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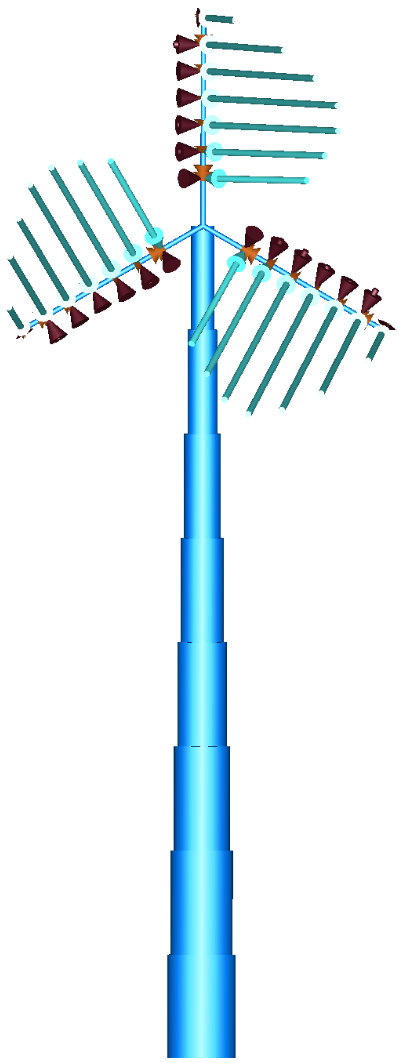

Wind Turbine Simulation in Dymola

Master's thesis in MPSEB

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Department of Mechanics and Maritime Sciences
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Gothenburg, Sweden 2020

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Cover: Wind turbine model with force vectors.

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Abstract

Modvion is building and developing towers made of timber, for modern commercial wind turbines reaching hub heights of 150 meters and above. Such wind turbines are machines with large flexible structures that need to handle turbulent wind loads. When designing and verifying the structural components, the interaction between structural dynamics, aerodynamics, the mechanical, electrical and control systems need to be considered. To achieve this, an aero-elastic model is used.

The purpose of this project is to create a tool for such aero-elastic simulations of horizontal axis wind turbines, in the modelling and simulation environment Dymola. The tool should be capable of running all simulations needed for the design and dimensioning of the structural components of a wind turbine and enable flexibility in terms of increasing or decreasing complexity of the simulations.

The tool was built up using many of the predefined components in the Modelica libraries while some of the more complex components were coded from scratch.

The accuracy of the tool was verified by running simulations on two wind turbine models, the NREL 5MW benchmark turbine and the research turbine on Björkö with a wooden tower constructed by Modvion. The verification was performed by running simulations with the Dymola tool and comparing the results with simulations made with the acknowledged softwares, FAST and Vidyn. Three different types of load cases are included, the Ramp case, the Extreme Operating Gust case and Turbulent cases.

A few studies were then performed on the Björkö turbine model to study what effect that different phenomena and design changes might have on the wooden tower structure.

It could be concluded that it is possible to create a tool for aero-elastic simulations of horizontal axis wind turbines in Dymola and that such a tool enables the study of different design changes and how they will affect the structure.

Keywords: system simulation, wind turbine, Dymola, aero-elastic, renewable energy

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Geir Soderin, Gothenburg, June 2020

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Introduction

1.1 Background

Our civilization is in need of sustainable energy that does not harm the environment. Wind power is one of the main technologies to produce sustainable clean energy and is often the cheapest alternative [1]. Modvion is developing towers for wind turbines made out of timber, which enables wind turbines to be constructed at a lower cost and with a smaller environmental footprint, the 30 meters tall prototype tower with the Chalmers research turbine can be seen in figure 1.1. In the construction of a wind turbine, the structural components need to be designed to handle the loads that they are subjected to during their lifetime while the cost of production is also minimized. Since wind turbines are dynamically loaded structures, aero-elastic simulation is used to predict the behaviour of the wind turbine, such simulations may also be used to predict the energy production and thereby the economic performance of the wind turbine. Aero-elastic simulations take into account the aerodynamics, the structural dynamics, the mechanical, electrical and control systems and the interaction between all of them. Commercial and non-commercial software, capable of such simulations, exist and are used in the wind turbine industry today [2]. The Modelica programming language and the Dymola simulation software is a powerful platform for simulations and it is of interest to explore the benefits and drawbacks of using Modelica for aero-elastic wind turbine simulations, at the moment, there is no ready-made tool available for such simulations in Dymola. The tool created in this thesis will be useful in evaluating the structural characteristics of the wooden towers constructed by Modvion and will allow an efficient design process.

Figure 1.1: The Chalmers research turbine on Björkö with the prototype wooden tower made by Modvion.

1.2 Aim and Objective

The aim of this thesis is to create a tool in Dymola which is capable of aero-elastic simulations of a horizontal axis wind turbine. Due to the nature of the programming environment in Dymola, there is potential to make efficient simulations and to allow for modifications of the working principles of the tool as well as the addition and removal of functionalities, thereby creating a tool with high flexibility.The tool shall enable the creation of different wind turbine models and simulation of a number of different load cases, including extreme wind and turbulent wind cases. The accuracy of the simulations made with the tool shall be verified by comparing the results with simulations made with acknowledged software. Studies will be performed on two different wind turbine models, one which represents the Chalmers research wind turbine being erected on Björkö with a wooden tower constructed by Modvion, and the other one will be a copy of the NREL 5MW reference wind turbine. A set of load cases will be studied that represent the most critical situations for the structure of a wind turbine.

