cheaper. Throughout the years, the size of wind turbines increased from 5 MW to 10 MW, and now the size continuously grows to 15 MW and even to 20 MW. General Electric (GE) Wind Energy developed and prototyped a 12 MW wind turbine, and since its operation in 2019, the turbine has been uprated to 14 MW [13]. In that same year of 2019, Siemens Gamesa developed and prototyped a 14 MW turbine [14]. As of the moment of writing, a 15 MW wind turbine is being developed by Vestas with production scheduled in 2024 [48]. In 2023, Mingyang revealed its wind turbine with a flexible rating of 18-20 MW and a rotor blade between 260-292m [37]. It is predicted that the trend will continue with wind turbine size increase in the future. The size increase will introduce structural and aerodynamic challenges [16].

The trend of increasing turbine size will continue due to the economic advantages. With larger turbines, fewer turbines are required in a wind farm with a given capacity due to each turbine yielding a higher rating. With fewer turbines, the number of substructures, total array cables, and total installation time decreases [43]. Understanding how the atmosphere influences the large wind turbines is important. This is because the characteristics of the atmosphere change with increasing height, and larger turbines are either partially or completely operating in different areas of the atmosphere and therefore may experience additional complex wind shear, stratification, and turbulence [25]. Veers et al. explained the most important challenges in wind turbine design [59]. The interaction between the atmosphere and wind turbines is one of the challenges. Atmospheric turbulence impacts the performance and loads of wind turbines. Veers et al. explained the importance of characterizing the turbulence to achieve optimal wind turbine performance due to how complex the atmospheric conditions are where the wind turbines are operating [59]. The importance of understanding how turbulence behaves at large heights is agreed upon in this research area, Nielsen noting that when the tip of the rotor blades reaches more than 250m above sea level, our current understanding of wind profiles and turbulence should be improved [38]. The paper Shaw et al. describes the components of the atmosphere and how the stability affects the wind characteristics [42].

As the size of turbines increases, the flexibility of rotor blades increases. Rotor blades that are large and slender will be more susceptible to aeroelastic effects [67]. The blades of modern large-scale wind turbines are manufactured from fiber-reinforced composite materials, where the anisotropic material properties and the geometry of the blade cross-section introduce a coupling between bending and torsional deformation, known as bend-twist coupling [51]. When the blade bends out-of-plane un-

der aerodynamic loading, the offset between the elastic axis and the aerodynamic center generates a torsional moment, causing the blade to simultaneously twist along its span [51]. This effect is intentionally implemented in blade design to passively control the extreme and fatigue loads [67]. As blade lengths exceed 100m, the out-of-plane deflections under operational loading become substantial, and the resulting torsional deformation has a non-negligible influence on the local angle of attack distribution along the blade span [51]. It is therefore important to understand how the flexibility of rotor blades impacts aerodynamic performance.

DTU Wind Energy (under cooperation with NREL) published a design basis for the next-generation wind turbines: the IEA 22 MW reference turbine [66]. This research will use this reference turbine for the case study to fill the knowledge gap of atmospheric flow interaction with large turbines.

1.2. Research questions and objective

The objective of the research is defined as: "To investigate the influence of atmospheric stability conditions on the aeroelastic properties and wake of a Horizontal-Axis Wind turbine (HAWT)". This research objective is relevant to the wind turbine scientific field because limited studies on considering the stable and unstable atmospheric conditions to perform simulations have been done. Research questions have been defined to achieve this objective. The research questions are defined as:

- **Research question 1:** "What is the influence of torsional force on the aerodynamic performance, blade structural response, and fatigue loading, and how does neglecting blade torsional flexibility affect load predictions?"
- **Research question 2:** "How do neutral, stable, and unstable atmospheric stabilities affect the aerodynamic performance and blade dynamic response across below-rated, rated, and above-rated operating conditions?"

1.3. Scope & Limitations

This thesis investigates the aeroelastic behavior and structural responses of a large wind turbine. The suitable turbine chosen is the IEA 22 MW reference turbine. The analysis is conducted in OpenFAST with a linear model, ElastoDyn, and the nonlinear model, BeamDyn. The scope of the analysis will focus on three specific operating wind speed conditions. The Blade Element Momentum (BEM) theory is used to resolve the aerodynamic loads, while the inflow conditions are resolved using LES. The analysis will focus on aerodynamic loading, structural deflections, frequency domain resonance, and fatigue life estimation at the blade roots and tower base. The limitation of this study is that the wind turbine is modeled as a bottom-fixed foundation with no presence of hydrodynamics and soil interactions. The turbine is simulated as a single offshore wind turbine, and thus wake effects are not considered.

1.4. Thesis Outline

The structure of this thesis is as follows. Chapter 2 describes the literature review of the atmosphere and wind turbine physics. The state-of-the-art review of the effects of the atmosphere and inflow conditions will be explained as well in this chapter. Chapter 3 will describe the methodology used for this research, where the simulation setup alongside its justification will be explained. The results will be presented in chapter 4, where the analysis of the influence of the bend-twist coupling and atmospheric stability are explained in detail. The thesis will finally close with a conclusion and recommendations on the findings in chapter 4.3.5.

2

Literature Review

2.1. Atmospheric Boundary Layer

First, a short historic introduction will be given on the origins of the development of the atmospheric boundary layer (ABL). The boundary layer theory was first developed by Ludwig Prandtl in 1904 [46]. A year later, Vagn Walfrid Ekman developed the laminar Ekman layer theory and wind spiral in the ABL [46]. Around this time several scientists made additional developments, Osborne Reynolds developed fluid dynamics and the Reynolds number, Andrey Nikolaevich Kolmogorov developed the similarity theory for turbulence which accelerated the research of turbulent processes [46]. From 1910 to 1940, Geoffrey Ingram Taylor investigated turbulent mixing while the mixing-length theory and eddy diffusivity have been developed by von Karman, Prandtl and Lettau [46]. Monin and Obukhov researched buoyancy effects on surface layers from 1950 to 1960 [46]. It was only starting from 1960 that the different boundary layer types and their stability conditions could be accurately observed and verified. From 1970, development started to resolve the ABL in 3D through LES and higher order turbulence [46]. In the next decades, the occurrence of various sensors like LIDAR or radars accelerated the research on ABL. Various studies has been made since then which helped understanding more of the boundary layer research [46].

The ABL is the lowest region of the troposphere, it is also known as the planetary boundary layer (PBL) and has a height of about 1 km [29]. Figure 2.1 shows a sketch of the lower atmosphere. The surface of the Earth can be seen as the bottom boundary of the ABL where it interacts with the properties. The ABL's physical state is characterized by variables such as temperature, pressure and wind. These variables are then related to dynamic properties such as turbulence and air stability [29]. The chemical state is characterized by variables describing gases and air pollutants, but these have no effect on the physical state variables. The ABL is primarily characterized by the turbulence and is considered to be the primary cause of the ABL state [49] [53], [29]. The turbulent flows introduces a transport problem that needs carefully analysed. The goal of this chapter is to explore more in depth on these state variables and the characteristics of the ABL.

The ABL is an area where turbulence occurs [49]. To understand the formation of turbulence, an understanding of atmospheric stability is needed. Stability of the air in the ABL is what affects the wind and temperature.

2.1.1. Atmospheric stability

The stability of the flow can be described by static stability and/or dynamic stability [49]. Static stability is when only buoyancy is considered while for dynamic stability, buoyancy and wind shear is included and will determine if the flow is turbulent [49]. The environmental conditions determines the static stability and has three characteristics: unstable, stable and neutral [49]. Unstable conditions are characterized by enhanced vertical mixing and higher turbulence intensity driven by surface heating, while stable conditions suppress vertical mixing resulting in lower and less chaotic turbulence and



Figure 2.1: Sketch of the division of the lower atmosphere [29].

stronger wind shear. Neutral conditions represent an intermediate state where buoyancy effects are negligible and turbulence is generated primarily by mechanical wind shear [49].

To understand static stability, we will use an air parcel (a ball of air) to make visualisation of stability a bit easier. If an air parcel becomes warmer than its environment, the buoyancy of this parcel is positive and will start to rise. If this air parcel supposedly is forcibly moved by an external force, the air parcel will keep rising and causes the air to be unstable. This type of movement is called convection and causes to stir up the flow and generates turbulence. When the air parcel is colder than the environment, the air parcel will sink which gives a negative buoyancy and if again is forcibly moved, it will return to its original position and is considered to be stable [49].

2.1.2. Boundary layer characteristics

Convective Boundary Layer (CBL)

The CBL is mainly made of three layers: the bottom part the surface layer, the middle part the mixed layer and the top part the entrainment zone. Followed by the entrainment zone is the free atmosphere above. The surface layer located in the bottom 20 to 200m of the ABL [49]. It is characterized by its rapid decrease of virtual potential temperature and strong increase of wind shear. Inside the mixed layer, variables such as the virtual potential temperature and wind speed are nearly constant with increasing height. The virtual potential temperature and wind speed increases further in the entrainment zone as can be seen in figure 2.2. It is found that wind-profiles empirically are similar when scaled, this is described by the Monin-Obukhov similarity theory.

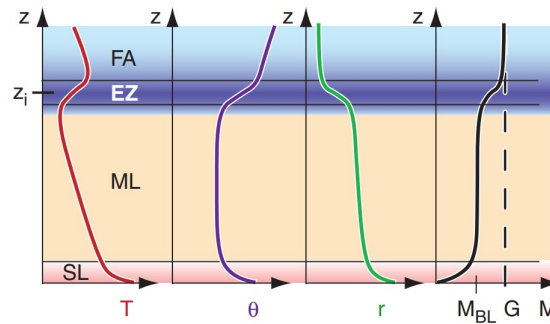


Figure 2.2: Vertical profiles potential temperature θ and wind speed M [49]. M_{BL} and G are the average and geostrophic wind speed respectively.

Stable Boundary Layer (SBL)

The SBL occurs when the ground is thermally stratified by cooling the surface. The temperature of the surface is then cooler than the air, which causes a stable layer. The properties of the SBL can be visualised in figure 2.3. It can be seen that the virtual potential temperature increases alongside with a strong increase of wind shear. This then decreases slowly when reaching the residual layer and slowly stabilising when reaching the capping inversion and the free atmosphere. The virtual potential temperature remains almost constant in the residual layer and increases strongly as it transition to the capping inversion and the free atmosphere.

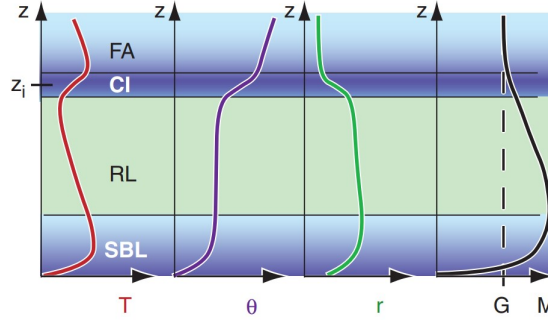


Figure 2.3: Vertical profiles potential temperature θ and wind speed M [49]. G is the geostrophic wind speed.

2.2. Wind turbine physics and aerodynamics

2.2.1. Inflow Conditions

Turbulence

Turbulence is a stochastic phenomena with an unpredictable behaviour, it's a type of flow that has random and irregular patterns. A fluid in motion is driven by kinetic energy and is slowed down by the viscosity of the flow [3]. Turbulence occurs when the kinetic energy is so strong that it is able to overpower the viscosity effects. If viscosity is the dominating force, then the flow is considered to be laminar, which is a type of flow that follows a regular pattern and can be predicted. A turbulent flow is characterized by eddies, diffusion and dissipation [3],[2]. The eddies comes in different sizes and strengths. The larger eddies breaks down in smaller eddies and these become so small that they dissipate due to the molecular viscosity. Turbulence has two sources: buoyancy forces caused by the heating of the surface (convection) and wind shear [46].

As mentioned before, the kinetic energy needs to overcome the viscous effects of the fluid for turbulence to occur. This can be characterized with the Reynolds number: $Re = \frac{UL}{\nu}$, where U is the velocity, L the length scale and ν the kinematic viscosity, which is defined as $\frac{\mu}{\rho}$ where μ is the dynamic viscosity and ρ the density. A high enough Reynolds number can indicate when the flow has transitioned from laminar to turbulent. The flow is considered to be laminar if $Re \sim 1$, when Re goes above 4000, the flow becomes turbulent [28]. Turbulence is closely related to the governing transport equations of fluid motion. These are the: continuity equation, Navier-Stokes equation that describes momentum and the energy equation. The exact relation is quite complex as it is not only related to the governing equations of fluid motion, but also variables such as temperature, pressure and density needs to be taken into account [4]. A more in depth discussion of the relation of turbulence and transport equations can be found in various literature, as this is beyond the scope of this research.

Turbulence can be described in terms of statistical values. A measure of level of turbulence can be described by turbulence intensity as seen in equation 2.1. In this equation, σ is the standard deviation of wind speed about the mean wind speed $\bar{U}$, usually over 10 minutes. When measuring turbulent wind speeds variations, it can be approximated to a normal distribution. The extreme regions however is found to be not completely accurate and so this approximation may not be suitable to determine the probability of gusts [4]. Turbulence intensity is dependent on surface roughness, type of terrain and height. Wind turbines are highly affected by turbulence in the ABL. Studies have shown that turbulence intensity has impact on aerodynamic performance on wind turbines. Stability effects of the ABL has shown to influence turbulence intensity. Wharton and Lundquist concluded in their research on the impacts of atmospheric stability on wind resources that wind speeds at hub height is over estimated in unstable atmosphere while underestimated in stable regions if not corrected for atmospheric stability [63]. If not accounting the atmospheric stability, inaccuracy will occur in the aerodynamic load analyses. This shows the importance of atmospheric stability effects.

$$I = \frac{\sigma}{\bar{U}} \cdot 100\% \quad (2.1)$$

Wind Shear

Understanding the development of wind shear is important in wind turbine design. Wind speed is often modelled using a wind profile model. This is described commonly in two ways. The first method is the power law, the second is the logarithmic law. The power law is shown in equation 2.2. In here, the wind speed u is a function of the vertical height z . The u_{ref} is the reference wind speed at the reference height z_{ref} which is commonly taken as $10m$ [30]. The exponent α_s is known as the wind shear exponent which is estimated based on empirical data, it varies depending on different types of variables like: atmospheric stability, wind speeds and surface terrains [64]. The IEC61400-1 standard recommends a shear exponent of 0.2 over land but it can vary between 0.05 to 0.3 depending on stability state and the turbulence [9].

$$u(z) = u_{ref} \left(\frac{z}{z_{ref}} \right)^{\alpha_s} \quad (2.2)$$

Equation 2.3 shows the log law where stability effects is accounted for by deriving it from the Monin-Obukhov similarity theory. In here: u_* represents the friction velocity as seen in equation 2.5. $\overline{w'u_0'^2}$ represents the covariances, κ the Von Karman constant which according to experimental results is commonly taken as 0.4 [50] and z_0 the surface roughness length. ψ_m is called the stability correction function which is represented by the ratio: $\zeta_m = \frac{z}{L}$. The correction function accounts for the stability effects of the ABL. The Obukhov length L as shown in equation 2.4 takes into account the surface heat and momentum flux.

$$u_z = \frac{u_*}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) - \psi_m(\zeta_m) \right] \quad (2.3)$$

$$L = - \frac{\overline{\theta_v} u_*^3}{\kappa g w' \theta_v'} \quad (2.4)$$

$$u_* = \left(\overline{w'u_0'^2} + \overline{w'v_0'^2} \right)^{1/4} \quad (2.5)$$

2.2.2. Turbulence inflow generation methods

Simulating turbulence can be categorized in synthetic, recycling and precursor method [52], [62], [65]. Synthetic methods generates random fluctuations and combine this with the mean flow at the inlet. An important condition for generating turbulence synthetically is that it has to be divergence-free, otherwise the turbulence characteristics would diverge from the target turbulence [62]. Precursor methods calculates the turbulence before the main simulation which will be then imposed at the inlet inside the domain. LES is typically used to simulate the ABL to predict the turbulence statistics [32]. Recycling method reuses the flow information from previous iterations to simulate turbulence in the next timestep [18], [65], it is often combined with the precursor method. Both the synthetic and precursor methods contains various models to simulate turbulence field. The most common models used for wind turbine research are the Mann model and the Kaimal Spectral model and are also considered to be the standard for wind turbine design [9].

Synthetic method

Synthetic turbulence can be useful when real turbulence data is not available or too costly to simulate. Various synthetic turbulence generation models exist that generate turbulence inflow. These models can be complex and can range from Fourier techniques or vortex methods [31], [58]. Vasaturo et al. [58] has listed various models researchers used. The turbulence that is generated will then be added to the mean inflow profile. All synthetic models have the common goal to generate a suitable turbulence-like flow to assess turbulence parameters like turbulence kinetic energy and the dissipation rate. The advantage of synthetic methods is that most models has low computational cost, however, synthesized turbulence does not satisfy the fluid flow governed by the Navier-Stokes equations [31]. Regardless, synthetic methods are still widely used for wind turbine research and provide good results. The Mann model by Mann and the Kaimal spectrum by Kaimal and Finnigan will be focused on in this research.

Table 2.1: Comparison of inflow generation methods [18], [65]

Method	Description	Pros	Cons	Complexity
Synthetic	Generates turbulence through spectral and spatial coherence characteristics	Low computational cost, useful when real turbulence data availability is limited.	Possibility in introducing less accurate results.	Medium
Recycling	Continuously reuses flow information to simulate turbulence in the next timestep.	Reduces complexity in inflow simulations.	Pre-computation of the recycling domain requires additional computational resources execution time.	High
Precursor	Simulates inflow data.	Highest possible accuracy.	Large computational cost and storage needed.	Highest

Mann modelled the spatial characteristics of a homogeneous neutral ABL turbulence with a stationary spectral velocity tensor. Mann assumed for an incompressible flow to derive the model. The spectral tensor can describe the spectra, cross-spectra and coherences that are needed for wind turbine design. Mann made use of the Rapid Distortion Theory (RDT) where he assumed uniform mean shear and took into account the eddy lifetime. The input parameters are: length scale of the turbulent eddies L , non-dimensional parameter eddy lifetime Γ and viscous energy dissipation rate ϵ [8], [19]. When used for non-neutral ABL conditions, the Mann model can be extended by including buoyancy effects through an uniform vertical temperature gradient [7]. The model then contains two additional parameters: the Richardson number (Ri) which represents the atmospheric stability and, a parameter proportional to the rate of destruction of temperature variance η_θ . This model is then able to produce two-point statistics of the coherence and phase for the temperature field [8]. Chougule et al. simplified the model by replacing the Ri and η_θ with the Obukhov length to make the model more practical [8]. The derivation of the Mann model is complex and so only the spectral tensor will be given. For a detailed derivation of the Mann model see [33], [33], [34]. The Mann model is given by the equation:

$$\Phi_{ij}(\mathbf{k}) = \frac{E(k)}{4\pi k^4} (\delta_{ij}k^2 - k_i k_j) \quad (2.6)$$

Where $\mathbf{k} = (k_1, k_2, k_3)$ is the non-dimensional spatial wave number for the three components: longitudinal (1), lateral (2) and vertical (3). The $E(k)$ is the energy spectrum. Von Kármán has suggested to use the following equation:

$$E(k) = \alpha \epsilon^{\frac{2}{3}} L^{\frac{5}{3}} \frac{(Lk)^4}{(1 + (Lk)^2)^{\frac{17}{6}}} \quad (2.7)$$

Here, it can be seen that the Mann model is dependent on three parameters. These are: $\alpha \epsilon^{2/3}$ [$m^{4/3}/s^{-2}$], L [m] and Γ [$-$] [20]. $\alpha \epsilon^{2/3}$ is the energy level constant that is the multiplication of the spectral Kolmogorov constant α and the viscous dissipation rate of the specific TKE ϵ . These values are adjusted depending what values are needed for the turbulence intensity. L is the length scale describing the size of the eddies and Γ is a non-dimensional constant related to anisotropy due to the effect of vertical shear in the atmospheric surface layer. Turbulence is isotropic when $\Gamma = 0$ [20]. Now, the equation of the Kaimal spectrum will be explained:

$$S_k(f) = \frac{4\sigma_k^2 L_k/u}{(1 + 6fL_k/u)^{5/3}} \quad (2.8)$$

Where equation 2.8 is the Kaimal spectrum that describes the time-series of wind speed [9], [23]. Here, σ is the standard deviation estimated by the turbulence intensity $TI(\%)$: $\sigma = \frac{TI}{100}u$, L is an integral scale parameter that is hub height dependent, u is the mean wind speed at hub height and f

is the cyclic frequency in Hz . The k subscripts indicates the velocity direction: longitudinal (1), lateral (2) and vertical (3).

Precursor method

The precursor method is a method where turbulence inflow is computed and written in a database so it can be used for a wind turbine simulation. The database is a separate and independent file that a wind turbine simulation can access anytime. An accurate way to generate turbulent winds is to use a LES solver. The process is as follows: the solver generates turbulence on a pre-defined domain with periodic lateral boundaries [36]. Planes from the most upwind lateral boundary is saved at every time-step once the boundary layer reached quasi-equilibrium state. This is saved to a file where then a wind turbine simulation can access it. Figure 2.4 shows a schematic of this process.

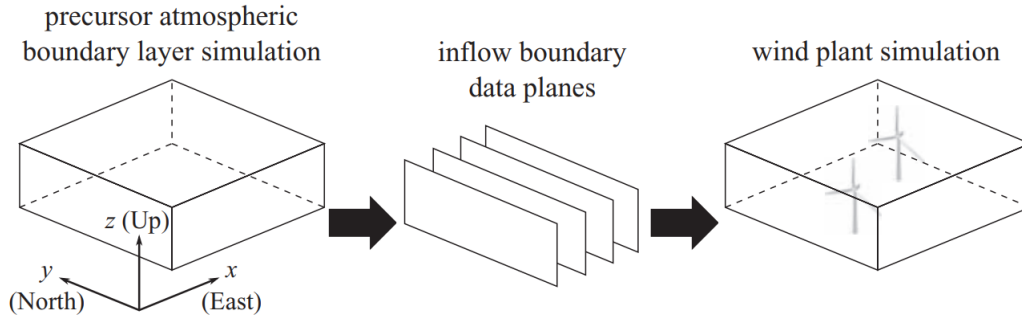


Figure 2.4: Schematic precursor method [36]

This method is considered to be most accurate of achieving turbulence inflow, however it contains many drawbacks [47], [52]. The first is that the main wind turbine simulation cannot be started before the precursor simulation is finished. The second is that a precursor simulation is highly computational expensive and requires massive data storage for storing the database [47], [35]. Furthermore, accessing the database can affect the efficiency of the simulation. Stevens, Graham, and Meneveau proposed to directly write the inflow data into the data memory of the wind turbine simulation instead to a separate file so that the two simulations can be performed simultaneously. This improved computational speed due to not needing to access a separate database and storage, however not on the actual computing of the turbulence inflow. Regardless, precursor methods still are been used in many research papers recent years like [12] and [55]. However the authors provided no reasoning why the precursor method has been chosen for generating turbulence inflow. It is however generally agreed on that the precursor method is considered to be the more high-fidelity [58]. Vasaturo et al. [58] has listed many comparative studies between many models of precursor and synthetic methods.