1.3 Limitations

The focus of the work will be to create a functioning tool and the user friendliness will be of lower priority. The tool will be made for simulation of horizontal axis wind turbines of modern type with pitch regulated blades. The richness of detail in the different phenomenons that are active in a wind turbine will be limited. For example, the second order effects of the turbine aerodynamics, caused by large deflections of the turbine, will not be considered. The number of studied load cases are limited to the most critical and relevant for verification of the functionality of the tool.

2

Operating Principles of Horizontal Axis Wind Turbines

In this chapter the operating principles of horizontal axis wind turbines will be explained. The main parts that makes up a wind turbine are shown in figure 2.1 and their functionality will be described in the following subsections.

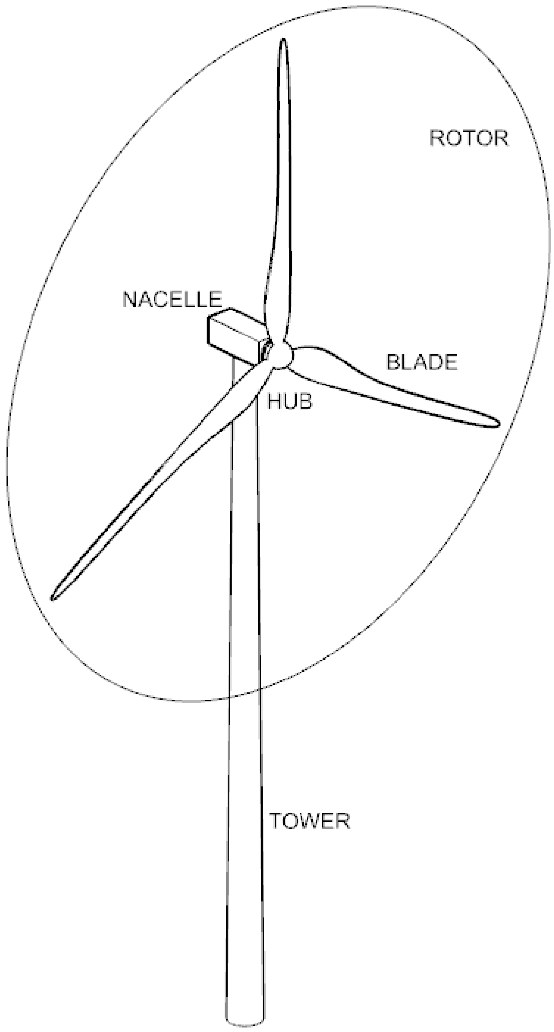

Figure 2.1: An overview of a wind turbine and its different components.

2.1 Wind

The wind is the source of energy for the wind turbine, as air moves across the rotor, kinetic energy in the wind is converted into mechanical energy. The power of the converted energy can be calculated as:

$$P_{rot} = \frac{1}{2} A \rho V^3 C_p \tag{2.1}$$

where A is the swept area of the turbine, ρ is the density of the fluid, V is the velocity of the flow and C_p is the coefficient of power which can be seen as an efficiency factor. As the turbine extracts kinetic energy of the wind, the wind is affected by slowing down and starting to rotate, which limits the amount of energy that the turbine can extract. There is a theoretical limit for how much of the kinetic energy an open turbine, such as a wind turbine, can extract from the moving fluid,it is called the Betz Limit and it's value is $C_{p,B} = 16/27 \approx 0.59$. This efficiency cannot be reached in real world conditions and the efficiency of a modern wind turbine is usually around $C_p = 0.45$, [12].

2.2 Blades

Turbine blades are normally made of fiber reinforced polymers, moulded into an airfoil shape where the chord length and twist angle change along the length of the blade. The shape of the blade determines how it interacts with the wind and thereby the amount of energy that is converted. The cross sections of the blade and the material properties determine the strength and stiffness. The stiffness of the blades has an indirect influence on the performance since deformations may affect the angle and velocity of the blade relative to the moving air [3].
In the case of high wind speed, the power extracted by the rotor needs to be limited in order not to overload the electrical and mechanical systems or the structural components. In modern large scale turbines, this is usually done by pitching the blades which means that the blades are rotated around their longitudinal axis, usually by electrical or hydraulic motors mounted in the hub. The pitch system is also activated during emergency shut down and during storms the blades are pitched out to reduce the wind loads. The angular velocity is limited by the capacity of the mechanical pitching system, this limitation has a significant effect on the behaviour of the turbine in certain load cases.

2.3 Rotor

The rotor can have different number of blades, in general, a rotor with more blades result in lower rotational speed and higher coefficient of power, see section 2.1. However, the efficiency increases by just a few percent when going from for example two to three blades, while the production cost of the rotor increases by roughly 50 %. Thereby, the most cost efficient turbines would have one or two blades, however, such rotors can have challenging dynamic behaviour and high rotational speeds which can lead to high noise. For this reason, modern turbines usually have three blades, this makes up a well balanced and efficient turbine. In order to assure sufficient clearance between the rotor blades and the tower, the rotor is often tilted backwards by a few degrees and has a pre-coning, i.e. the blades are pointing slightly forwards [3].

2.4 Hub

The blades of the rotor are connected to to the drive shaft via a hub which is usually a large machined steel structure, the hub is subjected to large cyclical forces and needs to be manufactured with high quality. The steel structure is often covered by a cap in order to improve the aerodynamic shape [2].

2.5 Nacelle

The nacelle contains the mechanical drive train as well as the electrical system and control units. The drive train of wind turbines can be divided into two main types, geared drive trains and direct drive. The geared type uses a gearbox to increase the rotational speed in the generator which enables the use of a "normal" generator. The direct drive type uses special generators with permanent magnets [3]. The nacelle also contains a yaw system for turning itself and the rotor in the horizontal plane, in order to make sure that the rotor faces the wind. There is a bearing between the nacelle and the tower structure and a number of actuators that enable this turning mechanism. The mass distribution of the nacelle has a significant effect on some of the structural components, such as the bearing connecting the nacelle and the tower as well as the tower itself. Different types of nacelles may have different mass distributions, some have the center of mass close to the center point of the tower while others are front heavy, with the center of mass between the tower center and the rotor hub. A front heavy nacelle will cause a constant bending moment on the tower which will put stress on the bearing as well as on the tower structure, however, the thrust on the rotor will cause a large bending moment on the tower in the opposite direction, as a result, the front heavy nacelle may reduce the highest stresses in the tower structure.

2.6 Generator

The power output of the generator is a function of rotational speed, torque and generator efficiency. This is described by the following equation:

$$P = T\omega\eta \tag{2.2}$$

Where P_{gen} is the generator power output, t is the generator shaft torque, ω is the rotational speed and η is the generator efficiency factor [8].

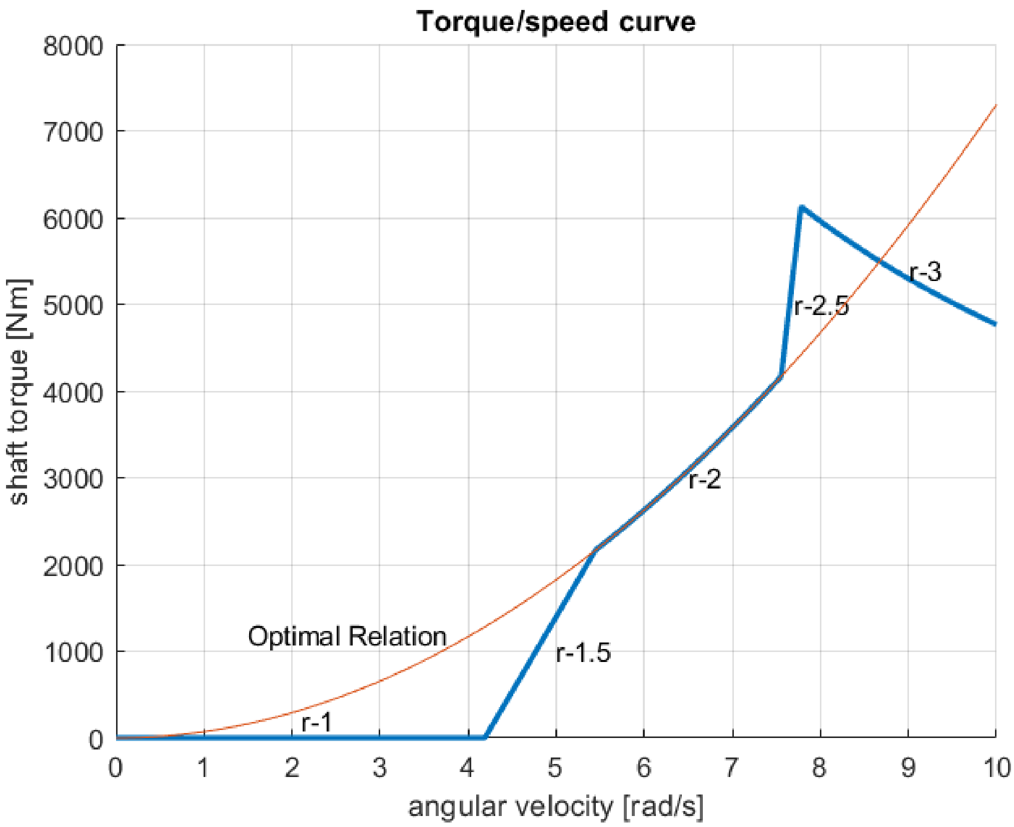

Figure 2.2: The torque speed curve describes what torque the generator will be operating at as a function of the rotational speed.

In optimal operation the rotational speed is proportional to the wind speed and the power output is the product of the torque and the rotational speed, equation 2.2, this results in a cubic relation between wind speed and power.
However, optimal operation is not always maintained, and the generator torque is controlled according to a torque/speed curve see figure 2.2. It describes the torque as a function of the rotational speed, the optimal relation is described by the orange line which is a quadratic curve and the blue line shows an example of how the relation may be in a real wind turbine. The generator torque is controlled according to a set of variables defining a number of regions in which the turbine operates. In region 1 the generator torque is zero to allow for the turbine to increase its speed faster, 1.5 is a start up region where the moment starts to increase linearly when the cut in speed is reached, the torque is directly proportional to the rotational speed. In region 2 the generator moment is set for optimal operation. Region 2.5 is a transition region which reduces acoustic noise from the turbine by reducing the highest tip speed at rated power. Region 3 is for rated speed and above where the torque is set to keep the power constant even at rotation speeds above rated speed, here the generator torque is inversely proportional to the speed. At high wind speeds, the generator torque must not be too high as this would damage the electrical system, the rotational speed of the rotor is instead controlled by pitching of the blades, as described in section 2.2, [9].
Using a torque level which is not optimal will cause a slightly lower energy pro-

duction, however, considering the wind speed distribution over time, commercial turbines will most often operate in region 2 [3].