2.2.3. Aerodynamic characteristics and loads

Blade Element Momentum Theory (BEMT)

The BEM theory's assumption states that the force on a blade element is independent of every other blade elements [4]. Rotor blades interacting with the wind will generate aerodynamic lift and drag forces along the spanwise length r of the blade. The aerodynamic forces vary for each blade element with length ∂r . The blade elements sweeps an annulus with radius r , which forms the actuator disc where air passes through as shown in figure 2.5. The aerodynamic forces on each blade element can be calculated by using 2D airfoil characteristics where the angle of attack (AoA) is determined by the rotor blade's velocity triangle (figure 2.6). From the airfoil data, C_l and C_d can be found and with the AoA, the axial and tangential induction factors a and a' can be calculated. The lift, drag, thrust and torque can then be calculated, with the assumption that the aerodynamic forces acting on an element is the same for an isolated element with the same AoA in 2D flow. This is called the blade element theory [4].

BEM theory assumes the rotor possesses an infinite number of blades. In reality this is not the case, where most wind turbines have either two or three blades. A finite number of blades means that the flow cannot be assumed to be uniform in the azimuthal direction, as it is for an actuator disk with infinite

blades. This causes a reduction in lift near the blade tip, where the bound circulation must reduce to zero at the tip, resulting in tip losses that reduce the overall rotor performance. Tip loss corrections can be applied to the BEM formulation, the most commonly used being the Prandtl tip loss factor, which accounts for the finite number of blades by correcting the axial induction factor in the azimuthal direction [4].

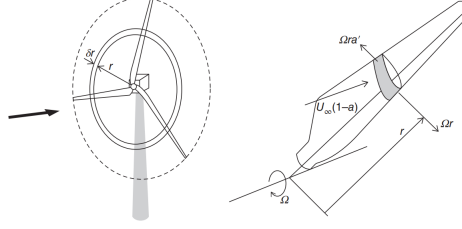


Figure 2.5: Overview blade element sweeping an annulus [4].

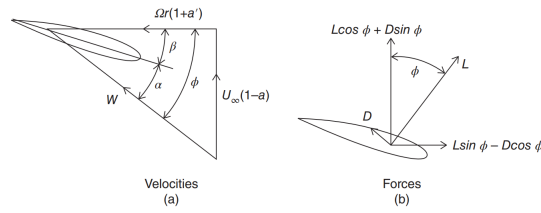


Figure 2.6: Blade element showing velocities (left) and forces (right) [4].

Actuator Line Model

The actuator line model is developed by Sørensen and Shen in [45] where an URANS solver is used to model wind turbine wakes for single wind turbines and in wind farms. In this model, the rotor blades are represented as a line of radially varying force. Depending on the amount of blades, two or three rotating actuator lines are modelled along the axis of the rotor blades. Actuator points (or nodes) are defined along the line, which needs to be between 10 and 20 larger than the number of meshes in the blade. The position of the points are updated through a specified rotational angular velocity each time step. Figure 2.7 shows how the points are distributed along the line. The normal and tangential forces on each node are then calculated from the local flow velocity and angle of attack. The velocity and aerodynamic forces can be seen in the velocity triangle in figure 2.8. Here, U_x and U_r are the local axial and tangential velocities. The local relative inflow velocity $U_{rel} = \sqrt{U_x^2 + (\omega r - U_r)^2}$ can then be calculated to find the angle of attack. The local angle of attack is defined as:

$$\alpha = \varphi - \gamma \quad (2.9)$$

Where φ is the inflow angle and γ the local pitch angle. The inflow angle can be determined as:

$$\varphi = \arctan \frac{U_0}{U_r - \omega r} \quad (2.10)$$

First, the actual flow velocity is determined through CFD simulation. U_{rel} and α is then calculated through the velocity triangle. The aerodynamic forces as the force per spanwise unit length are calculated by the following equations:

$$f_{2D} = \frac{1}{2} \rho U_{rel}^2 c (C_L e_L + C_D e_D) \quad (2.11)$$

Where $C_L = C_L(\alpha Re)$ and $C_D = C_D(\alpha Re)$ are the lift and drag coefficients, c the chord length and e_L and e_D are the unit vectors in the direction of lift and drag. C_L and C_D are determined from airfoil data. To avoid numerical oscillation, a smooth projection function is introduced:

$$\mathbf{f}_\epsilon = \mathbf{f} \otimes \eta_\epsilon \quad (2.12)$$

$$\eta_\epsilon(r) = \frac{1}{\epsilon^3 \pi^{3/2}} \exp \left[-(r/\epsilon)^2 \right] \quad (2.13)$$

In the above equations, $\mathbf{f}_\epsilon$ is the singular behaviour that needs to be avoided. To do this, the convolution of the computed normal load $\mathbf{f}$ and a regularization kernel η_ϵ is taken [45]. For a detailed explanation of these functions, the study by Sørensen and Shen [45] can be used as reference.

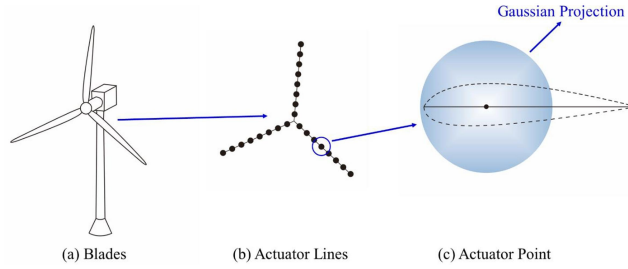


Figure 2.7: A schematic of the Actuator Line Model [22].

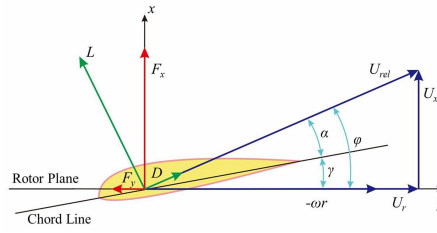


Figure 2.8: Velocity triangle of a cross-section blade element [22].

2.3. State of the Art review

This chapter will review the current state-of-the-art from the last decade on what work has been done in the field of ABL and its influence on wind turbines. Understanding recent studies is important as these give context on what currently researchers are trying to achieve, what gaps need to be filled and/or to build up on previous studies.

2.3.1. Effects of Atmospheric Boundary Layer

Several studies in the last years have focused on simulating the ABL and how this influences wind turbine performance. Porté-Agel, Lu, and Wu validated in 2014 Large-Eddy-Simulation (LES) framework to be used for wind farms. Here the impact of wind farms on a stable and convective ABL were also investigated using a 3 MW turbine as a case study. Results show that the wind-turbine motions enhance the vertical mixing of heat, resulting in near-surface warming under stable conditions and cooling under convective conditions [40]. Dörenkämper et al. studied in 2015 the impact of atmospheric stability. A case study is then performed on the effects of a stable ABL on wind turbine wakes in an offshore wind farm through measurements and LES using a reference turbine of 2.3 MW. This research concluded that in a stable ABL wake effects are stronger compared to neutral and unstable stratification [11].

Tian et al. realised in his study of 2020 an inconsistency on the agreement of researchers about the power extraction of wind farms [55]. Tian et al. noted that some researchers found that wind farms show maximum power output during stable conditions, while others say there is an efficiency loss

from 9% to 35% in the same conditions [55]. Tian et al. also noticed that some researchers focused on single turbines did not include atmospheric parameters such as the stability parameter Richardson number, which Ichenial and Elhajjaji for example did not use [21]. Tian et al. used LES to reproduce idealized diurnal evolutions of the atmospheric stability and its impact on the performance of a NREL 5 MW reference turbine [55]. Tian et al. concluded that a wind turbine produces more power in the daylight hours (unstable conditions) than during the nighttime (stable conditions). This means that for the same hub height wind speed, a convective atmosphere can enhance power performance from cut-in speed to the rated speed.

Chanprasert et al. evaluated in 2022 control responses and fatigue loading of a four-inline wind turbine array using a coupled LES and aeroelastic code under a neutral and unstable ABL with two different wind speeds, the NREL 5 MW reference turbine is once again used. The research concludes that for both incoming wind speeds, atmospheric stability has no impact on fatigue loads on the front row turbines but does affect wake characteristics which affects control response and fatigue of the downstream turbines [5]. The torsional load in neutral stability condition was 50% higher than the unstable case. Another research in 2022 has assessed wind loads in an offshore environment with taking into account the neutral ABL flow using the NREL 5 MW reference turbine [26]. The research concludes that by not taking into account the atmospheric turbulence offshore, significant errors may occur in the calculations used by the design standards at the time of this research's publication date [26].

2.3.2. Influences of inflow conditions

The wind turbine performance is dependent on the wind load which is characterised by various factors. One of these factors is the ABL because the wind shear and turbulence is influenced by the state of the atmosphere. The interaction of wind shear and turbulence on wind turbines still requires exploration to this day. These interaction can be investigated in wind tunnel studies like how Tian, Ozbay, and Hu did in their research on the effects of inflow characteristics in 2019 [56]. During this study, the influence of wind shear and turbulence intensity on the dynamic wind loads were simulated under two types of ABL winds with neutral condition. Results shows that wind shear significantly influences mean wind loads acting on the turbine and that the turbulence is the dominant factor in the rotation speed of the blades and lead to high variations of dynamic wind and fatigue loads [56].

Gao, Qian, and Wang did a similar study in 2021 on the influences of atmospheric turbulence with different atmospheric stability on the unsteady aerodynamic load response of wind turbines [17]. The research first validated the numerical accuracy of the atmospheric turbulence generation algorithm and wind turbine loads based on an experiment and then investigated the unsteady load response of a NREL 5 MW reference turbine under the Von Karman and Measured Spectral model [17].

Chanprasert et al. researched in 2022 the impact of directional sheared inflows caused by the Coriolis force on wake interaction of a four-inline turbine array using once again the NREL 5 MW turbine as reference in a neutral ABL. Plischka et al. studied in 2022 five synthetic turbulence generators to evaluate the applicability of synthetic inflow generation techniques for atmospheric boundary layer flow. Plischka et al. concludes that with utilization of synthetic generated turbulence at the inlet, the inflow domain length for simulations can significantly be reduced without introducing substantial uncertainties into the numerical solution [39].

2.3.3. Bend-twist coupling in large rotor blades

As wind turbines become larger in size, the rotor blades become increasingly long and slender. As the blades become more slender, aeroelastic effects become more apparent and cannot be ignored. The rotor blade of the IEA 22 MW turbine has a radius of 137.8 m, making it a highly flexible blade where torsional deformation plays a significant role in the aerodynamic and structural response. Due to the asymmetric cross-section of the blade, aerodynamic loading introduces bend-twist coupling along the blade span, where out-of-plane bending induces a torsional deformation that modifies the local angle of attack and consequently the aerodynamic forces. These complex aeroelastic interactions call for the need to use higher fidelity structural models to accurately assess turbine performance and structural

loads.

The impact of blade torsional flexibility on wind turbine performance has been researched in several studies. In the paper of Zhu et al. [67], the impact of blade flexibility is examined on the loads, power production and pitch settings of the NREL 5MW reference wind turbine using a free wake vortex lattice model combined with a geometrically exact beam formulation. This study found that blade torsional deformation is significantly affected by both the aerodynamic torsion moment and the offset between the sectional aerodynamic center and the blade elastic axis. The largest flapwise bending deflection was found to occur at rated wind speed, while the torsional deformation in the toward feather direction continuously increases above rated wind speed. Furthermore, rotor power was reduced at large wind speeds when blade flexibility was considered, which was shown to be driven primarily by torsional deformation rather than pure flapwise bending deflections. As a consequence, lower pitch angle settings were found to be required to maintain constant rotor power at above rated wind speeds when torsional flexibility is taken into consideration.

The aeroelastic behaviour of large flexible blades can be taken advantage of in blade design. This is done through passive load alleviation where intentional bend-twist coupling is implemented. Sun et al. [51] investigated passive aeroelastic coupling for load reduction on the IEA 15 MW reference turbine by introducing bend-twist coupling through composite fiber off-axis orientation of the blade spar cap, and geometric sweep coupling through a swept blade reference axis. The results showed that the highest coupling efficiency is achieved at a fiber off-axis angle between 12° and 15° . The bend-twist coupling reduces the load of the blade root with a small fiber off-axis angle, while the sweep coupling reduces the axis torque. When comparing to a steady state rotating turbine, the maximum thrust, flapwise moment and axis torque of the blade can be reduced by 8.8%, 13.4%, and 22.9% respectively.

In the study of Trigaux, Chatelain, and Winckelmans, the influence of blade flexibility on aerodynamic loads has been investigated using higher fidelity methods [57]. Trigaux, Chatelain, and Winckelmans studied the impact of blade flexibility on the aerodynamics of the IEA 15 MW reference wind turbine using a flexible actuator line method coupled to the BeamDyn structural solver in LES. It was found in the results that the mean flapwise and torsional displacements caused a reduction of 14% in thrust and 10% in power compared to a rotor with no deformation. Furthermore, the study demonstrated that the effect of blade flexibility on loads is more pronounced when predicted using the actuator line method compared to blade element momentum theory, suggesting that BEM based approaches may underestimate the full aerodynamic consequence of blade flexibility. These studies displays how structural deformations have a significant impact on turbine performance and emphasizes the importance of including flexibility of rotor blades in wind turbine simulations.

3

Methodology

This chapter describes the methods and simulation parameters used to analyse the aeroelastic response of an offshore wind turbine. In this study, the IEA 22 MW Reference Wind Turbine was used. The aeroelastic simulations are performed using OpenFAST with a defined wind field. The chapter begins with the definition of the geometric and structural properties of the reference turbine, followed by the characterization of the turbulent inflow and its atmospheric stability. Finally, the input settings in OpenFAST are detailed alongside how the results will be post-processed and validated.

3.1. IEA 22 MW Reference Turbine

The development of this reference turbine was done cooperatively between DTU and NREL, along with input and feedback from relevant industries and research collaborators [66]. The turbine is characterized by a 137.8 m long blade. With a rated wind of 11.0 m/s. The tip-speed ratio equals 9.153 and the maximum tip speed reaches 105.0 m/s. The full design report is described in [66]. Table 3.1 summarizes the main properties of the reference turbine.

Table 3.1: Summary overall properties IEA 22 MW reference wind turbine. [66]

Quantity	Value	Quantity	Value
Rated elec. power [MW]	22.0	Blade length [m]	137.8
Specific power [W m^{-2}]	351.410	Blade prebend [m]	7.0
Wind class	1B	Blade mass [t]	82.301
Rotor orientation	Upwind	Airfoil series	FFA-W3
Number of blades	3	Blade root diameter [m]	5.8
Control	Var. speed, coll. pitch	Rotor precone angle [deg.]	4.0
Cut-in wind speed [m s^{-1}]	3.0	Shaft tilt angle [deg.]	6.0
Rated wind speed [m s^{-1}]	11.0	Hub height [m]	170.0
Cut-out wind speed [m s^{-1}]	25.0	Drivetrain	Direct drive
Design tip-speed ratio	9.153	Generator efficiency [%]	95.4
Min. rotor speed [rpm]	1.807	Hub system mass [t]	120.0
Max. rotor speed [rpm]	7.061	Nacelle assembly mass [t]	821.2
Max. blade tip speed [m s^{-1}]	105.0	Tower mass [t]	1,574
Rotor diameter [m]	284.0	Monopile mass [t]	2,097
Hub diameter [m]	8.4		

3.2. Wind field

The inflow for the wind turbine is generated using a precursor LES ABL simulation. A detailed explanation of LES can be read in [41]. Figure 3.1 shows profiles of the averaged horizontal velocity, turbulent kinetic energy (TKE) and the turbulence intensity (TI) for all rated cases alongside the stability classes. All profiles show a quasi-steady state, where it can be clearly seen that the velocity profiles show the desired logarithmic law. The surface roughness is taken into account to include the wind shear. Wind veer is also correctly captured for the stable ABL due to the wind direction, which is caused by the Coriolis Force due to the Earth's rotation. The wind direction of all stability classes for the rated wind speed can be seen in figure 3.2. It can be further seen that the TKE for the unstable case is higher than the stable case. This is expected, during unstable conditions there is an increase of turbulence due to buoyancy being the dominant force as it is being increased [50]. In stable conditions, buoyancy is destroyed, and wind shear and veering are the dominant forces in the generation of turbulence [50].

3.3. Methods used for load analysis

The loads analyzed in this thesis are calculated using the BEM Theory as described in chapter 2.2.3. The load assessment addresses two areas. The first is the influence of the bend-twist behavior, in other words, the torsional degree of freedom. This is investigated by comparing results with simulations performed with ElastoDyn, where the blade is assumed to be rigid, with simulations performed in BeamDym, where torsional deformation and bend-twist are resolved by employing the geometrically exact beam theory. The second area is the influence of atmospheric stability. Offshore wind turbines operate within the atmospheric boundary layer, where thermal stratification affects the characteristics of the atmosphere. The wind turbine performance and loads will be analyzed in three stability classes: neutral, stable, and unstable.

To assess the fatigue damage for the rotor blades, the Damage Equivalent Load (DEL) method will be used as recommended by Dangi [10]. The DEL is computed as:

$$R_{eq} = \left(\frac{\sum_i n_i R_i^m \frac{M_u^m}{(M_u - |M_{m,i}|)^m}}{n_{eq}} \right)^{1/m} \quad (3.1)$$

where n_i is the number of cycles, R_i is the load range amplitude, $M_{m,i}$ is the mean load of the i -th rainflow cycle, M_u is the ultimate load, m is the Wöhler slope exponent, and n_{eq} is the reference number of equivalent cycles. Rainflow cycle counting is performed using the `rainflow` Python library, using the `rainflow.extract_cycles()` function without binning of load cycles. A reference number of equivalent cycles of $n_{eq} = 10^6$ is used, this corresponds to the number of 10-minute periods in a 20-year design lifetime [54]. A Wöhler slope exponent of $m = 10$ is used, which is standard practice for composite wind turbine blade materials [54].

3.4. OpenFAST

To address the main research question of this thesis, the IEA 22 MW reference offshore wind turbine is modelled and simulated under predetermined atmospheric conditions in order to generate representative datasets. The inflow conditions are derived from precursor simulations performed with LES-ABL, ensuring realistic atmospheric inputs. Using this, the aeroelastic response of the turbine is analyzed using OpenFAST, an open-source simulation framework developed by the National Renewable Energy Laboratory (NREL). OpenFAST is a multi-physics, multi-fidelity tool for simulating the coupled dynamic response of wind turbines [27].

The case study in this thesis focuses on the aeroelastic performance of the IEA 22 MW offshore reference wind turbine. The analysis is carried out under three atmospheric conditions: neutral, stable, and unstable stratification. For each atmospheric stability condition, three wind speeds will be investigated: below rated, at rated, and above rated wind speed. These stability conditions have a direct influence

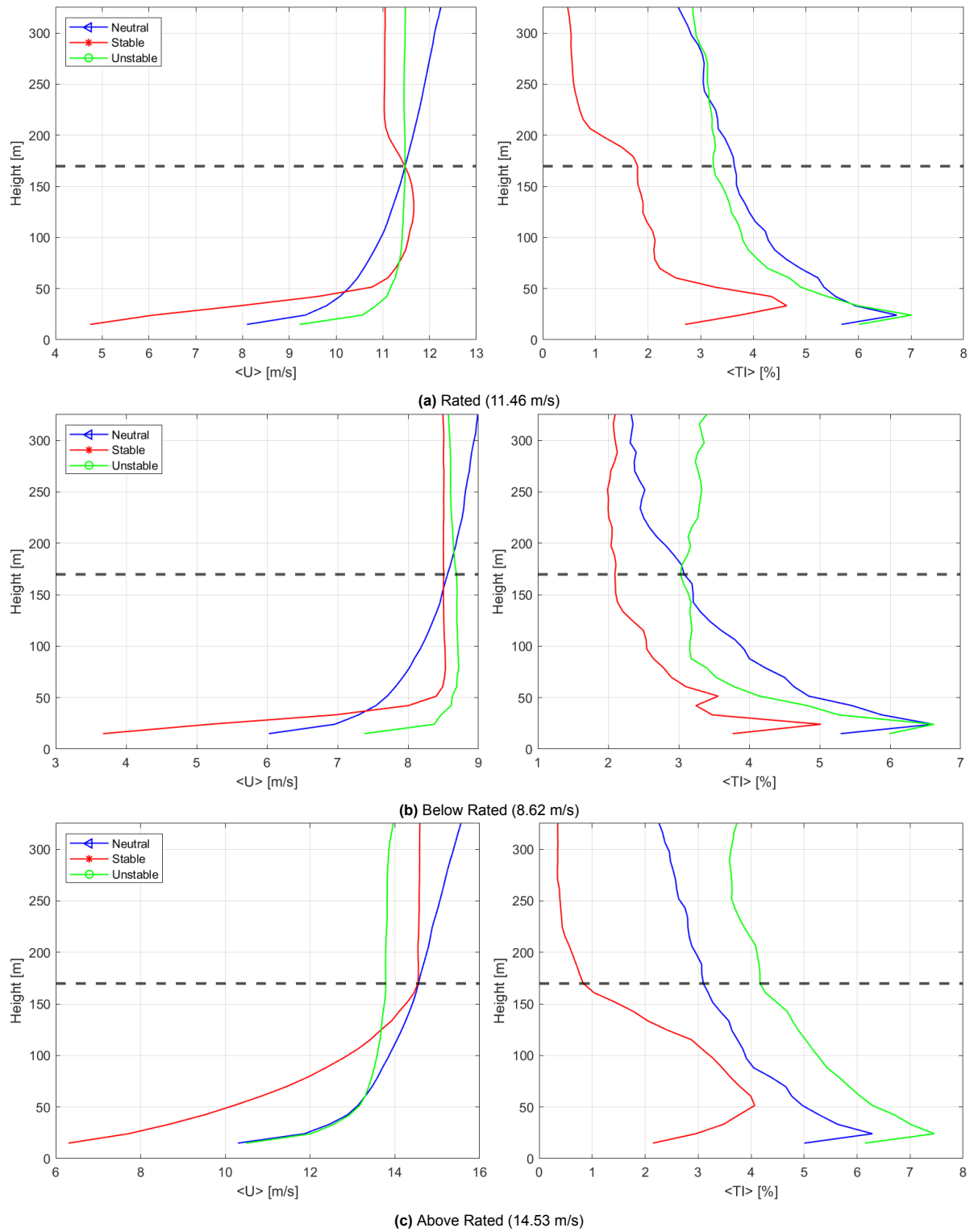


Figure 3.1: Inflow profiles for three wind speed operations and atmospheric stability classes, where U represents the horizontal wind velocity and TI the Turbulence Intensity. Black line represents the hub height for the IEA 22 MW reference turbine.