2.7 Tower

The tower structure makes up a large part of the materials being used in the wind turbine, it is often built as a large conical steel tube, but there exists towers made of concrete and timber as well. The structural and dynamic properties need to be considered to make it work with the turbine operation. The parameters to consider are strength, stiffness, mass distribution and damping, [15].
The tower needs to carry the mass of the nacelle and the turbine which on modern turbines can be on the scale of several hundred tonnes [9]. The thrust force caused by the wind on the rotor causes a large bending moment on the tower structure, it can be calculated according to:

$$T = \frac{1}{2} A \rho V^2 C_T \tag{2.3}$$

where T is the thrust force, A is the swept area of the rotor, ρ is the air density, V is the wind speed and C_T is the thrust coefficient. The value of the thrust coefficient is dependent on o number of properties of the rotor aerodynamics as well as the operation of the wind turbine, during optimal operation, it normally has a value close to 0.5 [13]. The bending moment at the tower base caused by the thrust force is obtained by multiplying it with the tower height.
As mentioned in section 2.5, depending on the mass distribution of the nacelle and the rotor, there will be a bending moment acting on the tower top around the pitch axis. This bending moment may reduce the highest bending moment at the tower base. In combination with this bending moment, the torque of the rotor causes an additional bending moment on the tower around the rotor axis which will usually be perpendicular to the main bending moment caused by the thrust.
Due to uneven and turbulent winds, the force on the rotor blades might differ significantly from side to side. Such uneven forces will cause a torsional moment on the tower. Certain fault conditions e.g. failure of the pitch mechanism in one blade can cause critical loads of this nature.
In addition to the forces acting on the top of the tower, the wind will cause a force acting directly on the tower wall. This type of load can be critical during a storm and a wider tower structure makes this type of load more significant since there is more area for the wind to affect.
The stiffness and mass distribution has an effect on the eigen-frequency which must not coincide with the frequencies of the rotor. When a blade passes in front of the tower, the wind loading on both the blade and the tower will be affected, resulting in a pulsating load on the structure. The frequency of this pulsating load is usually referred to as 3p and it is of high importance. The frequency of a full rotation is referred to as 1p and it can have an effect if the rotor is unbalanced in some way.
The tower, with the large mass on top often has a low eigen-frequency in the first mode, which can be close to the 3p or 1p frequencies, it must be made sure that these frequencies do not coincide when the wind turbine is in its working range. The

problem can be illustrated by a Campbell diagram as shown in figure 2.3, here we can see that the 3p line crosses the first tower frequency below the operating speed and that the 1p line crosses it above.

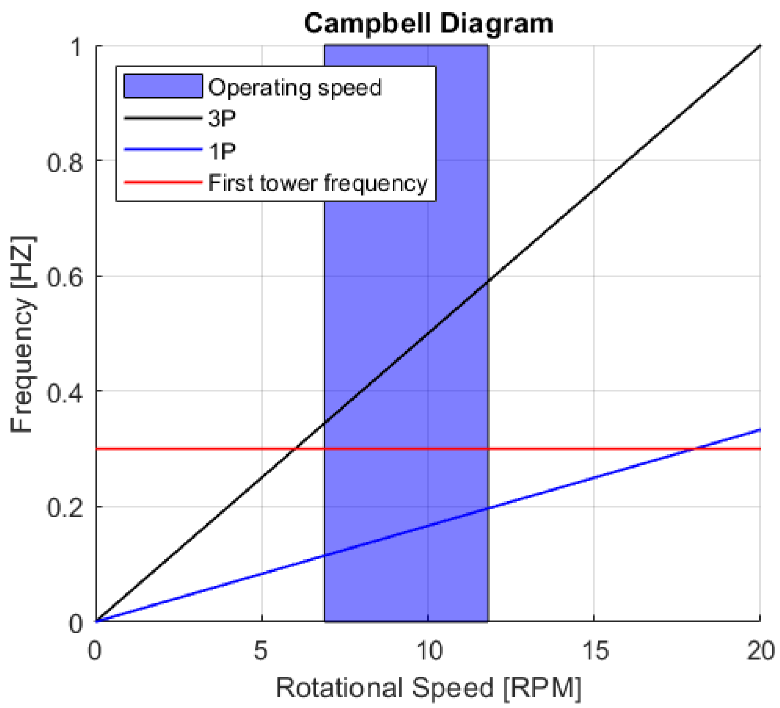

Figure 2.3: Example of a campbell diagram based on the NREL 5MW turbine. It important to make sure that the 1P and 3P lines do not cross the First tower frequency line within the area of the operating speed of the wind turbine.

2.8 Foundation

Foundations for modern onshore wind turbines usually consists of a concrete structure, depending on the soil conditions, different types of foundations can be used. In soft soil, a gravity foundation is used that relies on the weight of the foundation for stability. If there is solid rock where the wind turbine is placed, the foundation can be anchored to the rock and the amount of concrete and the cost of the foundation is significantly lower [3].

3

Wind Turbine Modelling

In this chapter, the principles of wind turbine modelling will be described and common assumptions and concepts will be outlined. A simulation model for wind turbines need to capture a number of interacting physical mechanisms, including the dynamics of all structural components, the wind field and its effect on the structure, the electrical system and the mechanical drive train.

3.1 Wind field

Proper modelling the wind field is of great importance for wind turbine simulations and the turbulent characteristic of the wind means that the speed and direction varies significantly on different parts of the turbine and over short periods of time.

The general characteristics of the wind varies depending on the site where the wind turbine is erected this is described in the wind turbine standard [4], by a set of classes that specify general wind speed and turbulence intensity. The standard also specifies a number of load cases that should be checked for wind turbine design. The load cases describe wind fields that can be combined with different occurrences of faults of the wind turbine e.g. control system faults, these combinations may put high stress on the wind turbine structure. Some of the load cases are for ultimate limit state, such as the EOG case and the turbulent storm cases, others are fatigue load cases where the turbine is subjected to turbulent winds over time.

To model the turbulent wind fields, a frozen field approach can be used where a rectangular space is filled with wind vectors is translated past the turbine as illustrated in figure 3.1, this has the same effect on the rotor as a wind field continuously changing over time. As the turbine structure deflects, it can do so inside the rectangular space.