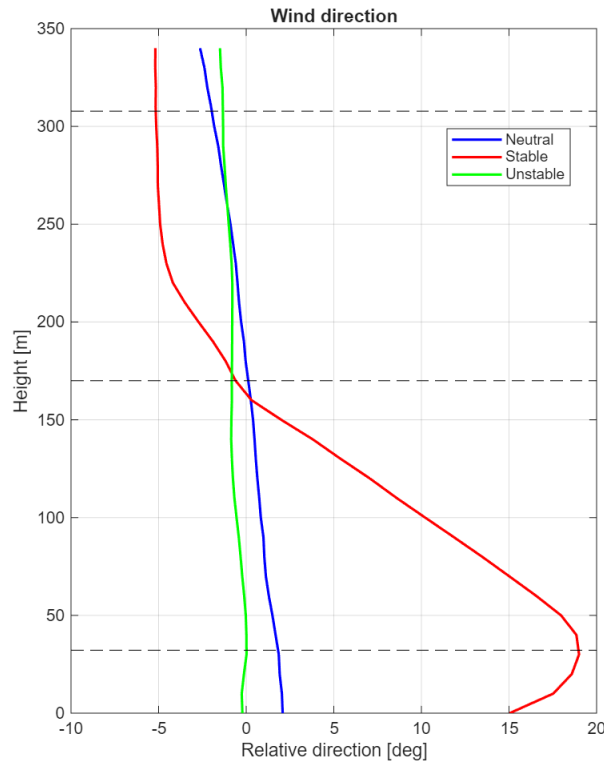


Figure 3.2: Wind direction for rated wind speed. Black lines represent the top end of the wind turbine, hub height, and the lowest end.

on wind shear, turbulence intensity, and wake behavior, thereby making them relevant to the research questions that were stated in chapter 1.2. OpenFAST contains various modules that are coupled to the tool. A brief explanation of the modules will be discussed here. Figure 3.3 shows the schematic of OpenFAST and how the modules are connected.

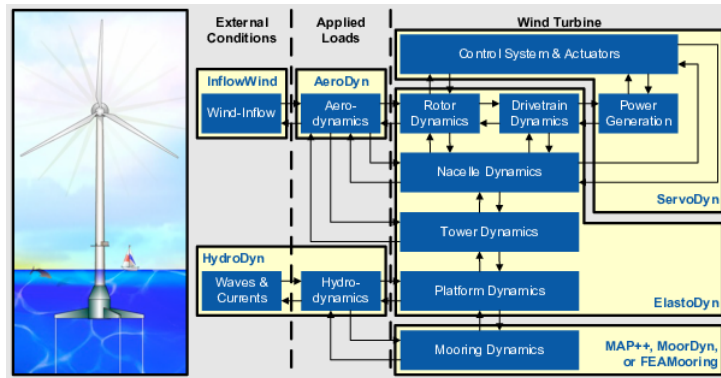


Figure 3.3: OpenFAST schematic [27].

3.4.1. Modules

InflowWind

The module InflowWind is responsible for processing the wind inflow. The module has the option to set the wind field to either uniform or to a predetermined full wind field file used as an input. The latter is called binary Bladed-style full-field (FF) and is used in this research. The binary wind files are inputted in OpenFast as a .wnd file, each wind file is accompanied by a text summary .sum file. The .wnd files contain normalized time-series data that are encoded as 2-byte integers, the wind speeds are described in the header NumGrid_Y and NumGrid_Z. The .sum files contain information on the grid on how they

are scaled. The interpolation method Taylor's frozen turbulence hypothesis is used to translate $V(y, z, t)$ to $V(x, y, z, t)$ by using the mean wind speed that is stored in the binary file as the advection speed. While for interpolating the grids, the trilinear interpolation scheme is used.

AeroDyn

The AeroDyn module is a time-domain module that can perform aeroelastic simulations. Aerodynamic loads are calculated based on actuator lines where the 3D flow is estimated by local 2D flows at the cross sections. Pressure and shear forces are approximated by the lift, drag forces, and pitching moments at the node in the cross section. The calculated distributed loads and moments are defined as loads per unit length along the 2D line. The discretization performed by AeroDyn may be independent by the nodes discretization of the structural modules. The actuator line approximation is only limited to slender structures, and 3D behavior like tip-loss or skewed-wake corrections must be implemented as corrections in the module or inside the input data. AeroDyn is also able to take into account for unsteady aerodynamics (UA). The UA models are considered as 2D dynamic corrections. There are three UA models: Beddoes-Leishman (B-L), extensions to the B-L developed by González, and extensions to the B-L model developed by Minnema/Pierce. Figure 3.4 shows how modules are integrated for AeroDyn.

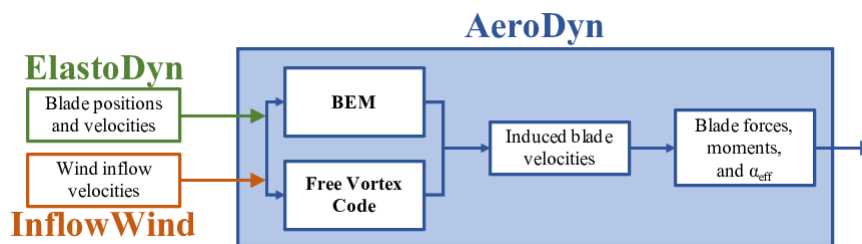


Figure 3.4: AeroDyn module integration [27].

ElastoDyn

The structural dynamics are modelled by the ElastoDyn module. It is a simplified blade model where it uses Euler-Bernoulli beam theory with assumed modes. The blades are modelled as straight and isotropic beams with limited geometric nonlinearities, only provide flapwise and edgewise bending deflections and no torsion, and can compute the velocities and accelerations. ElastoDyn uses the Kane's equations to determine the structural dynamics where it is updated at each timestep and receives directly the aerodynamic loads and control signals from AeroDyn and ServoDyn respectively. The degrees of freedom (DOF) can be set for the blade, as well as for the tower and platform. The module contains two flapwise-bending modes and one edgewise-bending mode coupled through the structural pre-twist, it however neglects axial, shear, and torsional DOF and the mass and elastic offsets from the pitch axis [60]. Some geometric and kinematic nonlinearities are accounted for, like the Coriolis and gyroscopic loading, radial shortening, and centrifugal [60].

BeamDyn

BeamDyn is a higher-fidelity blade model where it uses geometrically exact beam theory with Legendre spectral finite elements. It is developed to be used for slender structures where the ElastoDyn cannot accurately model it [15], [60]. Using the Legendre spectral finite elements, the six DOFs at each blade node are modeled and discretize the geometrically exact beam theory in the space domain to determine the large deflections, including bending, torsion, and shear [61]. The complete mass and stiffness matrices are used as input to model anisotropic composite materials, twisted and pre-coned configurations. A limitation of being a higher fidelity model compared to ElastoDyn is that using BeamDyn is more computationally expensive.

ServoDyn

The ServoDyn module is responsible for the control system of the turbine. It simulates blade pitch and generator torque controllers, which in turn regulate the power output and structural loads [27]. ServoDyn receives real-time feedback of rotor speed, blade pitch angle etc. from ElastoDyn, the signals are updated and passed back to AeroDyn and ElastoDyn. ROSCO (Reference Open Source Controller)

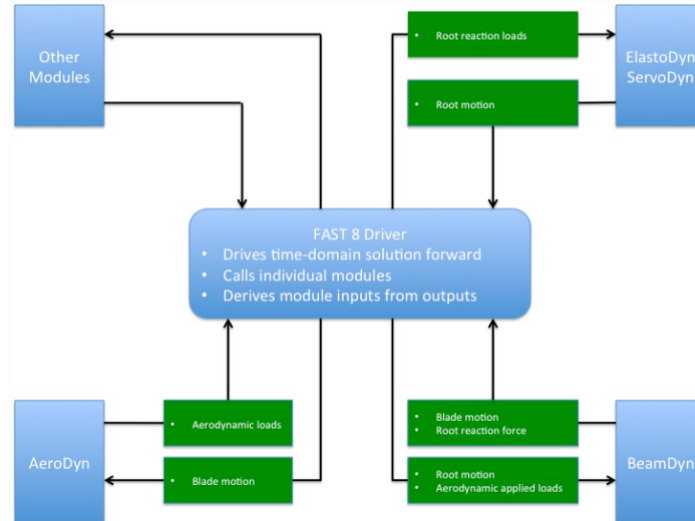


Figure 3.5: BeamDyn module integration [27].

is a wind turbine controller that ServoDyn uses to provide turbine control [1]. Like OpenFAST, ROSCO is developed using a Fortran-based structure so that it's compatible with communicating with OpenFAST, communication is done through the Bladed-style control interface. The controller input file is, in most cases, named "DISCON.IN" and only needs to be compiled once. A workflow diagram can be seen in figure 3.6.

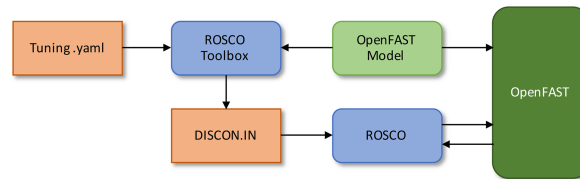


Figure 3.6: ROSCO workflow [1].

3.4.2. Input file settings

The aeroelastic simulations were performed using OpenFAST v3.5.4 where the reference turbine is modelled as a bottom-fixed monopile substructure. The simulation time step (Δt) has been tuned for each case to achieve numerical stability and convergence. Table 3.2 shows which (Δt) have been used for each case.

Table 3.2: Time steps (Δt) used for different operation wind speeds and atmospheric stability classes.

Stability Class	Rated	Below Rated	Above Rated
Neutral	0.0005s	0.0002s	0.0004s
Stable	0.0004s	0.0003s	0.0003s
Unstable	0.0003s	0.0003s	0.0004s

All simulations were run for a duration of 700 s so that the turbine can reach a steady operating state and the initial transient can be removed in the analysis. Structural dynamics are assessed using a combination of ElastoDyn and BeamDyn modules. ElastoDyn manages the DOF, these are the first and second fore-aft and side-to-side tower bending modes, drivetrain and generator DOFs, and the first two flapwise and first edgewise blade modes. BeamDyn manages the geometric nonlinearities and twisting as the IEA 22 MW turbine contains flexible blades due to the scale and slenderness. 50 defined blade nodes are defined. Initial conditions were prescribed to ensure numerical convergence, initial out-of-plane blade-tip deflection was set to 10 m to prevent tower strike during the startup phase. Initial blade pitch and rotor speed values were set according to the operational requirements specified

for each wind speed in the IEA 22 MW reference report [66]. Aerodynamic loads were computed by the AeroDyn v15 module using Dynamic Blade Element Momentum (BEM) theory. The model uses the Beddoes-Leishman (BL) Hansen-Guan-Madsen (HGM) 4-states unsteady airfoil aerodynamics model, utilizing a time-dependent τ_1 to resolve dynamic stall and delayed lift effects. The blade's aerodynamic profile was discretized in 59 airfoil polar files to capture chordwise and spanwise variations. Inflow conditions were provided through the InflowWind module and has been set to read binary bladed-style Full-Field (FF) files generated from the precursor LES. The turbine's control of the torque and pitch was governed by the ROSCO controller within the ServoDyn module.

3.4.3. Post-processing output files

Within the OpenFast modules, it can be decided which channels are desired to be outputted. The results are then written in .out files where it can be processed by Python. The first 300 s were not considered, as the turbine was still in the transient phase. Thus, only the remaining 400s are used for the analysis. Statistical analyses were then performed on the time-series, where the results are time-averaged to calculate the mean values and standard deviations to describe the steady state and load variability. Furthermore, spectral analysis was used to analyse the energy distribution.

Results & Discussion

This chapter will address both structural modelling fidelity and atmospheric inflow variability. Section 4.1 presents the validation of results, followed by Section 4.2 which presents the torsional DOF analysis, and finally the ABL stability analysis in Section 4.3.

4.1. Validation of results

It is important to validate the ABL wind field characteristics before using this for the analysis of the aeroelastic response of the wind turbine. This is to make sure that the structural and dynamic response of the turbine is correctly assessed. Figure 4.1 shows the PSD of the velocity fluctuations around the hub height for the rated wind speed. The lower frequencies represent the larger eddies in the PSD while the tail represents the smaller eddies. The higher frequency of the PSD shows good agreement with the $-5/3$ slope of the Kolmogorov spectrum [3]. Agreement with the slope can determine the LES's capabilities to reproduce the cascade of energy from larger to smaller scales [36]. It can therefore be concluded that the ABL inflow is correctly simulated since the eddies are reproduced in a correct way.

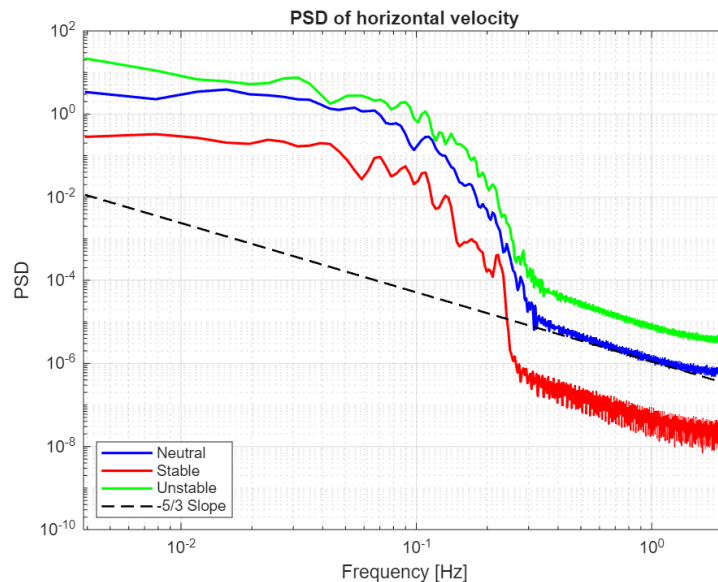


Figure 4.1: PSD of horizontal velocity fluctuations around the hub height area.

4.2. Effects of bend-twist coupling due to Torsional force

4.2.1. Aerodynamic Loads and Performance

Rotor Thrust To validate the load assessment, the results of the rotor thrust will be compared to the steady-state rotor performance reported in the design report of the IEA 22 MW turbine. In Figure 4.2 the timeseries of the rotor thrust calculated by ElastoDyn and BeamDyn can be seen for different operating conditions, alongside the mean. The first 300 s has been omitted from the analysis, as this is the transient phase of the wind turbine. The design report states that at a below rated wind speed of 8.62 m/s, the rotor thrust is 2346.25 kN, while at a rated wind speed of 11.46 m/s, the rotor thrust is 2656.25 kN and finally, for the above-rated at 14.53 m/s, the rotor thrust is 1917.50 kN [66]. These values are obtained from the steady-state inflow. When comparing to that of the OpenFAST results, it can be observed that both models consistently yield higher mean rotor thrust compared to the steady-state design report values across all operating conditions, with differences of approximately 14-22%. It is further observed that ElastoDyn overestimates the mean rotor thrust compared to that of BeamDyn. The physical reasoning behind this is due to the twisting that BeamDyn takes into account, which impacts the rotor performance. This is consistent with the results of Zhu et al. where it was concluded that torsion reduces the rotor thrust [67]. Another physical explanation behind this difference is due to the turbulent LES inflow used for the simulations that introduces fluctuations in wind speed and direction, in turn, this causes a higher angle of attack and therefore higher loads. Before analyzing the aerodynamic loads, an analysis of the angle of attack and induction factor is first needed.

Angle of Attack and Axial Induction Factor Figure 4.3 displays the angle of attack plotted against the normalized blade span of the rotor blade across all of the operating wind speeds. In the first 60% of the blade span in the below-rated condition, the structural models seem to agree with each other. It is only after this part of the blade that the models differ in determining the angle of attack, where ElastoDyn overestimates the angle of attack of the rotor blade, and this is consistent with all of the operating wind speeds. This is expected since the ElastoDyn model does not take into account the bend-twist coupling of the rotor blade. Because ElastoDyn models the blade as a straight and isotropic beam [60], it affects the natural twisting of the blade in the inner part, where it can be seen that the angle of attack for ElastoDyn is slightly lower compared to BeamDyn. This is consistent with the results of Trigaux, Chatelain, and Winckelmans where the results indicated that flexibility reduces rotor performance [57]. The point of twisting of the rotor blade is at around 67% of the blade span, where towards the inner part of the blade from this point the blade pitches to stall, while from this point to the tip of the blade pitching to feather occurs. Table 4.1 shows the statistics of the angle of attack comparison of the models at 80% blade span. Here it can be seen that ElastoDyn overestimates the mean angle of attack in all operating conditions. Another interesting note is that the standard deviation of BeamDyn across all wind speeds is slightly higher, the twisting of the blade seems to capture the turbulent field much more accurately. At above-rated conditions, the strength of the wind speed completely takes over the performance of the wind turbine. The overestimation of the mean values of the angle of attack implies that the aerodynamic loads will be overestimated as well. Before analyzing the loads, the axial induction factor needs to be examined.

Table 4.1: Angle of Attack statistics summary at 80% of blade span

Case	Model	Mean [°]	Std Dev [°]	Min [°]	Max [°]
Below Rated	ElastoDyn	10.53	0.26	9.79	11.50
	BeamDyn	8.27	0.41	7.12	9.32
Rated	ElastoDyn	5.21	0.42	4.00	6.30
	BeamDyn	4.15	0.61	2.59	5.78
Above Rated	ElastoDyn	2.02	0.30	0.89	3.17
	BeamDyn	1.09	0.30	-0.12	2.27

Figure 4.4 shows the axial induction factor plotted against the normalized blade span. Similar observations can be made as for figure 4.3. In all operating wind speeds, ElastoDyn overestimates the induction factor at the tip area. In below-rated condition, the two structural models diverge around the 40% area

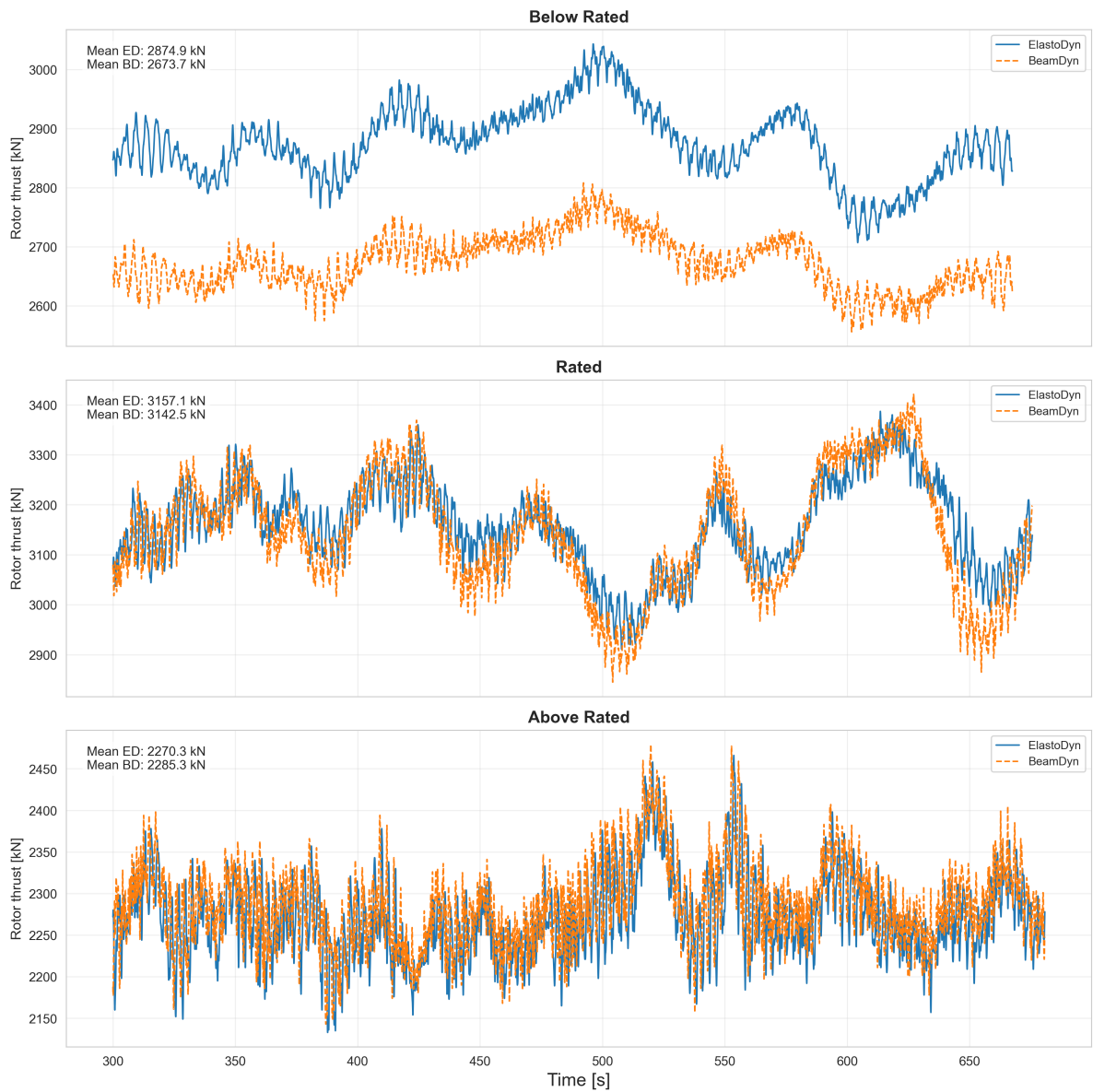


Figure 4.2: Timeseries of rotor thrust with mean.

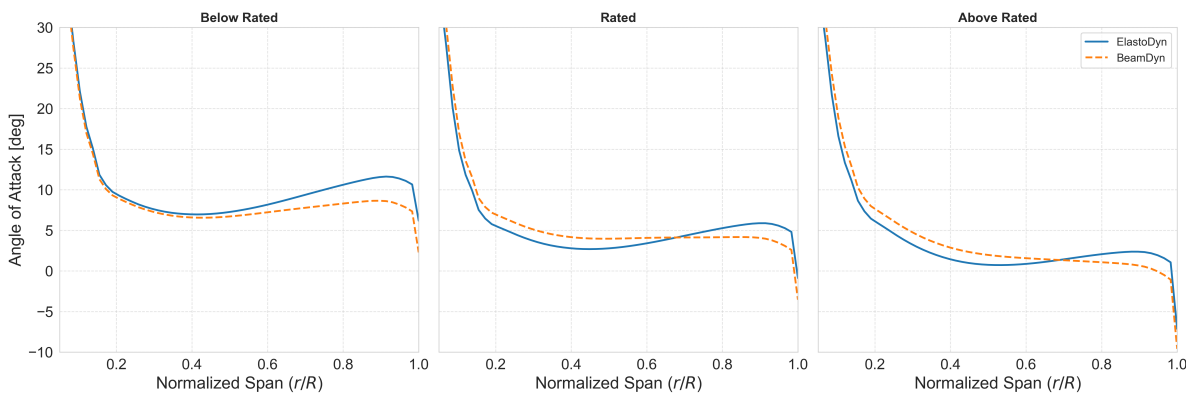


Figure 4.3: Angle of Attack vs the normalized blade span.

of the blade span. Due to the overestimation of the induction factor, the rotor thrust for below-rated wind speed is in turn being overestimated, as can be seen in figure 4.2. An important note is that the mean induction factor for ElastoDyn calculated at 80% of the blade span is 0.452 in below-rated condition, while BeamDyn yields 0.327. The Betz Limit states that the maximum achievable power is when the axial induction factor yields $1/3$ [4]. BeamDyn is well within this limit, the physical reasoning on why ElastoDyn overestimates this value is due to the overprediction of power. In all other cases, both models agree until around the 10% area of the blade. Table 4.2 shows the statistics summary of the induction factor at 80% blade span. The overprediction of the induction factor will influence the tangential aerodynamic forces.