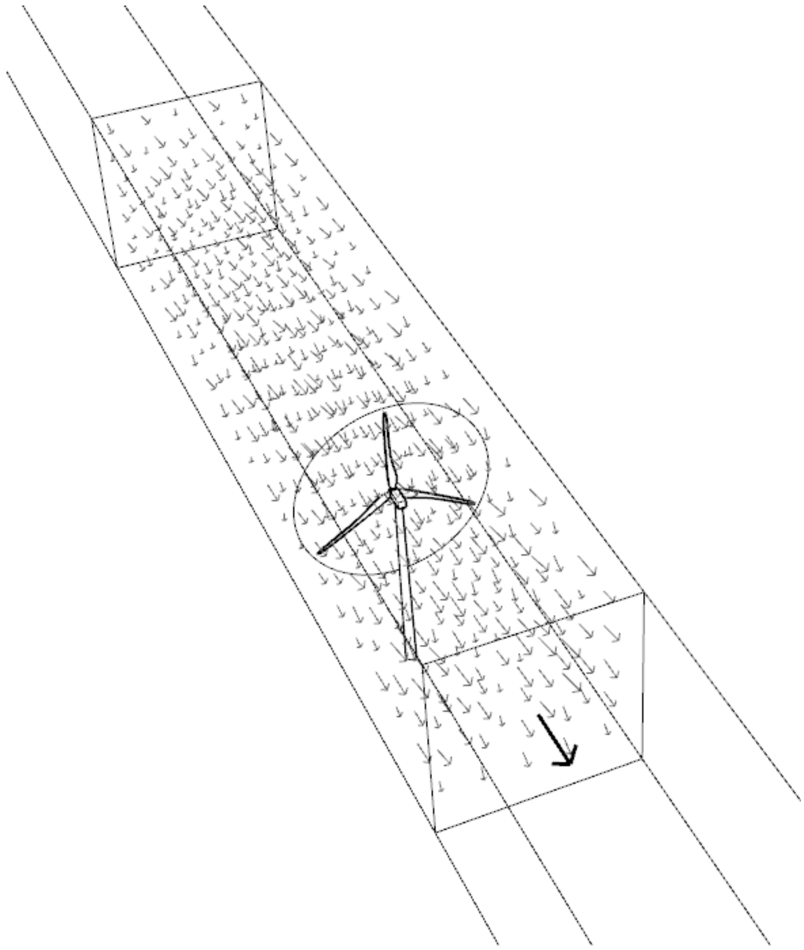

Figure 3.1: Illustration of a frozen vector field. the rectangular block, filled with vectors of different lengths and directions, moves across the wind turbine model at a steady pace during the simulation.

3.2 Blade element momentum

The purpose of the Blade element momentum [BEM] theory is to find the forces acting on the blades as they interact with the wind, it is often used due to its sufficient accuracy and low computational cost. It accounts for the effect of the slowing wind speed through the turbine as well as the rotation of air induced by the turbine [2].

The blade is divided along its length into a set of blade elements, the forces acting on each element is determined by the local wind vector and the properties of the airfoil. As the total angular and axial momentum, of the air and the turbine, stays constant, the induced wind speeds can also be calculated. It is assumed that the elements are independent, i.e. the elements do not affect each other.

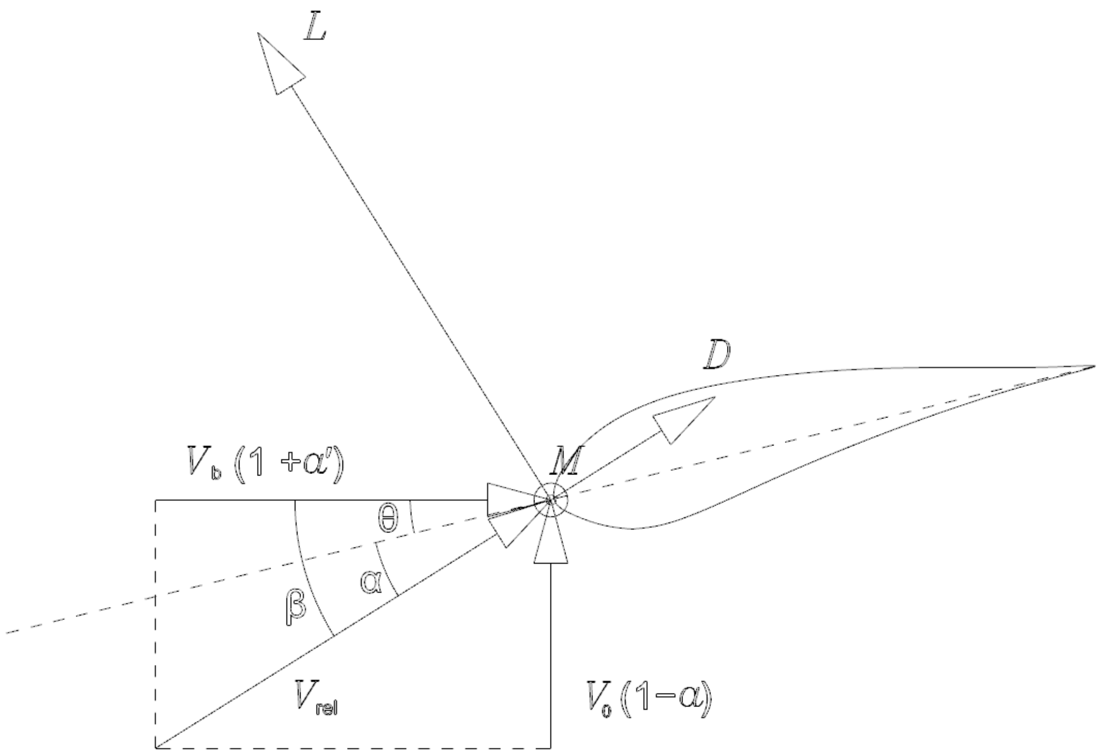

Figure 3.2: Principle illustration for the blade element momentum theory.

Figure 3.2 illustrates the forces, lift L and drag D and the torsional moment M acting on the blade element as well as the relative wind speed vector V_{rel}, its composants $V_b(1 + a')$ and $V_0(1 - a)$, where a' and a are the tangential and axial induction factors. The angle θ is the sum of the twist angle and blade pitch angle, α is the angle of attack and β is the angle between the relative wind vector and the blade movement vector. According to the airfoil theory, the forces acting on a blade element depends on the wind speed, plane area, air density, the angle of attack and a set of coefficients related to the shape of the airfoil. The forces are calculated according to the following equations:

$$L = \frac{1}{2}\rho V^2 S C_L \tag{3.1}$$

where L is the lift force, ρ is the air density, V is the relative air speed, S is the plane area of the blade element and C_L is the lift coefficient,

$$D = \frac{1}{2}\rho V^2 S C_D \tag{3.2}$$

where D is the drag force and C_D is the drag coefficient,

$$M = \frac{1}{2}\rho V^2 S C_M \tag{3.3}$$

where M is the torsional moment and C_M is the torsional moment coefficient.

The coefficients, C_L, C_D and C_M are in turn dependent on the angle of attack α) which is the angle between the relative wind vector, V_{rel} and the chord line of the blade profile, as illustrated in figure 3.2. In figure 3.3 we can see an example of how the three coefficients, C_L, C_D and C_M, relate to the angle of attack for a certain blade profile.

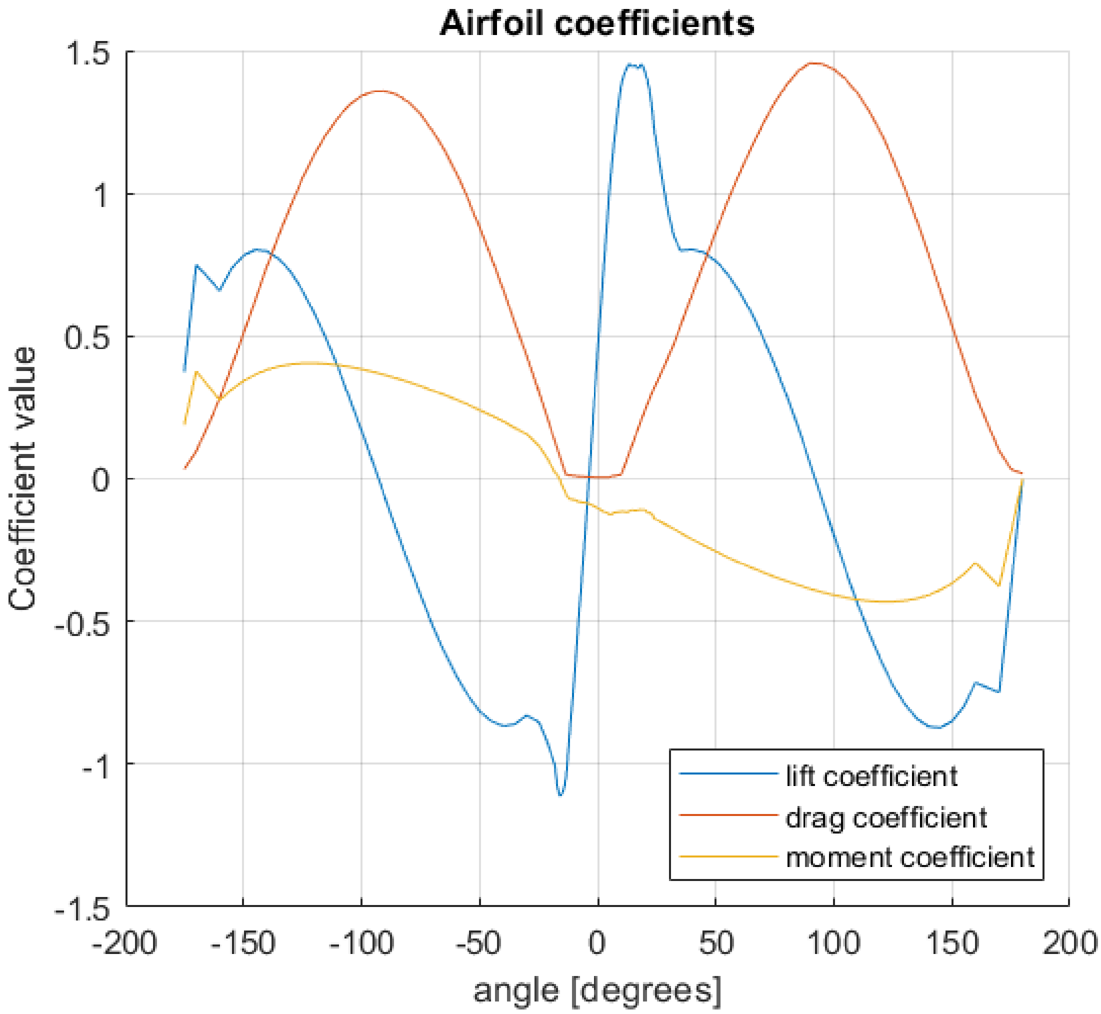

Figure 3.3: Airfoil coefficients as functions of the angle of attack

In order to calculate the lift, drag and moment forces, the vector V_{rel} needs to be found and it is calculated as,