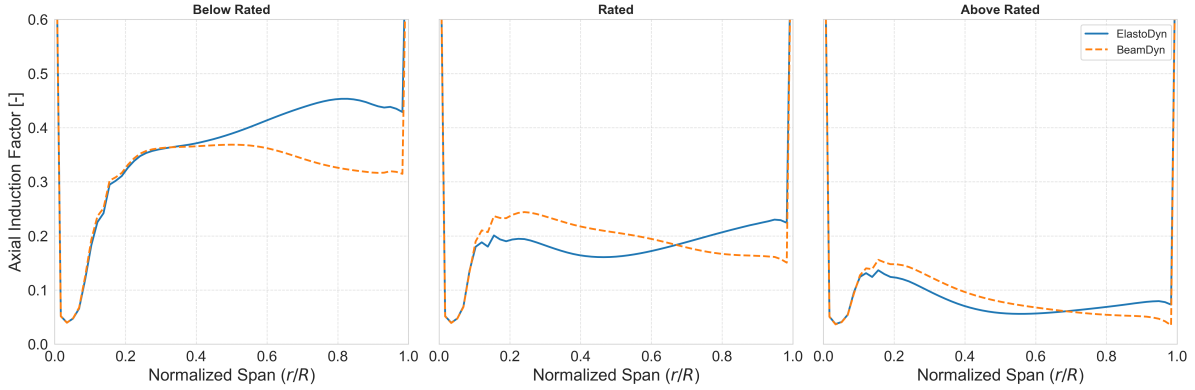


Figure 4.4: Axial induction factor vs the normalized blade span.

Table 4.2: Axial Induction Factor Statistics Summary

Case	Model	Mean [-]	Std Dev [-]	Min [-]	Max [-]
Below Rated	ElastoDyn	0.452	0.021	0.380	0.507
	BeamDyn	0.327	0.030	0.271	0.429
Rated	ElastoDyn	0.205	0.015	0.164	0.253
	BeamDyn	0.167	0.018	0.126	0.234
Above Rated	ElastoDyn	0.068	0.004	0.059	0.081
	BeamDyn	0.054	0.004	0.045	0.071

Aerodynamic Axial and Tangential load Figure 4.5 shows the axial aerodynamic load vs the normalized blade span. The models agree until around 40% of the blade span until it starts to diverge. For the other operating wind speeds, the structural models are not in agreement with each other. In all cases, ElastoDyn overestimates the load on the tip area. This is expected since the tip part of the blade pitches to feather and decreases the angle of attack (as seen in figure 4.3), thereby yielding lower lift force and in turn, lower axial force. The inner part of the blade is where ElastoDyn underestimates the axial force due to accounting for the twisting that causes the pitching to stall where it increases the angle of attack. At higher wind speeds, there are larger variations in forces than compared to below-rated wind speeds. In the study of Trigaux, Chatelain, and Winckelmans [57], it was found that rigid blades overestimate loads compared to that of a flexible blade [57]. The results found in this thesis are consistent with those of Trigaux, Chatelain, and Winckelmans.

The tangential aerodynamic forces can be seen in figure 4.6, where these are once again plotted against the normalized blade span. Similar observations can be made as for figure 4.5 where the two models are not completely in agreement with each other. For the below-rated wind speed, ElastoDyn agrees with BeamDyn until around the 40% blade span, after that the two models diverge. ElastoDyn strongly overestimates the tangential load in the below-rated wind speed case. It can be further observed that for the rated and above-rated case, ElastoDyn underestimates the load in the inner part of the blade while overestimating the load in the tip region. This is consistent with the results of Trigaux, Chatelain, and

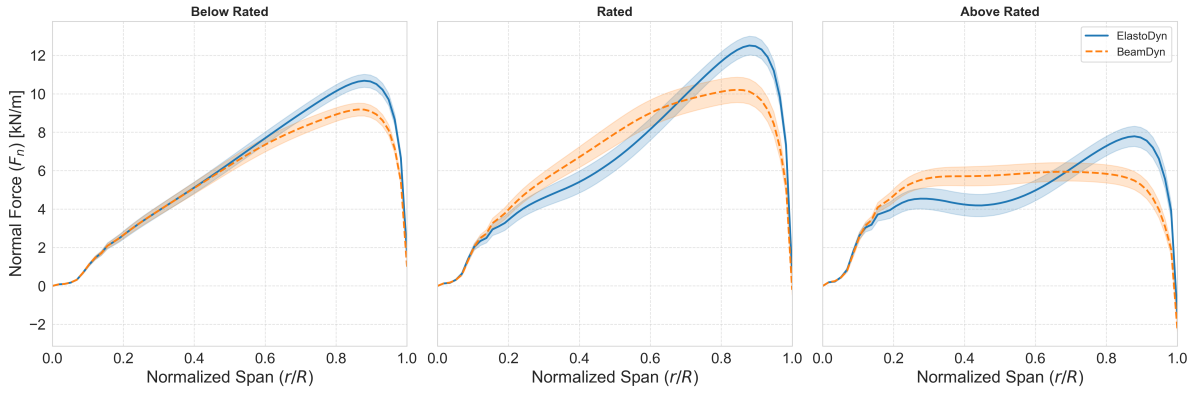


Figure 4.5: Axial aerodynamic load vs the normalized blade span. The shaded area represents the standard deviation.

Winckelmans. In the study of Trigaux, Chatelain, and Winckelmans, the tangential load predicted for a rigid blade yields underestimates in the inner part of the blade while overestimates in the tip region [57]. The disagreement between the load prediction has consequences on the tip deflection of the blade. A higher load implies a higher deflection, this will be further examined in the next section.

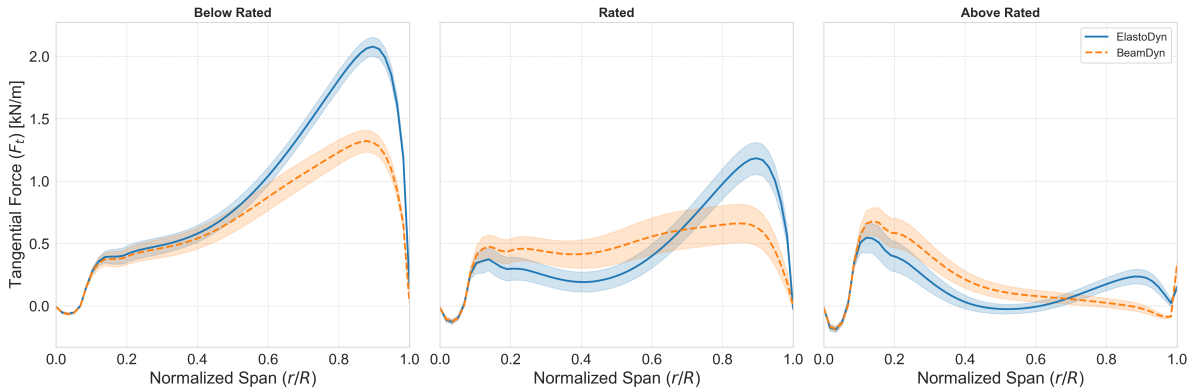


Figure 4.6: Tangential aerodynamic load vs the normalized blade span. The shaded area represents the standard deviation.

4.2.2. Blade Dynamic Response

Flapwise deflection The timeseries of the maximum flapwise tip deflection can be seen in figure 4.7. The first 300 s of the simulation has been once again filtered to remove the transient phase of the wind turbine before time-averaging the tip deflection. Overall, the mean tip deflection in the ElastoDyn model is slightly higher than that of BeamDyn. This is expected due to the overestimation of the axial load, as seen in figure 4.5. Both models exhibit oscillating motion during the simulation. The tip deflection in the ElastoDyn model varies more than that of BeamDyn.

Figure 4.8 shows the flapwise deflection along the normalized blade span. In all cases, ElastoDyn overestimates the flapwise deflection slightly compared to BeamDyn, this is due to the fact that tip deflection in the flapwise direction is caused by the thrust and axial forces, which ElastoDyn overestimates. In the below-rated operating wind speed, both models seem to agree with each other until the 40% blade span area. After that, the models diverge. In the rated wind speed condition, the models diverge starting around the 55% blade span. This is similar for the above-rated wind speed condition. The tip deflection difference is the largest for the above-rated case, with a difference of 6.24%. The maximum tip deflection of 19.7 m for the BeamDyn case is more than 14% of the blade radius, which is a significant amount. This displays how increased flexibility in blades impacts the deformation. Another type of deformation that is impacted is the torsional deflection, which will be discussed in the next section.

Figure 4.9 shows the phase-averaged flapwise tip deflection of the rotor blade. Table 4.3 displays the

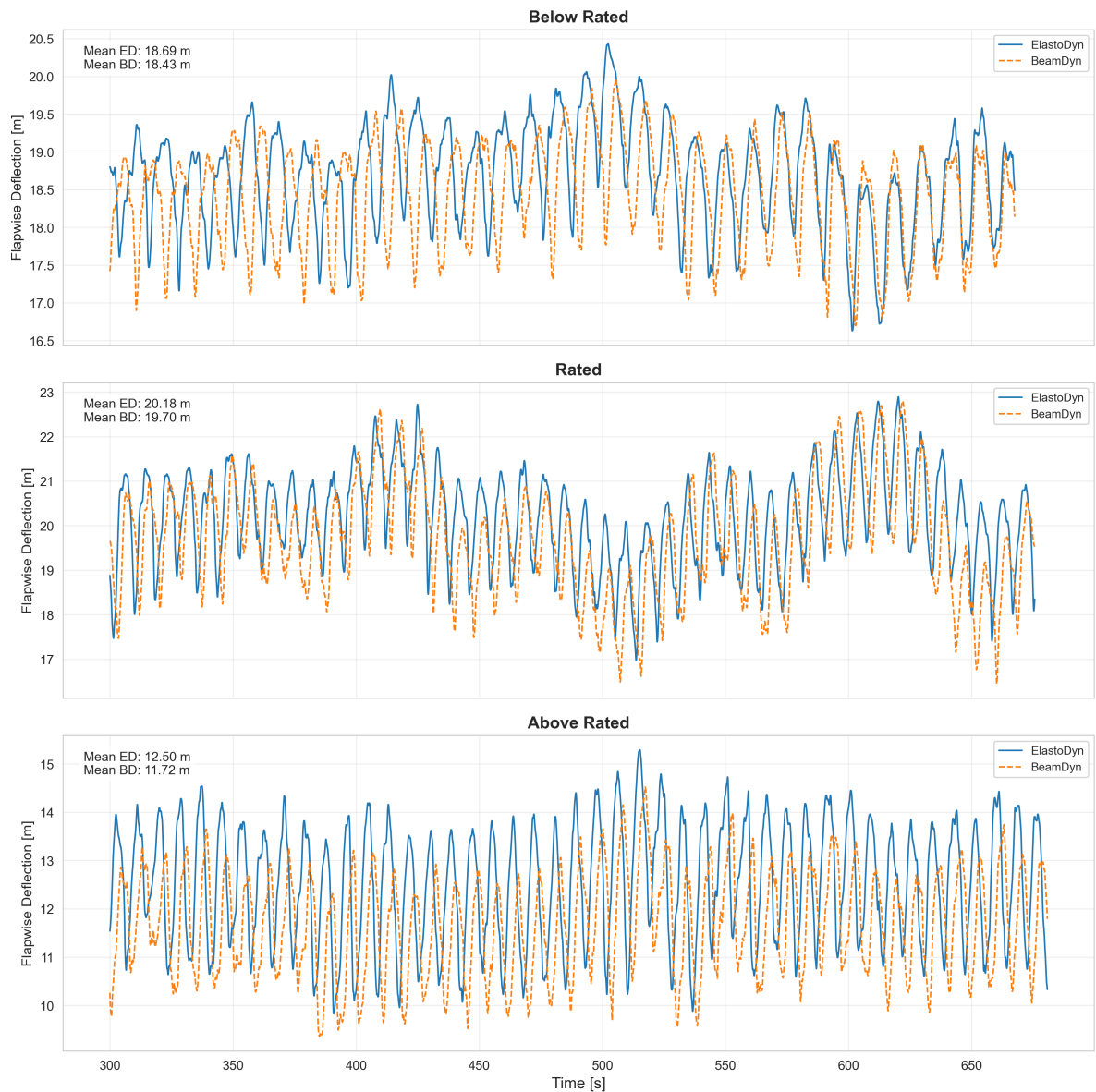


Figure 4.7: Timeseries of the flapwise tip deflection of the rotor blade

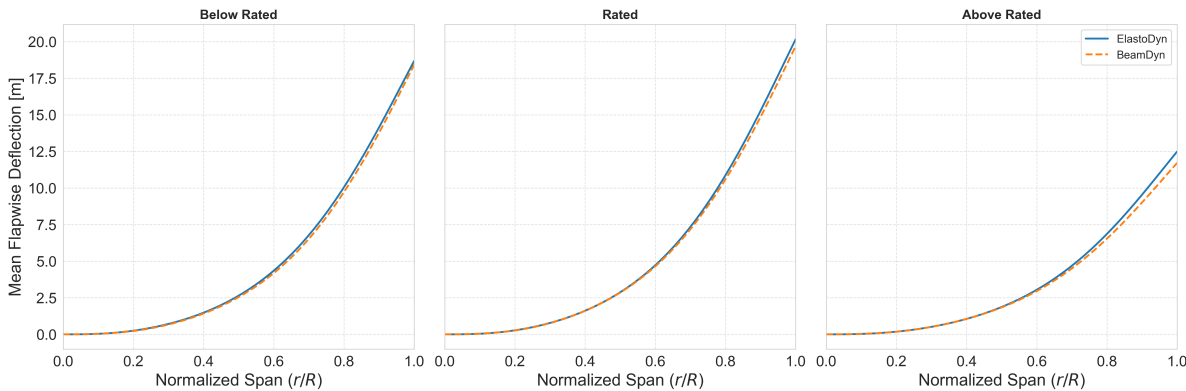


Figure 4.8: flapwise deflection of the rotor blade along the blade span

statistical values of the flapwise tip deflection where the mean, standard deviation, and the minimum and maximum are calculated. It can be seen that overall ElastoDyn shows a higher mean for the tip deflection across all operating conditions. The variability in the rated and above-rated conditions is similar. The variability is the lowest in the below-rated condition. Both models display a similar oscillatory motion across the azimuthal plane, where the lowest tip deflection occurs past the tower, while the highest occurs around the 45° angle.

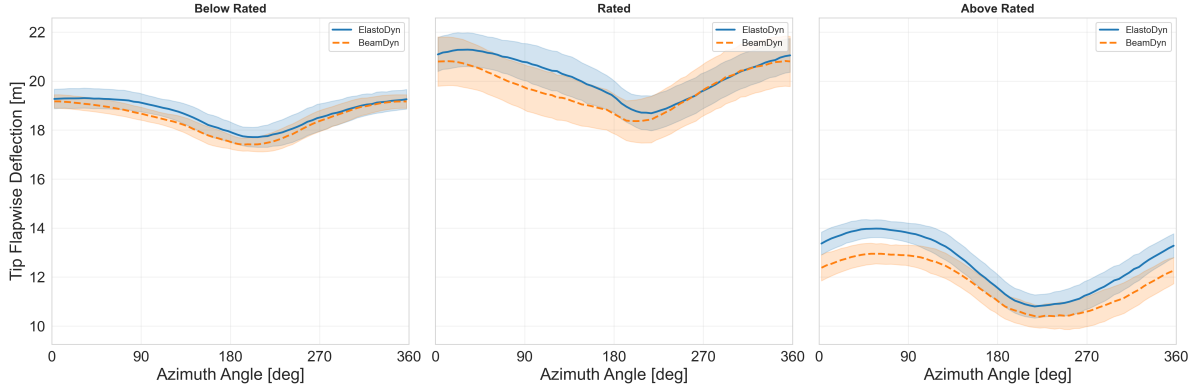


Figure 4.9: Phase average of the flapwise tip deflection of the rotor blade

Table 4.3: Blade Tip Flapwise Deflection Statistics Summary

Case	Model	Mean [m]	Std Dev [m]	Min [m]	Max [m]
Below Rated	ElastoDyn	18.69	0.70	16.63	20.43
	BeamDyn	18.43	0.68	16.70	19.96
Rated	ElastoDyn	20.18	1.10	16.97	22.89
	BeamDyn	19.70	1.25	16.45	22.79
Above Rated	ElastoDyn	12.50	1.23	9.83	15.29
	BeamDyn	11.72	1.08	9.35	14.52

The PSD of the flapwise tip deflection is determined and plotted in figure 4.10. Alongside the PSD, the flapwise modes are displayed in the figure, these are obtained from the IEA 22 MW reference turbine design report [66]. It can be observed that both models have significant peaks in the lower frequency range. The tip deflection in the BeamDyn model coincides with the 1P in all operating conditions, while for the ElastoDyn model, it only does so in the above-rated wind speed condition. At the 3P, the peaks of BeamDyn in all operating conditions coincide as well, where in only the above-rated condition ElastoDyn coincides alongside. This indicates that ElastoDyn exhibits different values for its frequencies.

Torsional Deflection Figure 4.11 shows the timeseries of the tip torsional deflection of the blade. The first 300s has been filtered to remove the transient phase. The torsional deflection is negative across all operating conditions, confirming that the blade tip pitches toward feather in the nose-down direction under aerodynamic loading. This is consistent with Zhu et al. [67], who explained that under a negative torsional moment, the blade twists toward feather in the nose-down direction, which reduces the local angle of attack (as seen in figure 4.3) and consequently lowers the aerodynamic loading (as seen in figure 4.5 and 4.6, resulting in reduced flapwise bending deformation compared to a rigid blade [67]. Furthermore, Zhu et al. note that torsional deformation is primarily governed by the torsional moment itself rather than by centrifugal force. The mean torsional deflection is largest at rated conditions and smallest at below rated, this is expected as the largest tip deflection occurs in the rated condition, as seen in figure 4.8 where the large tip deflection implies a higher bending moment in the root of the rotor blade. The torsional deflection along the normalized blade span is shown in figure 4.12. The torsional twist is the highest in the rated operating condition, followed by the above-rated, and then the lowest is the below-rated. An explanation for why the torsional twist is lower than that of the rated wind speed

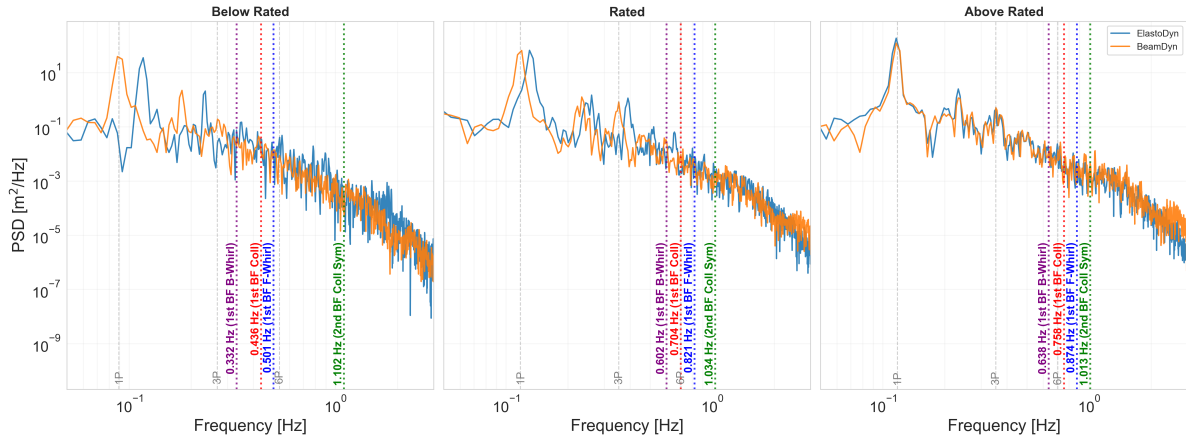


Figure 4.10: PSD of the flapwise tip deflection

is that the blade pitching mechanism pitches the rotor blade higher in above-rated wind speeds. For all operating conditions, the torsional deflection displays a similar oscillating character driven by the turbulent inflow, with the standard deviation remaining small relative to the mean across all cases, as shown in Table 4.4.

As previously stated, the torsional deformation implies a reduced flapwise bending [67]. This will be further examined in the next section.

Table 4.4: Torsional tip deflection statistics summary

Case	Mean [°]	Std Dev [°]	Min [°]	Max [°]
Below Rated	-3.89	0.29	-4.53	-3.28
Rated	-5.20	0.42	-6.15	-4.27
Above Rated	-4.80	0.16	-5.27	-4.19

The PSD of the torsional tip deflection is determined and plotted in figure 4.13. Alongside the PSD, the torsion mode is displayed in the figure, this is obtained from the IEA 22 MW reference turbine design report [66]. It can be observed that both models have significant peaks in the lower frequency range. The tip deflection in the BeamDyn model coincides with the 1P in all operating conditions. At the 3P, the peaks of BeamDyn in all operating conditions coincide as well.

4.2.3. Blade Structural Response

Flapwise Blade Root Moment Figure 4.14 displays the phase-averaged flapwise root bending moment plotted against the azimuthal angle. It can be seen in all operating wind speeds, that ElastoDyn overestimates the root moment of the rotor blade in the flapwise direction. The overestimation occurs due to the overestimation of the thrust and axial force. Furthermore, ElastoDyn does not model the root moment in the below-rated condition realistically, as it is almost constant in the whole rotation, except where it slightly drops due to a decrease in wind speed when the blade passes the tower. The flapwise bending moment is reduced in the BeamDyn case due to the torsional influence, as it was discussed in the previous section. This was expected and is consistent with the findings of Zhu et al. [67].

The variations of the root bending moment can be seen in the PDF displayed in figure 4.15, the calculated statistics values can be seen in table 4.5. It can be observed that ElastoDyn exhibits lower variations in root bending moment compared to BeamDyn since the standard deviation is lower. The mean root bending moment differences become smaller as the wind speed increases. Furthermore, BeamDyn PDF almost displays a more symmetric plot when compared to ElastoDyn PDF. Overall, BeamDyn captures the fluctuations more realistically than that of ElastoDyn.

The PSD of the flapwise root bending moment of the blade is determined and plotted in figure 4.16 as

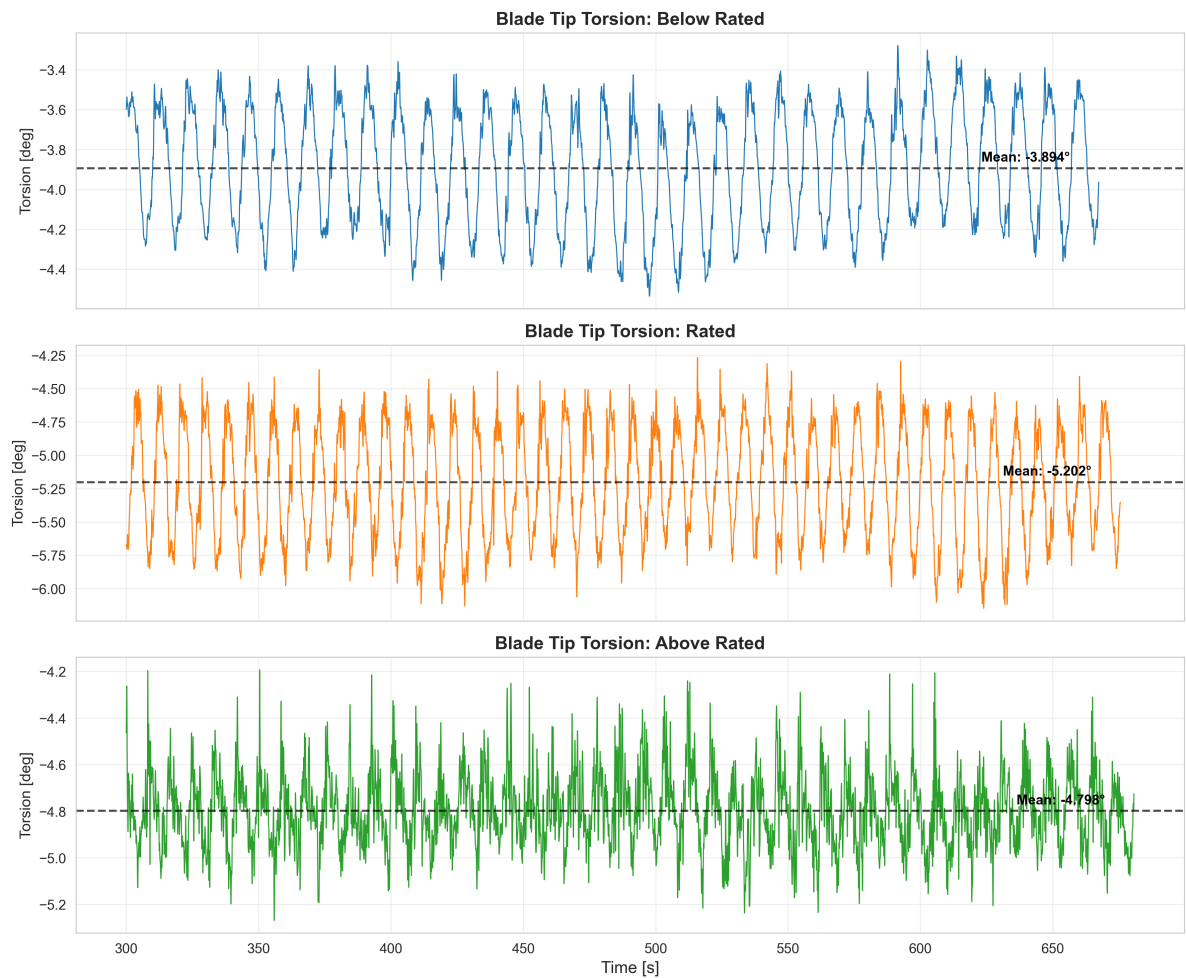


Figure 4.11: Timeseries torsional tip deflection

Table 4.5: Flapwise toot bending moment statistics summary

Case	Model	Mean [kN-m]	Std Dev [kN-m]	Min [kN-m]	Max [kN-m]
Below Rated	ElastoDyn	78579.17	2185.14	70680.00	84270.00
	BeamDyn	72106.62	4533.77	60970.00	81370.00
Rated	ElastoDyn	87238.85	4723.69	73130.00	98100.00
	BeamDyn	82985.35	6730.33	65420.00	97550.00
Above Rated	ElastoDyn	60028.07	6765.64	43360.00	73970.00
	BeamDyn	56184.05	9303.54	36870.00	74080.00

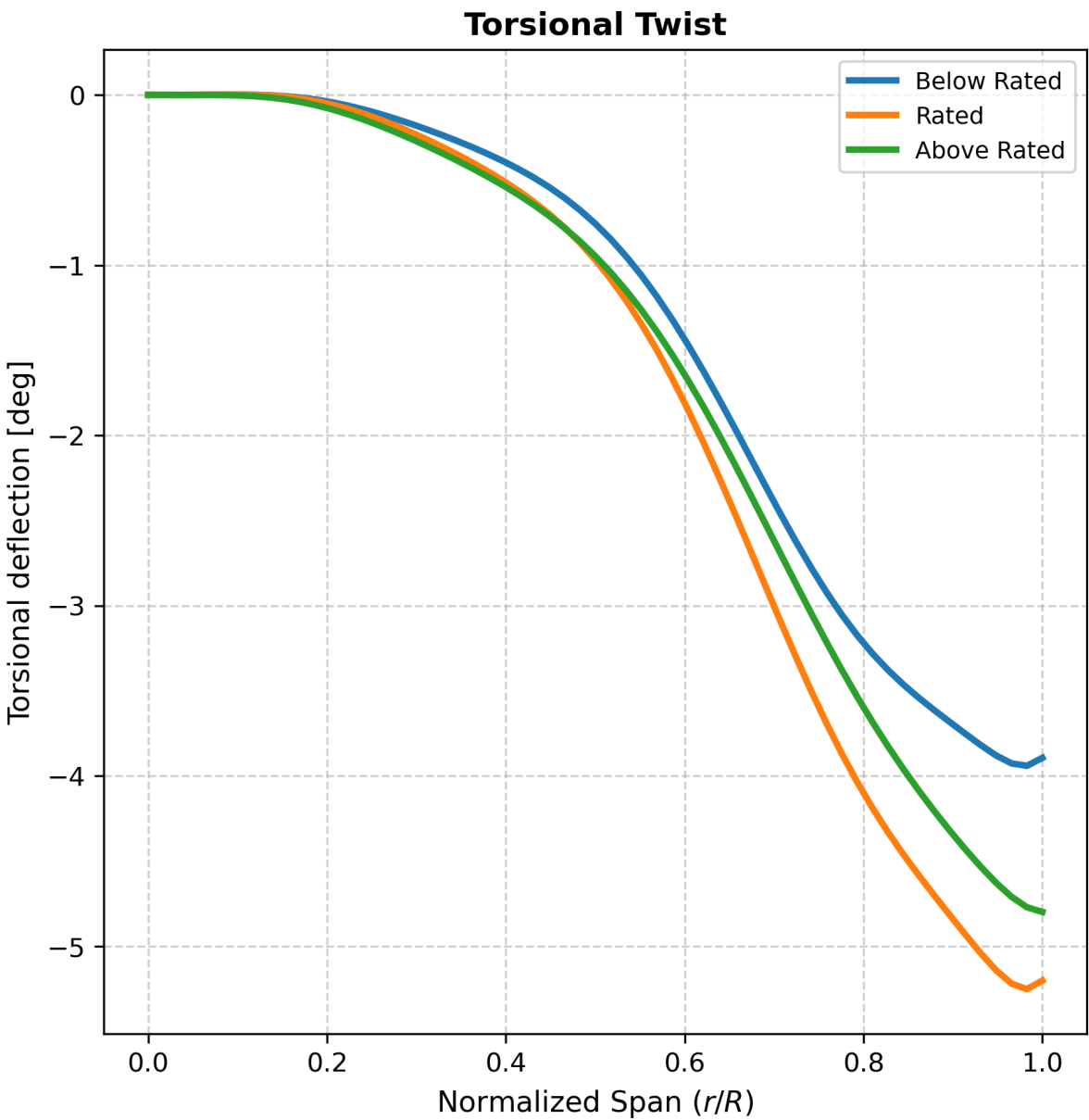


Figure 4.12: Torsional deflection along the blade span

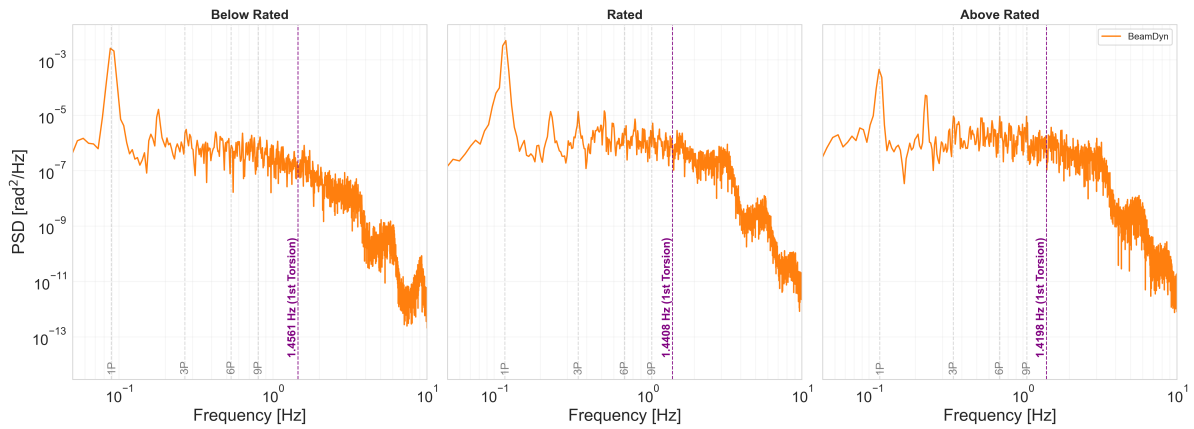


Figure 4.13: PSD torsional tip deflection

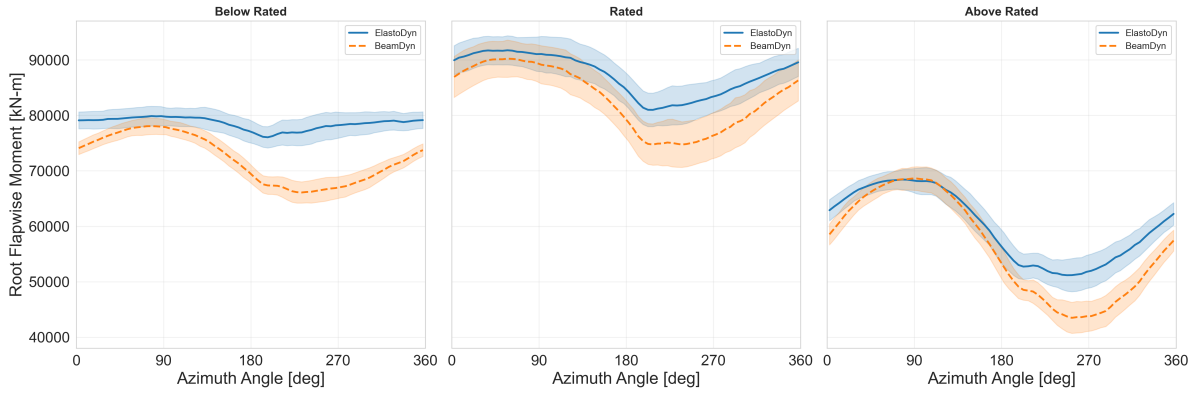


Figure 4.14: Phase averaged flapwise root bending moment

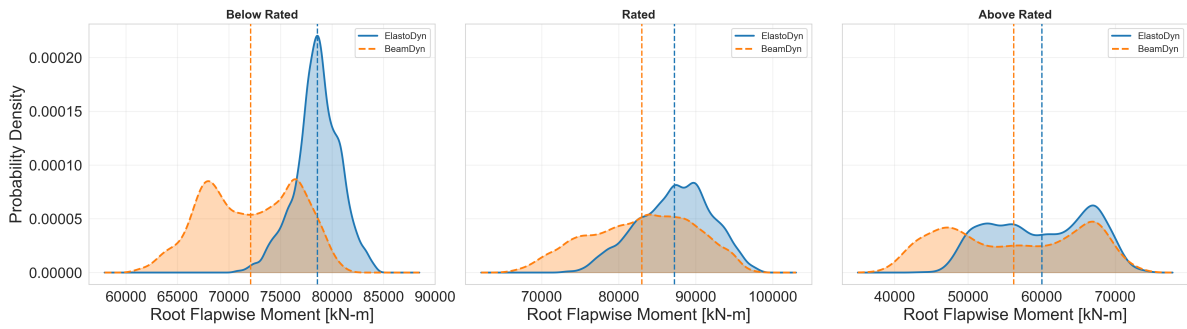


Figure 4.15: PDF flapwise root bending moment

well as the 1P, 3P and 6P frequencies. Overall, both models display distinct peaks at the blade-passing frequencies. BeamDyn shows a higher energy spectrum in the lower frequency range in the below-rated wind speed condition. As the wind speed increases, the peaks match more closely. BeamDyn captures more energy in the higher frequency range when compared to ElastoDyn.

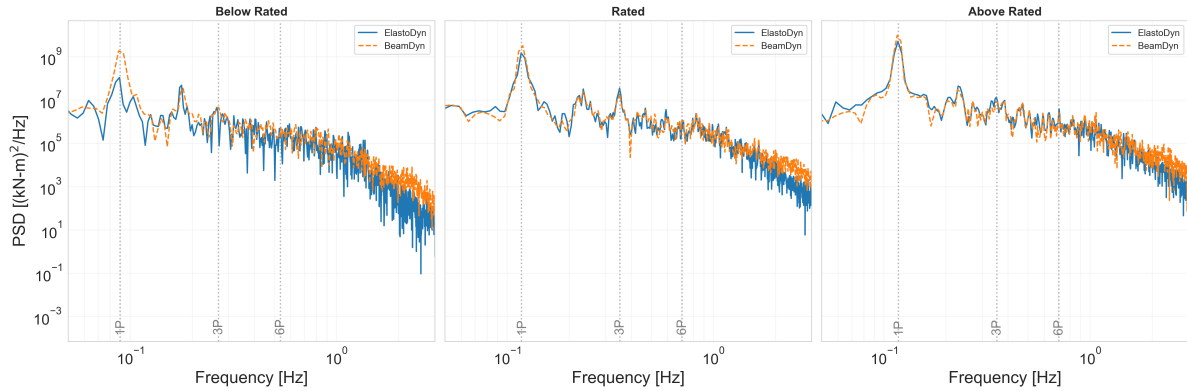


Figure 4.16: PSD flapwise root bending moment

4.2.4. Tower Base Loads

To understand how the bend-twist coupling of the rotor blade affects the tower base, a statistical and spectral analysis will be performed. Figure 4.17 and 4.18 displays the PDF of the tower base moment in the fore-aft and side-side motion. The statistical values are displayed in table 4.6. It can be observed that the structural models are quite close in agreement for the rated and above-rated wind speed conditions. It is only for the below-rated case where the differences are apparent. The fore-aft moment is much higher predicted in the ElastoDyn model due to an overestimation of the axial and

thrust loads. For the side-side motion, ElastoDyn seems to underestimate the moment.

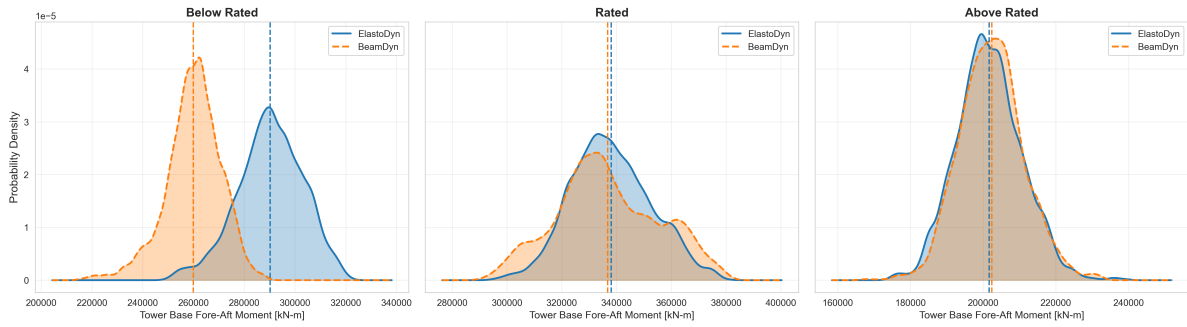


Figure 4.17: PDF Fore-aft moment tower base

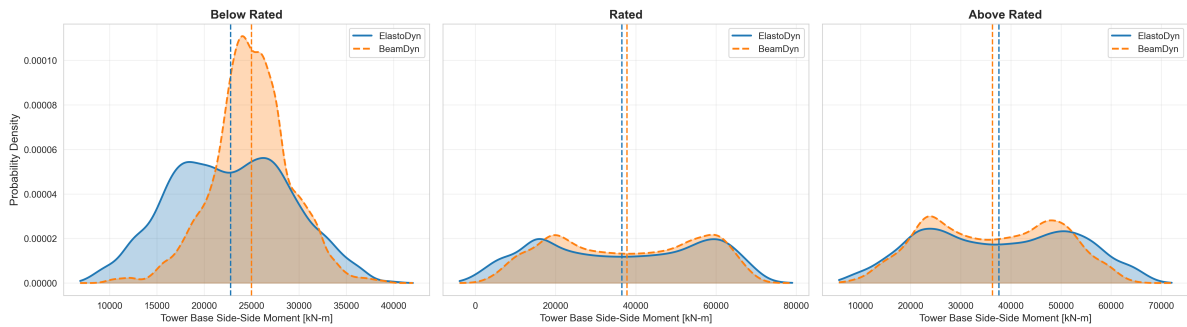


Figure 4.18: PDF Fore-aft moment tower base

Figure 4.19 and 4.20 show the PSD of the tower base moments in the fore-aft and side-side directions. The peaks that can be seen in both of the fore-aft and side-side figures coincide with the blade passing frequency 3P and 6P. As the wind speed increases, the energy spectra of the two structural models come closer in agreement.

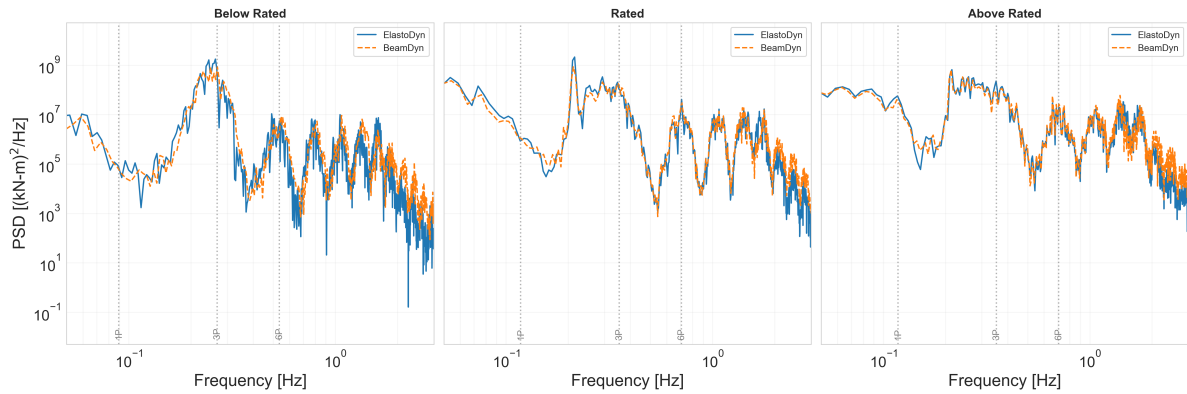


Figure 4.19: PSD Fore-aft moment tower base

4.2.5. Fatigue

The Damage Equivalent Load (DEL) of the flapwise blade root moment is calculated and plotted in figure 4.21, the point values can be seen in table 4.7. The last column in table 4.7 represents the difference in values for the Ultimate Load Ratio 1.0. In all cases, it can be observed that BeamDyn consistently contains higher DEL values than ElastoDyn at all load ratios. This is caused by the bend-twist coupling effect, as it introduces rapid vibrations in the wind turbine's lifespan. The constant twisting adds to the mean stress of the blade, which contributes to the total fatigue damage [54]. Furthermore, the higher calculated DEL for BeamDyn is expected and consistent with the results of Sirigu et al.,

Table 4.6: Tower base loads statistics summary

Direction	Case	Model	Mean [kN-m]	Std Dev [kN-m]	Min [kN-m]	Max [kN-m]
Fore-Aft	Below Rated	ElastoDyn	290238.57	12884.42	249800.00	322000.00
		BeamDyn	259963.23	10871.62	215100.00	289400.00
	Rated	ElastoDyn	338045.83	14618.10	295400.00	380200.00
		BeamDyn	336758.73	18662.29	290900.00	381200.00
	Above Rated	ElastoDyn	201666.40	9014.15	173800.00	239800.00
		BeamDyn	202376.54	8834.04	166800.00	233100.00
Side-Side	Below Rated	ElastoDyn	22786.19	6228.07	7256.00	40030.00
		BeamDyn	24978.90	4117.34	9540.00	39100.00
	Rated	ElastoDyn	36537.28	20071.50	-4130.00	75250.00
		BeamDyn	37792.10	18006.21	2380.00	71150.00
	Above Rated	ElastoDyn	37603.01	14807.83	6004.00	68650.00
		BeamDyn	36343.00	12847.75	6444.00	64910.00

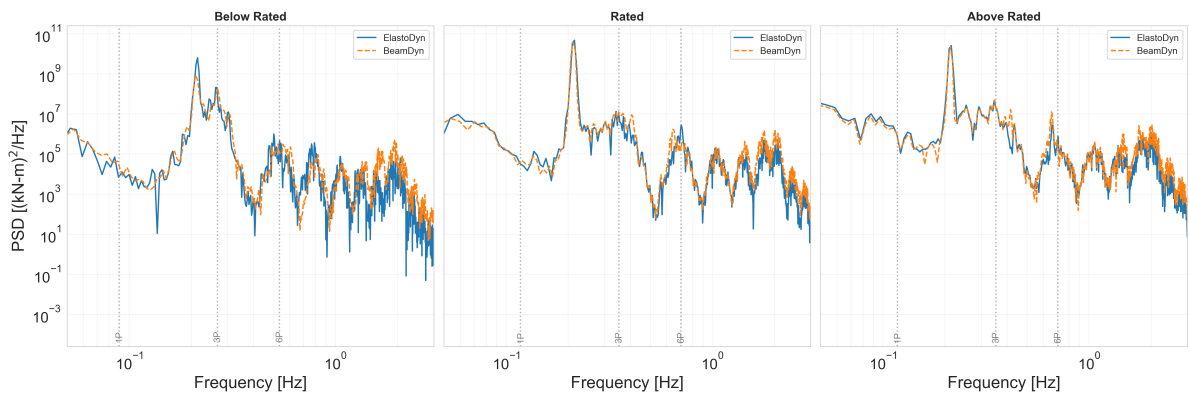


Figure 4.20: PSD Side-side moment tower base

where the author compared DEL values calculated for BeamDyn and ElastoDyn cases [44]. At the Ultimate Load Ratio of 0.2, the difference is 64% for the below-rated case between the two structural models. This difference converges as the amplitude cycle increases to a difference of 7.9%. This convergence occurs the same for the rated and above-rated cases, where the differences are 1.7% and 4.1%, respectively. At the high load ratios of 0.9 and 1.0, the DEL is dominated by the largest amplitude cycles in the load history. The implication that ElastoDyn and BeamDyn produce similar values for the DEL is that the largest load cycles in both models are comparable in amplitude, regardless of torsional influence.