$$V_{rel} = V_w + V_{tan} \tag{3.4}$$

where V_W is the axial vector composant and V_{tan} is the tangential vector composant. As mentioned in section 2.1, the turbine influences the airflow, slowing it down and making it twist. In the BEM theory, this effect is described by the axial induction factor, a and the tangential induction factor a' respectively. The vector V_{tan} is then calculated as

$$V_{tan} = V_b(1 + a'). \tag{3.5}$$

The vector V_w is calculated as

$$V_w = V_0(1 - a). \tag{3.6}$$

To complete the system of equations we also need the following expressions:

$$\sigma' = \frac{Bc}{2\pi r} \tag{3.7}$$

σ' is the local solidity factor which describes the sum of the cord lengths of all blades in relation to the circumference, at the local radius. B is the number of blades, c is the cord length and r is the local radius of the blade element.

$$\lambda_r = \frac{|V_b|}{|V_0|} \tag{3.8}$$

λ_r is the local speed ratio, i.e. the relation between the wind speed and the velocity of the blade element.

$$\beta = \arctan\left(\frac{1 - a}{\lambda_r(1 + a')}\right) \tag{3.9}$$

β is the angle between the tangential vector, $V_{tan} = V_b(1 + a')$ and the relative wind vector V_{rel} as can be seen in figure 3.2.

F is a factor describing the tip- and hub-losses, this is calculated according to the following equations:

$$F = F_{tip}F_{hub}, \tag{3.10}$$

$$F_{tip} = \frac{2}{\pi}\arccos(e^{-f_{tip}}) \tag{3.11}$$

$$f_{tip} = \frac{B}{2}\frac{R - r}{r\cos\beta} \tag{3.12}$$

R is the radius of the rotor .

$$F_{hub} = \frac{2}{\pi}\arccos(e^{-f_{hub}}) \tag{3.13}$$

$$f_{hub} = \frac{B}{2}\frac{r - R_{hub}}{r\cos\beta} \tag{3.14}$$

R_{hub} is the radius of the hub.

The induction factors a and a' are given by the following equations:

$$a = \left(1 + \frac{4F\sin^2\beta}{\sigma'(C_L\cos\beta + C_D\sin\beta)}\right)^{-1} \tag{3.15}$$

$$a' = \left(-1 + \frac{4F\sin\beta\cos\beta}{\sigma'(C_L\sin\beta - C_D\cos\beta)}\right)^{-1} \tag{3.16}$$

To solve this system of equations, an iterative process is normally used. [13]

3.3 Blade and Tower Flexibility

The structural dynamic properties of the blades and the tower need to be properly modelled in order to ensure the structural integrity of the wind turbine. It is important to capture the right stiffness, eigen frequencies and modes as well as damping properties.

The tower and blades are essentially cantilever beams and shall be modelled as such. Beams can be modelled in different ways, for example by the finite element method, Bernoulli beam theory, elementary cases, modal analysis etc. [16]

3.4 Mechanical, Electrical and Control Systems

The dynamic properties of the drive train can to some extent be modelled in isolation from the rest of the wind turbine. The frequencies of the torsional vibrations of the drive train is studied and compared to the rotational speed of the generator. It is important to make sure that there is no excitation at the eigen frequencies. The eigen frequencies are governed by inertia and torsional stiffness of the different parts of the drive train, including the turbine, the main shaft, the gearbox and the rotor of the generator [3].
The generator torque is controlled directly according to the torque/speed curve described in section 2.6. The generator power output can be modelled simply by multiplying the torque, the rotational speed and an efficiency factor [8].

$$P_{gen} = t\theta\eta \tag{3.17}$$

Here P_{gen} is the power output, t is the generator shaft torque, θ is the rotational speed and η is the generator efficiency factor.
The blade pitch is controlled by a PI-regulator. The angular velocity of the blade pitch is limited by the mechanical system that rotates the blades, this value can have significant impact on the behaviour of the turbine in certain load cases.

4

Wind Turbine Tool in Dymola

In this chapter, the tool that has been developed in this project will be described in detail, including the different parts of the tool an how they have been programmed.

4.1 Software

Dymola is a modelling and simulation environment, based on the object-oriented programming language Modelica that enables non-causal programming which is useful for modelling and simulation. Many physical systems, such as wind turbines and other machines, can be described mathematically by systems of equations, the non-causal modelling allow simulation of models directly described by their governing system of equations. The model developer does not need to perform the tedious and error prone task of reformulating the equations to solve for any particular variables, this is instead done automatically in the initialization step where the software generates efficient code for the simulations. The non-causal modelling profoundly changes the work of the model developer and allows for a different code structure that also enables multi-purpose use of functions describing components in a model [5]. In the Dymola environment, models can be created in a graphical interface where different components are connected in accordance to the corresponding physical connections, this makes the modelling intuitive and simplifies the overview of the model structure. It is possible to use components from openly available libraries such as the Modelica standard library and new components can also be defined in the Modelica language, this allows for large flexibility in the modelling work [6]. There are a number of different integration algorithms available in Dymola. When a model is set up and ready for simulation, the user can choose the algorithm based on the different properties of the model. In this project it has been found that the ESDRIK algorithm is efficient and gives accurate results, it is described as A-stable, meaning that it is suitable for systems with discontinuities or events and it is also suitable for stiff systems.

4.2 Main Model

The model shown in figure 4.1, is divided into three main sub-models, the tower, the nacelle and the rotor, the tower base is connected to a world component where the origin frame of reference is defined as well as a gravitational field. The sub models are connected via local frames of references ensuring that the orientation and position of the components align, forces and moments are also transferred between the sub-models. Other information can also be passed between the different components, i.e. the rotational speed of the turbine.