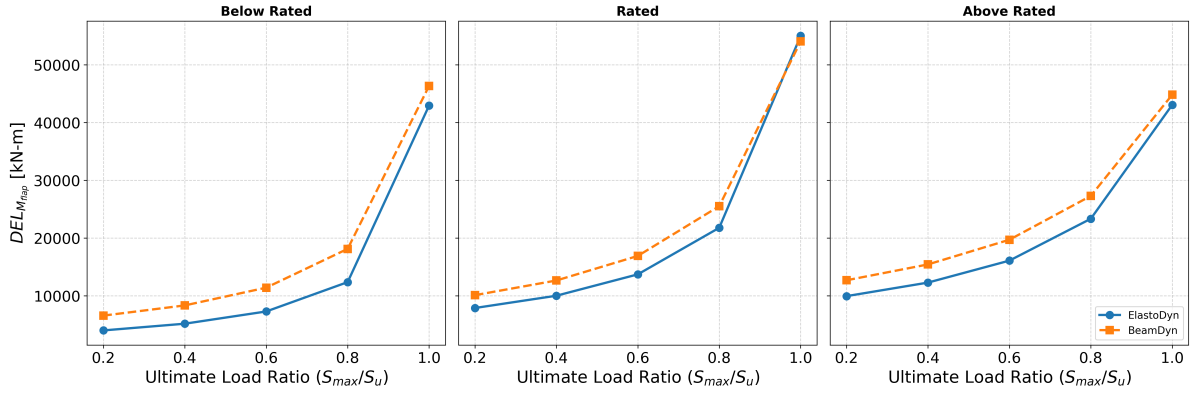


Figure 4.21: DEL of the flapwise blade root bending moment

Table 4.7: DEL point values for the flapwise bending root moment

Condition	Model	S_{max}/S_u Ratio					Δ [%]
		0.2	0.4	0.6	0.8	1.0	
Below Rated	ElastoDyn	4002	5166	7286	12369	42953	+7.9%
	BeamDyn	6567	8334	11410	18131	46353	
Rated	ElastoDyn	7885	10012	13712	21777	55017	-1.7%
	BeamDyn	10109	12650	16904	25519	54055	
Above Rated	ElastoDyn	9940	12286	16089	23341	43071	+4.1%
	BeamDyn	12686	15432	19704	27296	44824	

4.3. Effects of Atmospheric Boundary Layer Stability

4.3.1. Aerodynamic Loads and Performance

Rotor Thrust Figure 4.22 presents the phase-averaged rotor thrust plotted against the azimuthal angle for the three atmospheric stability classes for the three operating wind conditions: below rated, rated, and above rated. The shaded areas represent the standard deviation around the phase-averaged mean, these reflect the variability introduced by the turbulent inflow characteristic of each stability class. At below-rated conditions, the characteristics of the unstable ABL dominate the generated rotor thrust force. Due to the higher turbulence intensity, the convective boundary layer contains an increase in velocity fluctuations, which in turn affects the aerodynamic loading. The rotor thrust for the neutral and stable ABL seems to come in close agreement, this implies that wind shear, which is more dominant in stable ABL, has a lesser impact in below-rated wind speed conditions. In rated operating condition, the means for all stability classes are close in agreement, where the only difference is in the variability. Neutral and unstable have a much higher varying standard deviation than stable ABL. This is explained by the higher available turbulence. At above-rated condition, the thrust force in the unstable ABL is once again dominated by the much higher turbulent wind field. It can be observed that the mean thrust force in the stable case is higher than for the neutral case, implying that with increasing wind speed where pitch control is active, wind shear has an additional influence on the performance of the wind turbine.

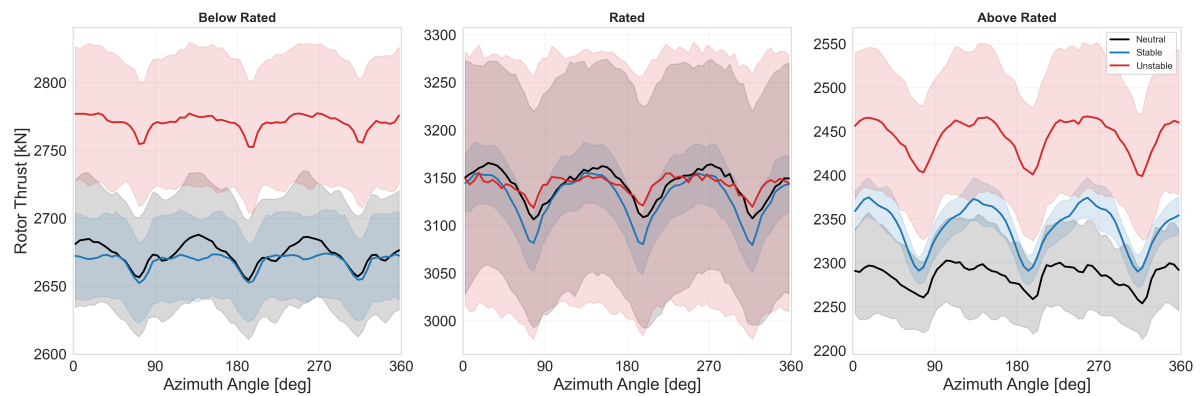


Figure 4.22: Phase average of rotor thrust. Standard deviations are presented by the shaded area.

Figure 4.23 shows the PDF of the rotor thrust for the three atmospheric stability classes across the three operating conditions. The variability caused by the turbulent wind field can be more clearly seen in this figure. When the ABL is under stable stratification, the thrust force has the least amount of fluctuations, which reflects the low turbulence in the wind field. The mean of the thrust in stable conditions comes in close agreement with that of the neutral condition, although the neutral ABL displays a more turbulent wind field, as it can be seen that the standard deviation is slightly broader. The unstable ABL displays a higher thrust force in all cases, although for the rated operating wind speed case, the other two stability classes come in close agreement. The unstable case displays higher fluctuations in all cases regardless.

The PSD of the rotor thrust for the three ABL cases can be seen in figure 4.24. The 1P, 3P, and 6P rotational frequencies are represented by vertical dashed lines. Overall, the spectral energy content of the unstable case is higher than the other two in all operating conditions. Furthermore, distinct peaks can be observed for all three stability classes at the 3P and 6P lines. The blade passing excitation seems to have a prominent effect for the unstable case in the below-rated condition, while the excitation has a larger effect on the stable case for both the rated and above-rated conditions due to the presence of a higher wind shear.

Angle of Attack and Axial Induction Factor Figure 4.25 shows the mean angle of attack plotted against the normalized blade span for the three atmospheric stability classes across all operating conditions. The most notable observation is that atmospheric stability has a negligible effect on the mean angle of attack distribution along the blade span. The three stability classes are nearly overlapping

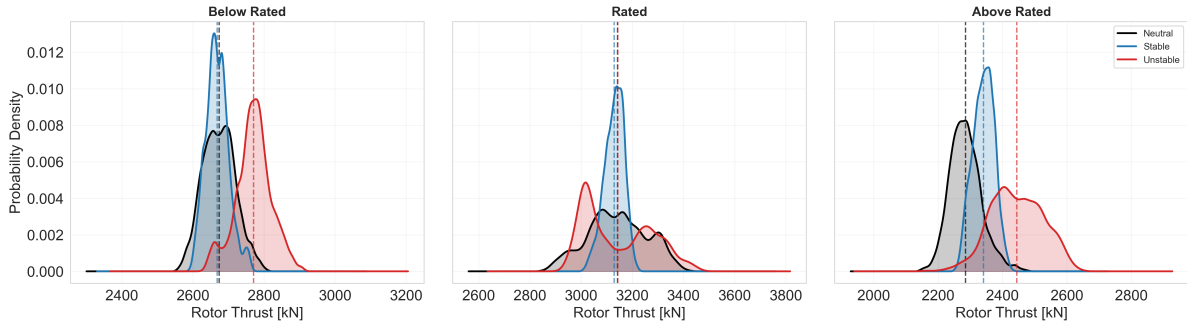


Figure 4.23: PDF of rotor thrust

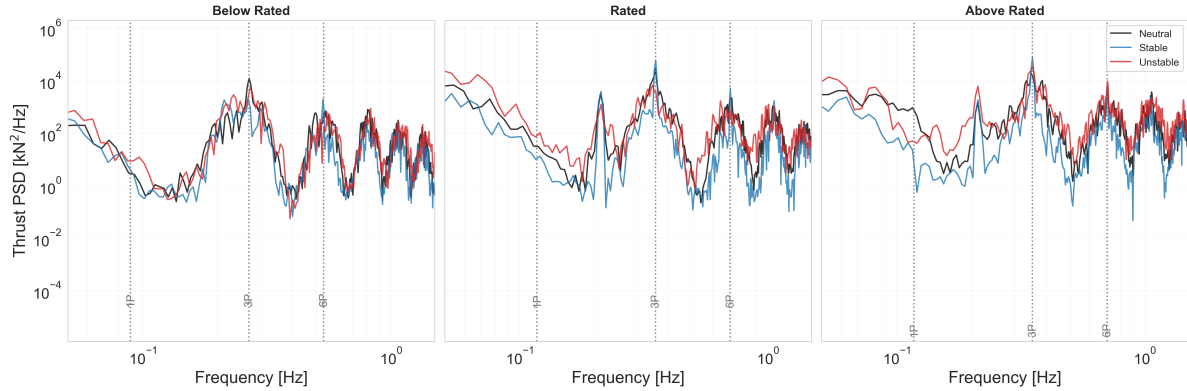


Figure 4.24: PSD of rotor thrust

spanwise in all operating conditions. Table 4.8 shows the statistics at 80% blade span. The mean values across stability classes differ by less than 0.2° at below-rated conditions, with neutral at 8.27° , stable at 8.31° , and unstable at 8.15° . At rated conditions, unstable conditions yield a slightly higher mean angle of attack of 4.35° compared to 4.15° for neutral. The differences are more apparent at above-rated wind speeds, where unstable produces a mean of 1.76° compared to 1.09° for neutral. This trend is consistent with the higher mean wind speeds and increased turbulent fluctuations under unstable stratification, in which pitching towards stall occurs. The effect of atmospheric stability is observed in the standard deviation of the angle of attack. Unstable conditions consistently exhibit the highest variability across all operating points, with a standard deviation of 0.88° at rated conditions compared to 0.51° for stable and 0.61° for neutral. This increased variability reflects the energetic turbulent fluctuations of the convective boundary layer, which cause larger instantaneous changes in the local angle of attack along the blade span. This is consistent with the broader rotor thrust distributions observed under unstable conditions in the previous section.

Table 4.8: Angle of Attack ABL stabilities statistics summary

Condition	Stability	Mean [$^\circ$]	Std Dev [$^\circ$]	Min [$^\circ$]	Max [$^\circ$]
Below Rated	Neutral	8.27	0.41	7.12	9.32
	Stable	8.31	0.48	7.26	9.60
	Unstable	8.15	0.54	6.32	9.72
Rated	Neutral	4.15	0.61	2.59	5.78
	Stable	4.26	0.51	3.01	5.47
	Unstable	4.35	0.88	2.67	6.87
Above Rated	Neutral	1.09	0.30	-0.12	2.27
	Stable	1.29	0.34	0.03	1.93
	Unstable	1.76	0.59	-0.30	3.59

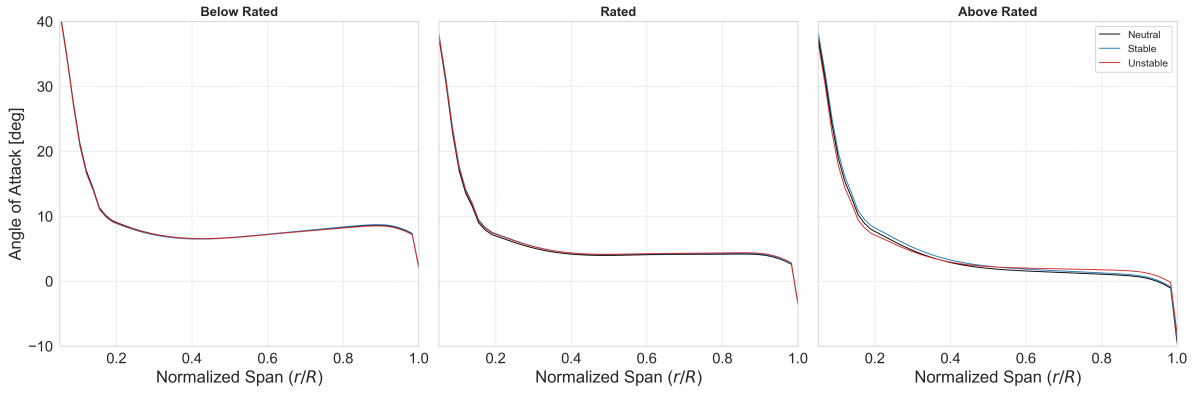


Figure 4.25: Angle of Attack vs the normalized blade span.

Figure 4.26 shows the axial induction factor plotted against the normalized blade span for the three atmospheric stability classes. Similar to the angle of attack results in figure 4.25, atmospheric stability has a negligible effect on the mean spanwise distribution of the axial induction factor. At below-rated conditions, the induction factor exceeds the Betz limit of $1/3$ across most of the mid-span region for all stability classes, with mean values at 80% blade span of 0.327, 0.323, and 0.318 for neutral, stable, and unstable, respectively. As discussed in section 4.2, induction factor values exceeding $1/3$ indicate that the BEM formulation requires empirical corrections in this operating condition, and these values should be interpreted with care. At rated and above-rated conditions, the induction factor falls well below the Betz limit across the full blade span, and the three stability classes remain in close agreement throughout. Table 4.9 presents the statistics at 80% blade span. The mean induction factor differences between stability classes are small across all operating conditions, with the largest separation observed at above-rated, where unstable yields 0.072 compared to 0.054 for neutral. The standard deviation of the stable ABL yields consistently the lowest value across all operating wind speeds. This shows that atmospheric stability primarily affects the variability of aerodynamic performance.

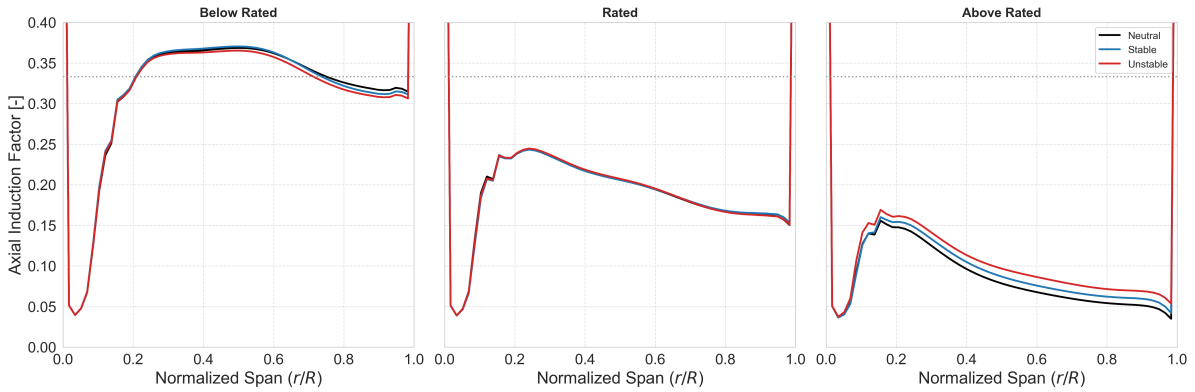


Figure 4.26: Axial induction factor vs the normalized blade span.

Aerodynamic Axial and Tangential load Figure 4.27 shows the mean axial aerodynamic force plotted against the normalized blade span for the three atmospheric stability classes. At below-rated conditions, the three stability classes are in close agreement across most of the blade span, with unstable conditions yielding a marginally higher mean normal force of 9.24 kN/m at 80% blade span compared to 8.88 kN/m for neutral and 8.91 kN/m for stable, as shown in Table 4.10. The standard deviations are wider for unstable conditions due to the higher turbulence intensity of the convective boundary layer. At rated conditions, the mean spanwise profiles of all three stability classes are almost entirely in agreement, with mean values at 80% span ranging from 10.03 to 10.08 kN/m, while the variability remains higher for unstable conditions. At above-rated conditions, the axial load diverges in the outer blade region, where unstable conditions show a mean axial force of 6.82 kN/m compared to 5.98 kN/m for

Table 4.9: Axial induction factor ABL stabilities statistics summary

Condition	Stability	Mean [-]	Std Dev [-]	Min [-]	Max [-]
Below Rated	Neutral	0.327	0.030	0.271	0.429
	Stable	0.323	0.019	0.263	0.387
	Unstable	0.318	0.024	0.249	0.448
Rated	Neutral	0.167	0.018	0.126	0.234
	Stable	0.169	0.005	0.150	0.183
	Unstable	0.167	0.020	0.137	0.247
Above Rated	Neutral	0.054	0.004	0.045	0.068
	Stable	0.062	0.003	0.054	0.071
	Unstable	0.072	0.008	0.050	0.091

stable and 5.85 kN/m for neutral. This difference is explained by the higher wind speeds and turbulent fluctuations under unstable stratification.

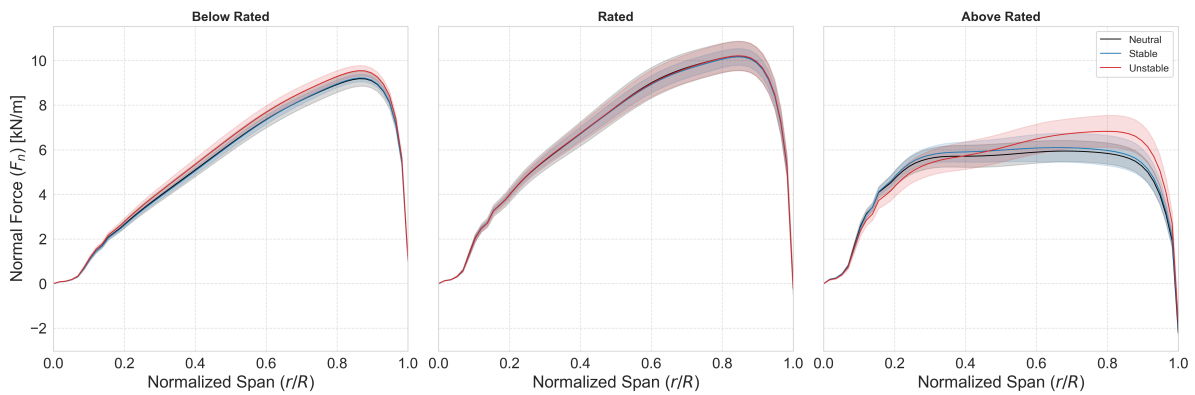
**Figure 4.27:** Axial load vs the normalized blade span.

Figure 4.28 shows the mean tangential aerodynamic force along the normalized blade span. At below-rated conditions, the three stability classes show very close agreement, with mean values at 80% span of 1.22, 1.23, and 1.25 kN/m for neutral, stable, and unstable, respectively. A negative tangential force is visible near the blade root at rated and above-rated conditions. This implies that the drag force dominates the lift. At rated conditions, unstable conditions yield a higher mean tangential force of 0.69 kN/m compared to 0.66 kN/m for stable and 0.65 kN/m for neutral.

4.3.2. Blade Dynamic Response

Flapwise deflection Figure 4.29 shows the mean flapwise deflection plotted against the normalized blade span for the three atmospheric stability classes. At below-rated and rated conditions, the three stability classes agree over most of the span of the blade, with differences only becoming visible near the blade tip. The mean tip deflection at below-rated conditions is 19.07 m for unstable, neutral ABL the tip deflection yields 18.43 m and 18.46 m for stable. At rated conditions, all three stability classes converge to a mean tip deflection of approximately 19.7 m. At above-rated conditions, the ABL cases diverge starting from the 40% blade span, with unstable conditions yielding the highest mean tip deflection of 13.55 m, followed by stable at 12.05 m and neutral at 11.72 m. Table 4.11 presents the tip deflection statistics. The variability of the neutral case increases as the wind speed increases, this holds the same for the unstable case except in the above-rated condition, where it is slightly lower. The stable case variance in tip deflection increases the most out of all three ABL cases. This implies that wind shear in higher wind speeds has more influence on the tip deflection than in lower wind speeds.

Figure 4.30 presents the power spectral density of the flapwise tip deflection. The vertical lines show the flapwise blade frequency modes. At below-rated conditions, neutral carries the highest low-frequency spectral energy, while stable shows the lowest broadband content. At rated conditions, the stable

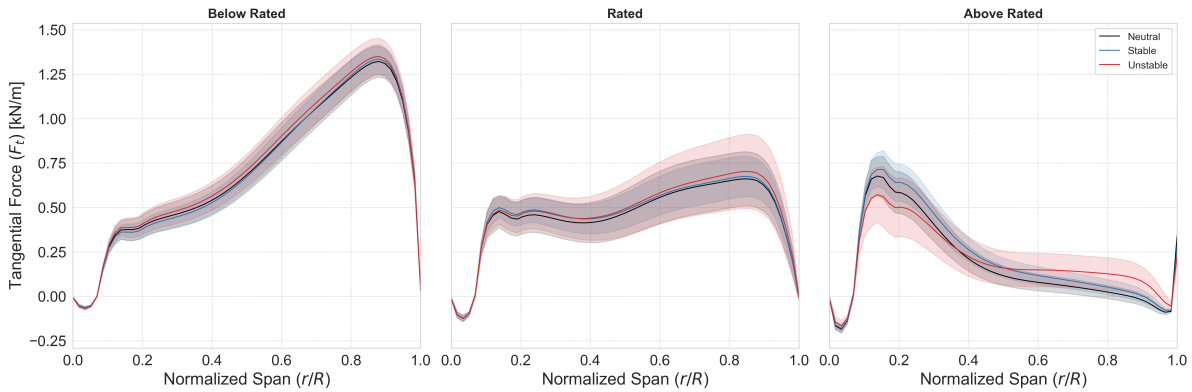


Figure 4.28: Tangential load vs the normalized blade span.

Table 4.10: Axial and tangential aerodynamic loads statistics summary

Condition	Stability	Axial Load (F_n) [kN/m]				Tangential Load (F_t) [kN/m]			
		Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
Below Rated	Neutral	8.88	0.35	7.70	9.73	1.22	0.10	0.95	1.48
	Stable	8.91	0.17	8.30	9.50	1.23	0.09	1.02	1.51
	Unstable	9.24	0.26	8.05	10.08	1.25	0.11	0.86	1.62
Rated	Neutral	10.08	0.66	7.96	11.92	0.65	0.15	0.29	1.10
	Stable	10.03	0.38	9.02	11.19	0.66	0.12	0.39	0.95
	Unstable	10.08	0.64	8.54	11.92	0.69	0.20	0.31	1.24
Above Rated	Neutral	5.85	0.47	4.06	7.47	0.03	0.04	-0.09	0.19
	Stable	5.98	0.68	3.89	6.92	0.05	0.04	-0.07	0.14
	Unstable	6.82	0.71	4.03	8.99	0.13	0.09	-0.11	0.45

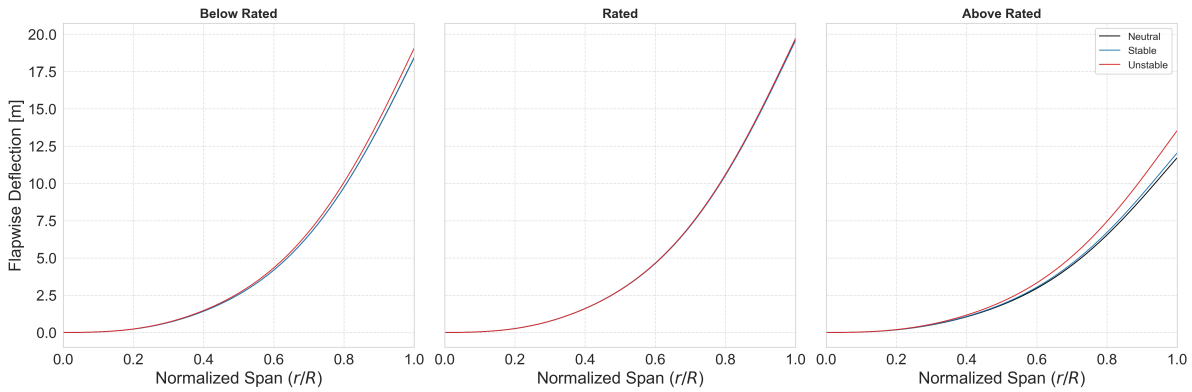
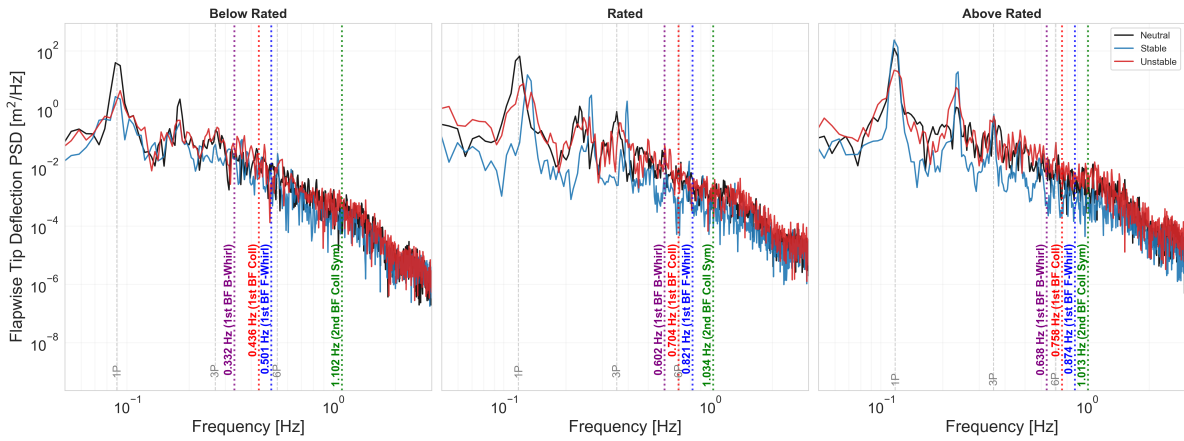


Figure 4.29: Flapwise deflection vs the normalized blade span.

Table 4.11: Flapwise tip deflection statistics summary

Condition	Stability	Mean [m]	Std Dev [m]	Min [m]	Max [m]
Below Rated	Neutral	18.43	0.68	16.70	19.96
	Stable	18.46	0.29	17.55	19.24
	Unstable	19.07	0.39	17.81	20.10
Rated	Neutral	19.70	1.25	16.45	22.79
	Stable	19.60	0.49	18.46	20.94
	Unstable	19.74	1.18	17.61	22.90
Above Rated	Neutral	11.72	1.08	9.35	14.52
	Stable	12.05	1.44	8.95	14.05
	Unstable	13.55	1.08	10.67	16.17

ABL case shows lower spectral energy across the frequency range when compared with the neutral and unstable cases. The peaks of the stable case in the above-rated wind speed are however, more distinct and sharp. It is implied that the wind shear adds an additional excitation.

**Figure 4.30:** PSD Flapwise tip deflection

Torsional deflection Figure 4.31 shows the mean torsional deflection plotted against the normalized blade span for the three atmospheric stability classes. The torsional deflection is negative throughout the blade span in all operating conditions, indicating a consistent pitch-to-feather twist. The mean torsional deflection has small differences across the stability classes, the values can be seen in table 4.12. Similar observations can be made for the variance in torsion by analyzing the standard deviation. This indicates that atmospheric stability has limited influence on the torsional deformation.

Figure 4.32 presents the PSD of the torsional tip deflection. The dominant spectral feature across all operating conditions is the sharp 1P peak. The 1st torsion frequency mode is labeled at 1.456 Hz, 1.441 Hz, and 1.420 Hz for below rated, rated, and above-rated conditions, respectively. The torsional mode lies in the higher frequency range and it is implied that it does not impose a resonance risk since it is not being excited by the harmonics. The spectral differences between stability classes are relatively small for torsional deflection compared to the flapwise results.

4.3.3. Blade Structural Response

Flapwise Blade Root Moment Figure 4.33 shows the phase-averaged flapwise blade root bending moment plotted against the azimuthal angle for the three atmospheric stability classes. A clear sinusoidal motion for all operating conditions and stability classes can be observed. As expected, the moment reaches its maximum when the blade is pointing upwards and reduces when it passes the tower. At below-rated conditions, unstable stratification yields the highest mean flapwise root moment of 74874.86 kNm, compared to 72106.62 kNm for neutral and 72060.57 kNm for stable, as shown in

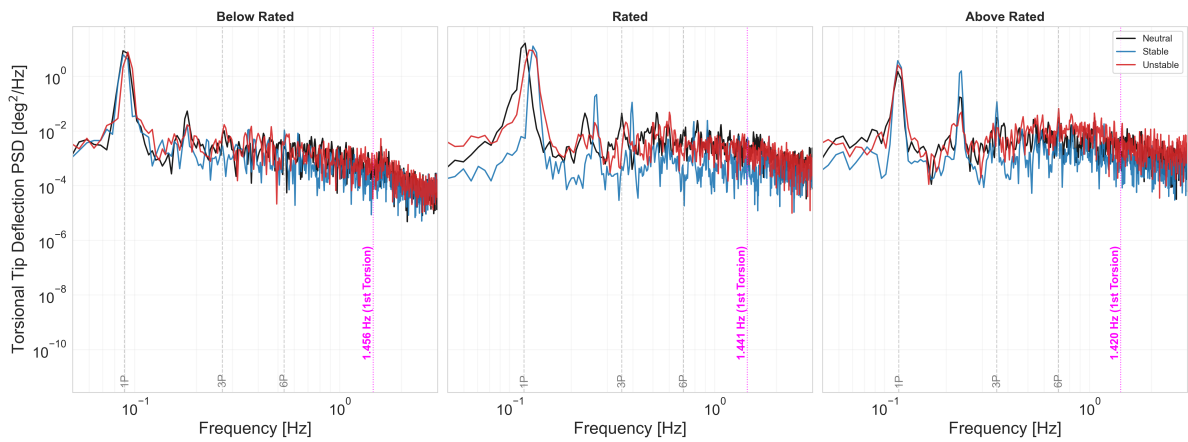


Figure 4.31: Torsional deflection vs the normalized blade span.

Table 4.12: Torsional tip deflection statistics summary

Condition	Stability	Mean [°]	Std Dev [°]	Min [°]	Max [°]
Below Rated	Neutral	-3.89	0.29	-4.53	-3.28
	Stable	-3.89	0.24	-4.40	-3.44
	Unstable	-4.05	0.26	-4.70	-3.52
Rated	Neutral	-5.20	0.42	-6.15	-4.27
	Stable	-5.10	0.35	-5.78	-4.44
	Unstable	-5.13	0.38	-6.13	-4.20
Above Rated	Neutral	-4.80	0.16	-5.27	-4.19
	Stable	-4.73	0.22	-5.14	-4.14
	Unstable	-4.85	0.21	-5.60	-3.86

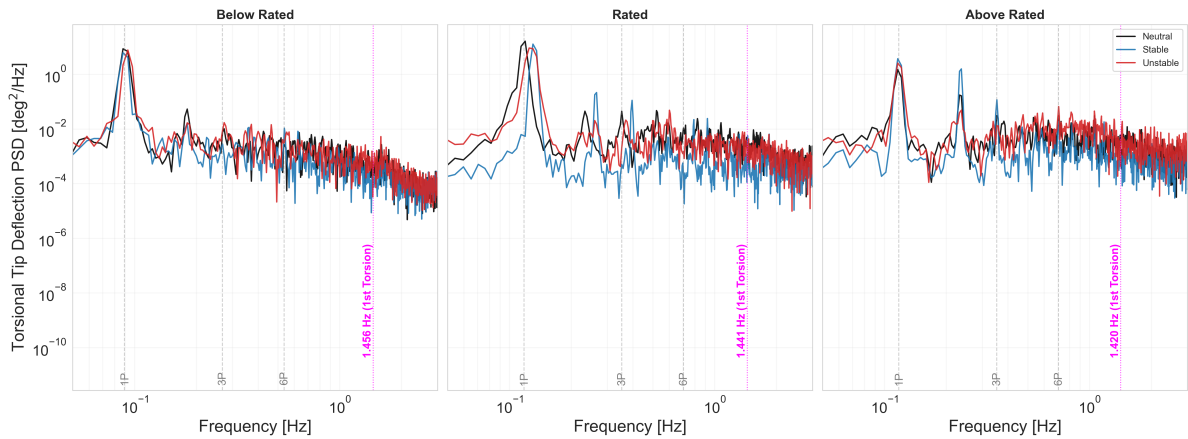


Figure 4.32: PSD Torsional tip deflection

table 4.13. At rated conditions, the time-averaged means of the three stability classes are in close agreement. The standard deviation however, differs greatly, with neutral showing the largest variance in bending. At above-rated conditions, unstable conditions show the highest mean moment of 61644.37 kNm. In this case it contains the least amount of variance in bending, while the stable case shows the largest with a standard deviation of 9727.95 kNm. The pitching mechanism in unstable conditions seems to regulate the loading more effectively than during a stable ABL where the wind shear is more pronounced.

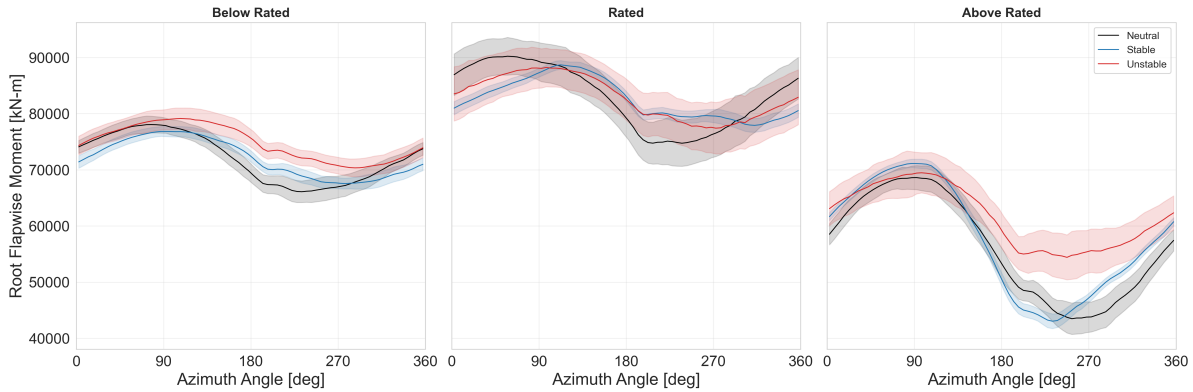


Figure 4.33: Phase averaged flapwise root bending moment

Table 4.13: Flapwise root bending moment statistics summary

Condition	Stability	Mean [kN-m]	Std Dev [kN-m]	Min [kN-m]	Max [kN-m]
Below Rated	Neutral	72106.62	4533.77	60970.00	81370.00
	Stable	72060.57	3506.24	65350.00	79420.00
	Unstable	74874.86	3508.72	66480.00	82670.00
Rated	Neutral	82985.35	6730.33	65420.00	97550.00
	Stable	82609.48	3705.24	74500.00	90220.00
	Unstable	82926.97	5623.69	67280.00	95550.00
Above Rated	Neutral	56184.05	9303.54	36870.00	74080.00
	Stable	57642.77	9727.95	39760.00	73020.00
	Unstable	61644.37	6443.52	46000.00	77280.00

Figure 4.34 presents the power spectral density of the flapwise root bending moment. The 1P rotational frequency peak is the dominant spectral feature across all operating conditions and stability classes. At 3P, the neutral and unstable cases are being excited by this frequency, the stable case however does not seem to receive excitation by the blade-passing frequency. The stable case does react to this excitation at twice the blade passing frequency, stronger than that to the neutral and unstable cases. In the rated case, the neutral case receives excitation of the 3P, this is not the case for the unstable case. There is a profound peak of the stable case slightly higher up in the frequency, this peak could be a reaction by the 3P in the stable case simulation, where it yields a slightly higher rotational speed and therefore does not match completely with the peak of the neutral case. At above-rated condition, it can be seen that the 3P excitation has a clear effect on all three stability classes. This excitation effect can be observed as well at the 6P line, although the neutral case appears to be less affected by it.

Torsional Blade Root Moment Figure 4.35 shows the phase-averaged torsional root bending moment plotted against the azimuthal angle for the three atmospheric stability classes. The sinusoidal motion is more consistent in the below and rated wind speeds. In the above-rated case however, the torsional moment seems to vary quickly as it reaches and passes the tower. The unstable ABL has a stronger effect on the moment in the below-rated wind speed after the blade passed the tower, while the stable and neutral cases are in close agreement with minor differences after the blade passage

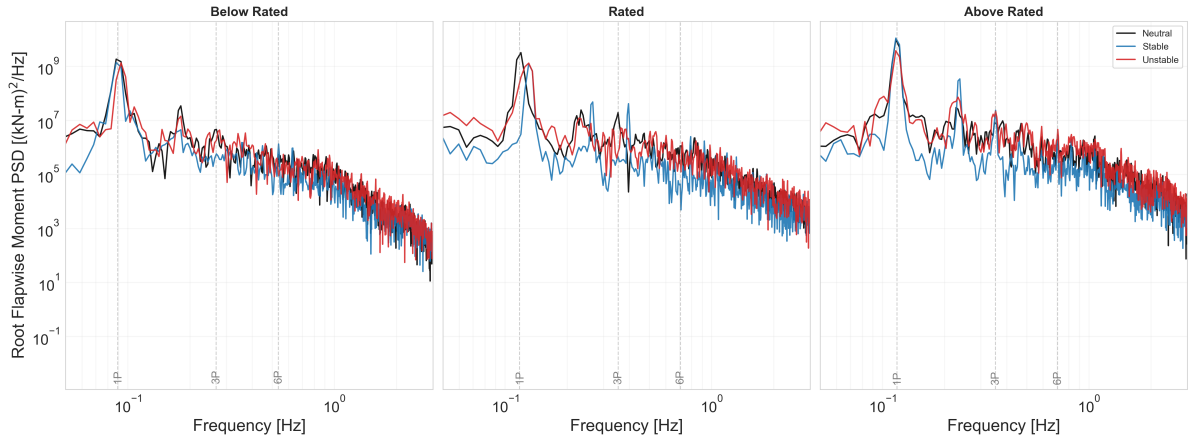


Figure 4.34: PSD flapwise root bending moment

until they converge. In the rated case, the wind shear of the stable case has a stronger influence on the torsional moment, followed by the unstable case and then the neutral. In the above-rated case, the pitching mechanism regulates the flow of the wind differently in all cases. The unstable case induces the strongest torsional moment after the blade passes the tower, followed by the stable case and finally the neutral case. Table 4.14 presents the torsional root moment statistics. At below-rated and rated conditions, the mean values are small relative to the standard deviations, which reflects the large amplitudes of the moment.

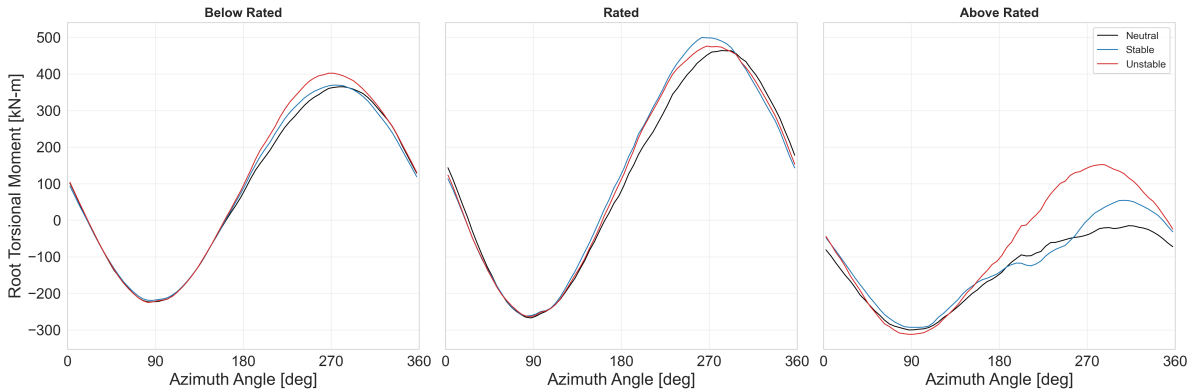


Figure 4.35: Phase averaged torsional root bending moment

Figure 4.36 presents the PSD of the torsional root moment. The 1P excitation primarily contributes to the increase in energy of torsional moment in all stability classes across all operating wind speeds. At below-rated wind speed, the 3P frequency gives limited excitation to the torsional moment in all stability classes. At rated condition, however, torsional moment does receive some excitation of the 3P frequency. The torsional moment excitation in the stable and unstable class can be properly seen in the above-rated condition. The 6P frequency has a limited effect on the energy spectrum for the torsion moment.

4.3.4. Tower Base Loads

Figure 4.37 shows the phase-averaged tower base fore-aft bending moment plotted against the azimuthal angle. Unstable ABL yields the highest fore-aft moment in the below-rated wind speed condition due to the higher turbulence intensity. Wind shear in the stable ABL seems to have less effect on the tower loading. In the rated operating condition, an observation can be made that the neutral ABL yields a higher mean tower fore-aft moment, while once again the stable case sits as the lowest. It is only once the wind speed goes above-rated, the stable ABL starts to display a higher tower base moment than the neutral case, while the unstable ABL displays the highest. In figure 4.38, the tower base

Table 4.14: Torsional root bending moment statistics summary

Condition	Stability	Mean [kN-m]	Std Dev [kN-m]	Min [kN-m]	Max [kN-m]
Below Rated	Neutral	83.01	207.97	-247.40	403.80
	Stable	86.58	208.98	-235.20	390.00
	Unstable	94.82	221.00	-244.40	435.50
Rated	Neutral	106.69	258.10	-306.10	586.10
	Stable	121.14	264.15	-282.20	544.10
	Unstable	117.94	265.02	-326.60	614.80
Above Rated	Neutral	-139.82	102.27	-350.70	111.10
	Stable	-119.56	112.05	-309.40	81.70
	Unstable	-74.72	165.61	-374.30	298.00

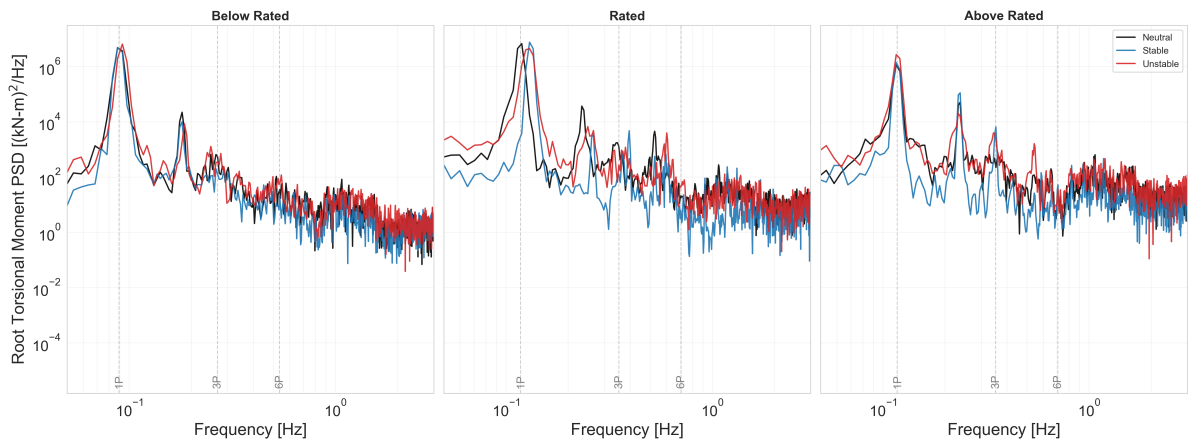


Figure 4.36: PSD torsional root bending moment

loading of the side-side direction can be seen, where once again all stability plots are plotted for each wind speed condition. Similar to figure 4.37, stable ABL exhibits lower tower loading in the below-rated and rated conditions, while for above-rated it is higher.

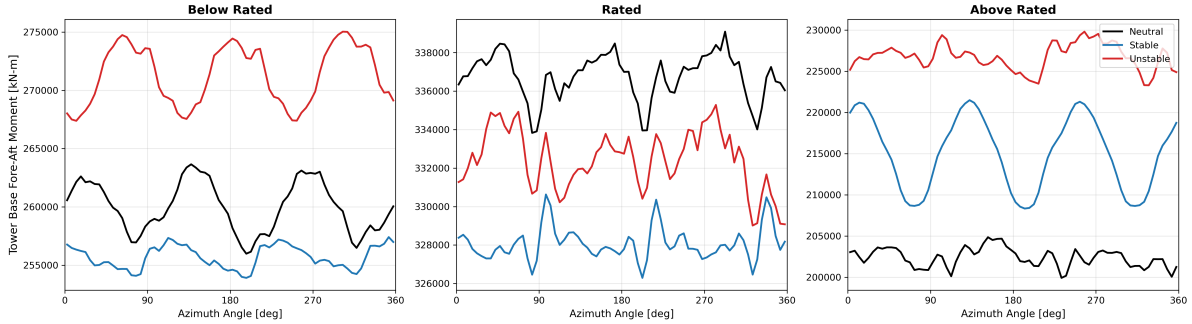


Figure 4.37: Fore-aft moment tower base. Each figure has their own scaling to better visualize the differences

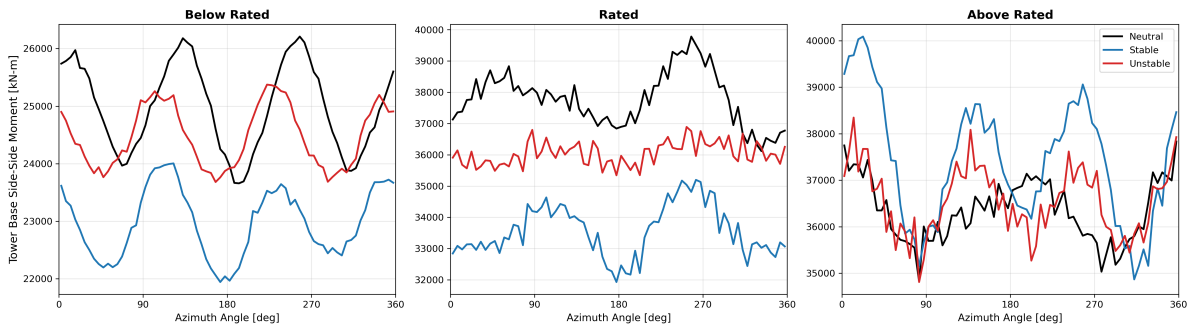


Figure 4.38: Side-side moment tower base. Each figure has their own scaling to better visualize the differences

To gain a better understanding of the fluctuations, a PDF is made of the fore-aft and side-side tower base moment. The plots can be seen in figure 4.39 and 4.40. Furthermore, the statistics table can be seen in table 4.15. At below-rated wind speed, stable ABL exhibits the lowest variance, while unstable yields the highest. This is to be expected due to the high turbulent energy that is present in the unstable ABL. The narrow variance of the stable ABL is to be present in the rated and above-rated as well, while unstable ABL shows the highest variability in fore-aft moment. The load variations in the side-side moment for the three stability classes seem to vary less with each other. The mean loading is for each operating condition close to another, with the above-rated condition almost in agreement with each other. Furthermore, the variability in side-side moment loading is comparable, where the difference only lies in the below-rated condition.

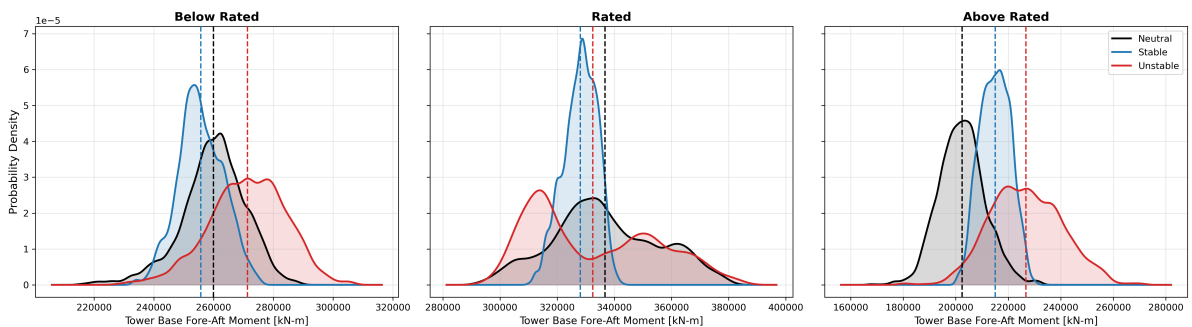


Figure 4.39: PDF Fore-aft moment tower base

The PSD of the fore-aft and side-side tower base moment can be seen in figure 4.41 and 4.42. In the fore-aft spectral analysis, it can be observed that the first distinct peak lies close to but not coinciding

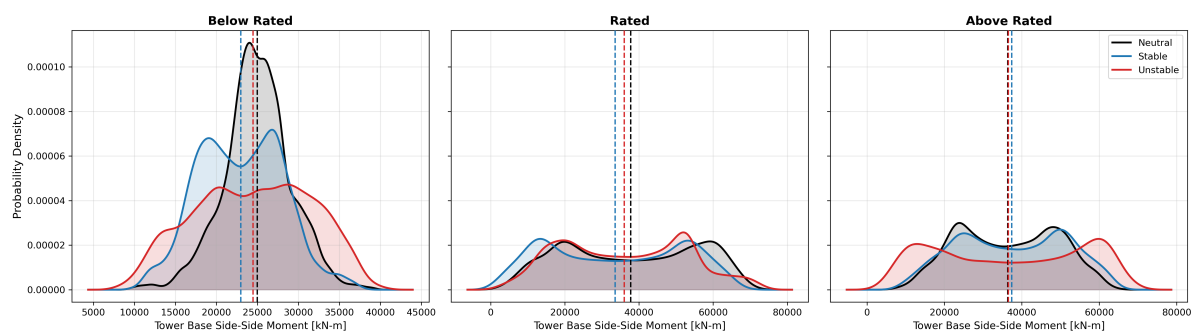


Figure 4.40: PDF Side-side moment tower base

Table 4.15: Tower base loads statistics summary

Direction	Condition	Stability	Mean [kN-m]	Std Dev [kN-m]	Min [kN-m]	Max [kN-m]
Fore-Aft	Below Rated	Neutral	259963.23	10871.99	215100.00	289400.00
		Stable	255693.77	7553.12	233300.00	276100.00
		Unstable	271321.52	12798.48	227100.00	307100.00
	Rated	Neutral	336758.73	18662.85	290900.00	381200.00
		Stable	328073.40	5886.32	310000.00	343200.00
		Unstable	332428.39	22250.75	292400.00	387100.00
	Above Rated	Neutral	202376.54	8834.33	166800.00	233100.00
		Stable	215054.32	5760.03	199900.00	231400.00
		Unstable	226740.40	13669.06	178200.00	271500.00
Side-Side	Below Rated	Neutral	24978.90	4117.48	9540.00	39100.00
		Stable	22976.69	5169.81	9654.00	37780.00
		Unstable	24472.97	7056.69	7652.00	40660.00
	Rated	Neutral	37792.10	18006.75	2380.00	71150.00
		Stable	33570.89	18232.74	1025.00	67780.00
		Unstable	36041.73	16951.85	1871.00	73980.00
	Above Rated	Neutral	36343.00	12848.17	6444.00	64910.00
		Stable	37408.52	13975.97	7237.00	66290.00
		Unstable	36548.91	19049.30	1744.00	71640.00

with the 3P frequency. This is the same as for the rated condition, although the peaks are more in the lower frequency range. This indicates that the structure lies in the soft-stiff range. The same observation can be made for the above-rated condition. The second peaks in the below-rated conditions are being excited by the 3P, it however drops quickly in spectral energy and rises again due to the excitation of the 6P frequency. This same observation is also seen in the rated and above-rated condition. The peak for the stable ABL in the above-rated condition is excited strongly by the 3P frequency. Similar observations can be made for the PSD of the side-side tower bending moment in figure 4.42. The first distinct peak lies between the 1P and 3P lines, indicating a soft-stiff structure. The second peaks of the ABL cases are as well being excited by the 3P frequency, whereas the stable case in the above-rated condition has a pronounced peak indicating stronger excitation.

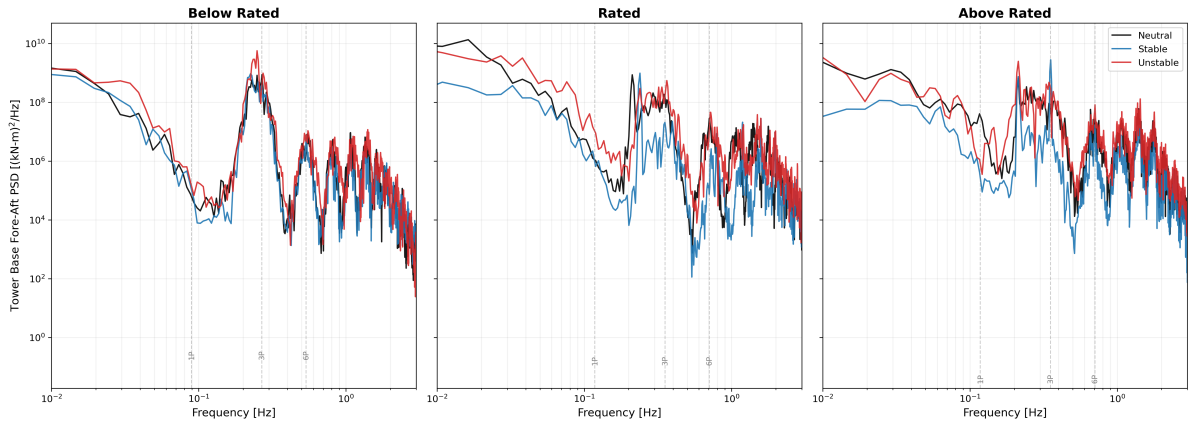


Figure 4.41: PSD Fore-aft moment tower base

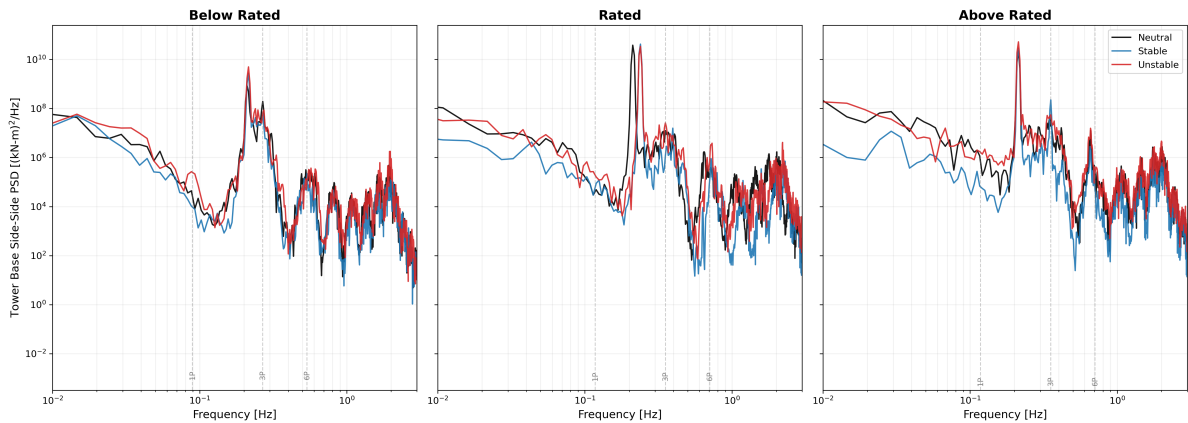


Figure 4.42: PSD Side-side moment tower base

4.3.5. Fatigue

Flapwise Blade Root Moment Figure 4.43 presents the damage equivalent loads of the flapwise blade root bending moment as a function of the ultimate load ratio S_{max}/S_u for the three atmospheric stability classes. The highest determined DEL occurs in neutral ABL across all load ratios. Stable ABL yields lower DEL values, all stability classes converge as the load ratio approaches 1.0. At rated wind speed, the neutral ABL once again shows higher DEL across the ratios, it is only as the ultimate load ratio reaches 1.0 that the DEL calculated in a stable ABL surpasses the other two stability classes. The DEL calculated in the stable ABL in above-rated wind speed once again is higher than the other stability classes.

Torsional Blade Root Moment Figure 4.44 presents the damage equivalent loads of the torsional blade root bending moment as a function of the ultimate load ratio S_{max}/S_u for the three atmospheric

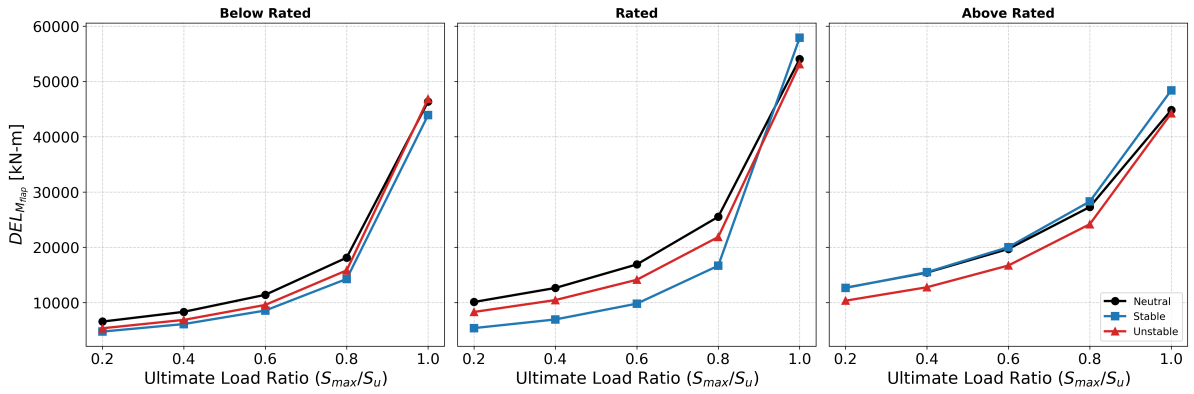


Figure 4.43: DEL of the flapwise blade root bending moment

Table 4.16: DEL point values for the flapwise bending root moment

Condition	Stability	S_{max}/S_u Ratio					$\Delta_{1.0}$ [%]
		0.2	0.4	0.6	0.8	1.0	
Below Rated	Neutral	6567	8334	11410	18131	46353	—
	Stable	4762	6121	8567	14282	43915	−5.3%
	Unstable	5359	6873	9582	15832	46828	+1.0%
Rated	Neutral	10109	12650	16904	25519	54055	—
	Stable	5390	6956	9811	16671	57894	+7.1%
	Unstable	8310	10461	14129	21865	53123	−1.7%
Above Rated	Neutral	12686	15432	19704	27296	44824	—
	Stable	12649	15504	20028	28288	48394	+8.0%
	Unstable	10347	12778	16710	24181	44232	−1.3%

stability classes. The torsional DEL shows a clear sensitivity to atmospheric stability that varies with operating condition. A higher DEL under the unstable case can be observed in below-rated wind speed. The DEL for neutral and stable are in agreement with each other. The calculated DEL for the rated case is higher than that of the below-rated wind speed condition, however it can be observed that the three stability classes are in close agreement. The most distinct difference can be seen in the above-rated wind speed, where the DEL in the unstable case is much higher than that of the stable and neutral cases.

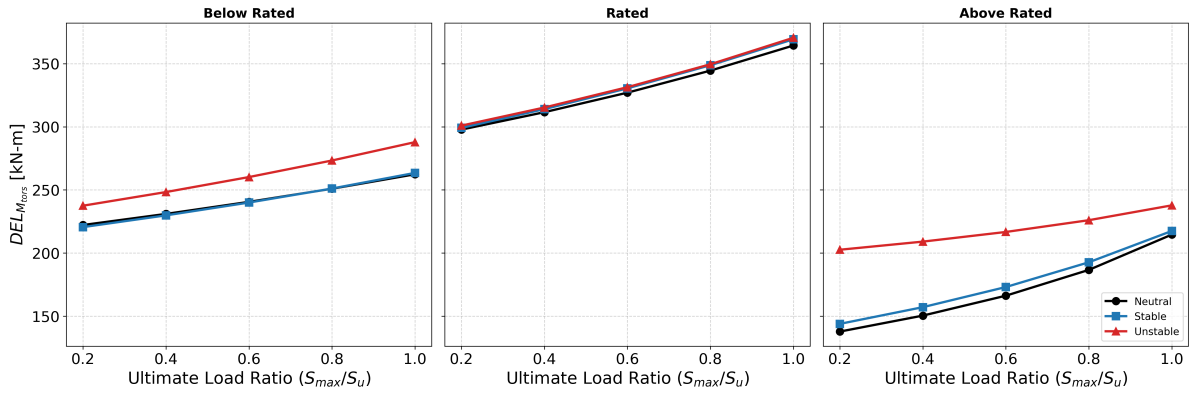


Figure 4.44: DEL of the torsional blade root bending moment

Table 4.17: DEL point values for the torsional bending root moment

Condition	Stability	S_{max}/S_u Ratio					$\Delta_{1.0}$ [%]
		0.2	0.4	0.6	0.8	1.0	
Below Rated	Neutral	222	231	241	251	262	—
	Stable	221	230	240	251	263	+0.4%
	Unstable	237	248	260	273	288	+9.7%
Rated	Neutral	298	312	327	344	364	—
	Stable	299	314	330	349	369	+1.4%
	Unstable	301	315	331	350	370	+1.7%
Above Rated	Neutral	138	150	166	187	215	—
	Stable	144	157	173	193	217	+1.3%
	Unstable	203	209	217	226	238	+10.8%

Conclusion & Recommendations

Summary of study

As the trend continues with the upscaling of offshore wind turbines, the increased size will introduce significant aeroelastic and atmospheric challenges that cannot be fully captured by linear structural models and simplified inflow assumptions. The flexibility of rotor blades increases as the size of the blade increases. The increased blade flexibility will introduce a significant amount of torsion that cannot be neglected. Simultaneously, the large wind turbine operates in the Atmospheric Boundary Layer (ABL), where the atmosphere is thermally stratified and influences the inflow characteristics on the turbine. This thesis investigated both of these areas for the IEA 22 MW reference wind turbine. The aeroelastic analysis is performed using OpenFAST under a turbulent precursor inflow. The structural models ElastoDyn and BeamDyn were used across three operating conditions, while the influence of atmospheric boundary layer stability was evaluated for unstable, neutral, and stable inflow conditions across the same operating points using BeamDyn as the main structural solver. Based on the outcomes of the results, the following research questions can be answered.

Research question 1: What is the influence of torsional force on the aerodynamic performance, blade structural response, and fatigue loading, and how does neglecting blade torsional flexibility affect load predictions?

In the comparison analysis of ElastoDyn and BeamDyn, it was revealed that torsional blade flexibility has a significant impact on the aerodynamic performance and structural loading of the IEA 22 MW wind turbine. The rotor thrust of the wind turbine at below-rated condition was reduced by 201.2 kN when torsional flexibility is accounted for, which is a reduction of approximately 7.0%. The twisting of the blade's deformation causes the angle of attack to be reduced, which impacts the aerodynamic loading of the blade. It was found that torsional force significantly reduces the angle of attack in the tip region in all operating conditions. For the rated and above-rated condition, the angle of attack is reduced in the tip region after 67% of the blade span, while being increased in the inner part of the blade. The overestimation of the angle of attack in the ElastoDyn case impacts the aerodynamic loading, where the loading is overestimated in the tip region, and in turn predicts a higher tip deflection. This displays the influence of torsional flexibility in large rotor blades as it impacts most of the characteristics of the blade. The consequence of the bend-twist coupling impacts the fatigue damage of the rotor blade. The Damage Equivalent Load (DEL) of the flapwise blade root moment was calculated, and it was shown that the bend-twist coupling increases the DEL of the rotor blade. For all operating conditions, the DEL of the ElastoDyn case converges to that of the BeamDyn case at the load ratio of 1.0, where the difference is 1.7% for the rated condition. This implies that torsional influence has limited impact at large load cycles. Nevertheless, the use of a geometrically exact beam formulation such as BeamDyn is necessary for accurate load prediction.

Research question 2: How do neutral, stable, and unstable atmospheric stabilities affect the aerodynamic performance and blade dynamic response across below-rated, rated, and above-rated operating conditions?

The influence of atmospheric boundary layer stability on the aerodynamic performance and blade dynamic response of the IEA 22 MW reference wind turbine was found to be strongly dependent on the operating condition. The three stability classes impose distinct inflow characteristics on the rotor, producing systematic differences in aerodynamic loading and blade response that vary with wind speed condition. Atmospheric stability was found to have a limited effect on the mean spanwise distributions of angle of attack and axial induction factor, with the three stability classes producing nearly overlapping profiles along the blade span. The primary aerodynamic effect of stability was instead observed in load variability, unstable ABL displays the highest thrust variability, while the stable ABL displays the lowest.

This is, however, reversed for the flapwise root bending moment, where it was found that the stable ABL has the highest variability. However, the mean root bending moment for the unstable ABL was still the highest. It was further found that the ABL stability has a severe impact on the torsional root force for the above-rated wind speed case. This is further observed for the calculated DEL for the torsional root moment, where the unstable ABL causes a higher DEL of up to 10% compared to the neutral ABL case.

Recommendations for future research

Several limitations of this study should be acknowledged when interpreting the results presented in this thesis. The simulations performed in this study model an isolated single turbine without accounting for wind farm wake effects. Future research should extend the analysis to a wind farm configuration, where upstream turbine wakes modify the inflow turbulence intensity and wind speed experienced by downstream turbines. This would provide a more representative assessment of the load and fatigue conditions experienced by turbines operating within an offshore wind farm array under different atmospheric stability classes.

The statistical reliability of the results is inherently limited by the duration of the simulations. Future work should consider longer simulation time windows to improve the statistical convergence of the fatigue damage equivalent load calculations, particularly for low-frequency load cycles driven by large convective turbulent structures under unstable stratification.

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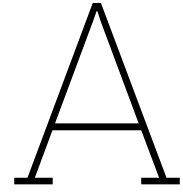
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Campbell diagram

First 20 aeroelastic frequencies of the full system as reported in the IEA22MW documentation[66]

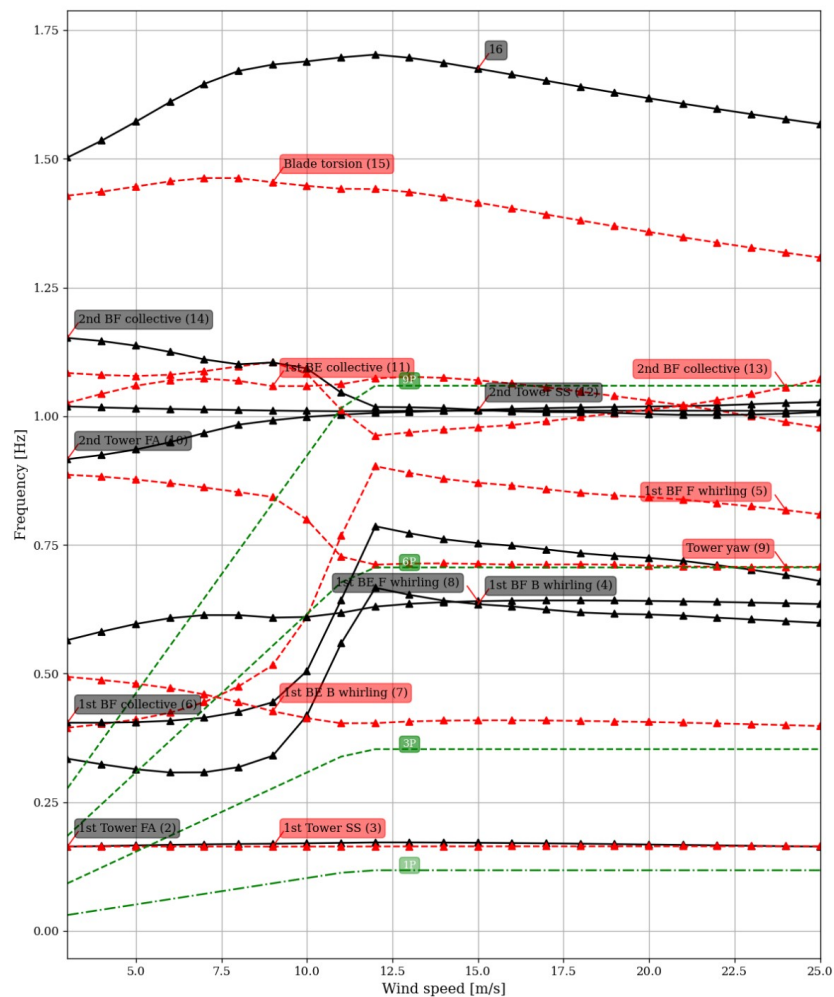


Figure A.1: Full system frequencies. BF: blade flapwise, BE: blade edgewise, SS: side-side, FA: fore-aft. B: backward, F: forward. Numbers in parentheses indicate mode index where lowest number corresponds to lowest frequency [66]

B

Full system frequencies

Table B.1: Natural Frequencies [Hz] for the 22MW Turbine Modes (Indices 2–15)

Index	Mode Description	Below Rated (8.62 m/s)	Rated (11.46 m/s)	Above Rated (14.53 m/s)
2	1st Tower FA	0.1718	0.1724	0.1737
3	1st Tower SS	0.1622	0.1641	0.1654
4	1st BF B whirling	0.3321	0.6018	0.6380
5	1st BF F whirling	0.5013	0.8212	0.8741
6	1st BF collective	0.4364	0.7036	0.7576
7	1st BE B whirling	0.4332	0.4027	0.4078
8	1st BE F whirling	0.6094	0.6228	0.6387
9	Tower yaw	0.8454	0.7201	0.7125
10	2nd Tower FA	0.9866	1.0025	1.0102
11	1st BE collective	1.0611	1.0649	1.0719
12	2nd Tower SS	1.0108	1.0089	1.0108
13	2nd BF collective (asym)	1.1018	0.9905	0.9746
14	2nd BF collective (sym)	1.1018	1.0344	1.0127
15	Blade torsion	1.4561	1.4408	1.4198