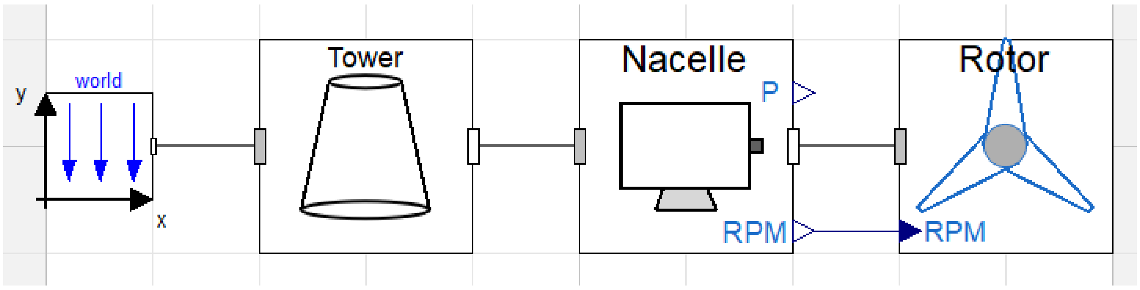

Figure 4.1: Main model diagram

4.3 Foundation

A real foundation is not completely rigid and therefore it has an effect on the total stiffness of the wind turbine structure. It is possible to model the foundation by a rotational spring, in this project, the deformations of the foundation will not be considered and it will be modelled as a rigid connection.

4.4 Tower

The tower is built up by a set of beams elements with certain stiffness, inertia, and damping properties see figure 4.2.

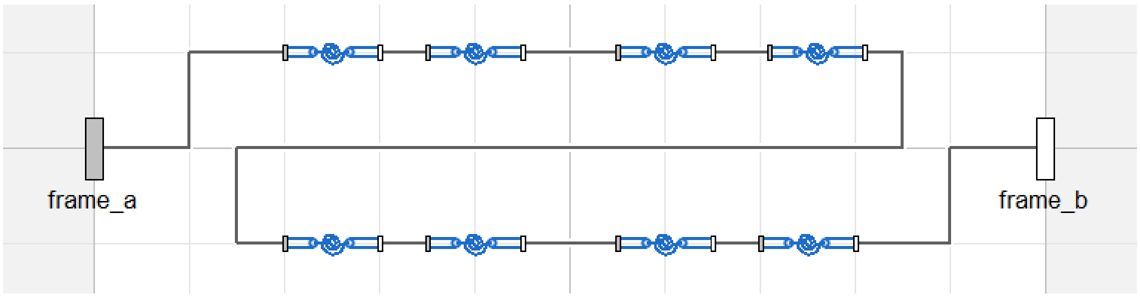

Figure 4.2: Tower model diagram

4.4.1 Beams

A simplified beam model has been utilized, modeled with the existing mechanical components from the open Modelica standard library, the model can be seen in figure 4.3. Bending and torsional deformations are captured by by this type of model while longitudinal and shear deformations are neglected.

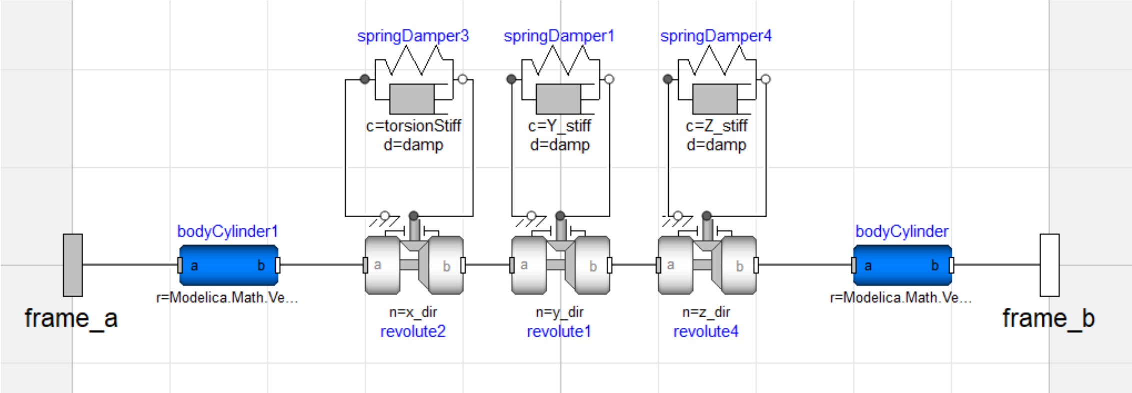

Figure 4.3: Beam model in Dymola

The beam model needs to capture bending in two directions as well as torsion. One way to achieve this is to create a beam by two rigid bodies connected by a set of springs that allow rotation around 3 axes with a certain stiffness. Since beam bending stiffness is usually quantified by the elasticity modulus E and the second moment of inertia I, the spring stiffness needs to be derived from these parameters. The torsional spring stiffness is described by,

$$M = c\phi \tag{4.1}$$

Where M is the moment, c is the spring stiffness and ϕ is the rotation. The tip of a cantilever beam subjected to a bending moment will rotate according to

$$\phi = ML/EI \tag{4.2}$$

Where L is the beam length, E is the modulus of elasticity and I is the second moment of inertia [7]. By combining equations 4.1 and 4.2 we get the spring stiffness for the beam bending.

$$c_b = EI/L \tag{4.3}$$

Such a beam model will properly describe the deflection under a pure bending moment load but not under a lateral force load. This problem can be handled by discretization of a beam into several elements. A convergence study was performed showing that satisfactory accuracy is achieved with around 6 beam elements as can be seen in figure 4.4.

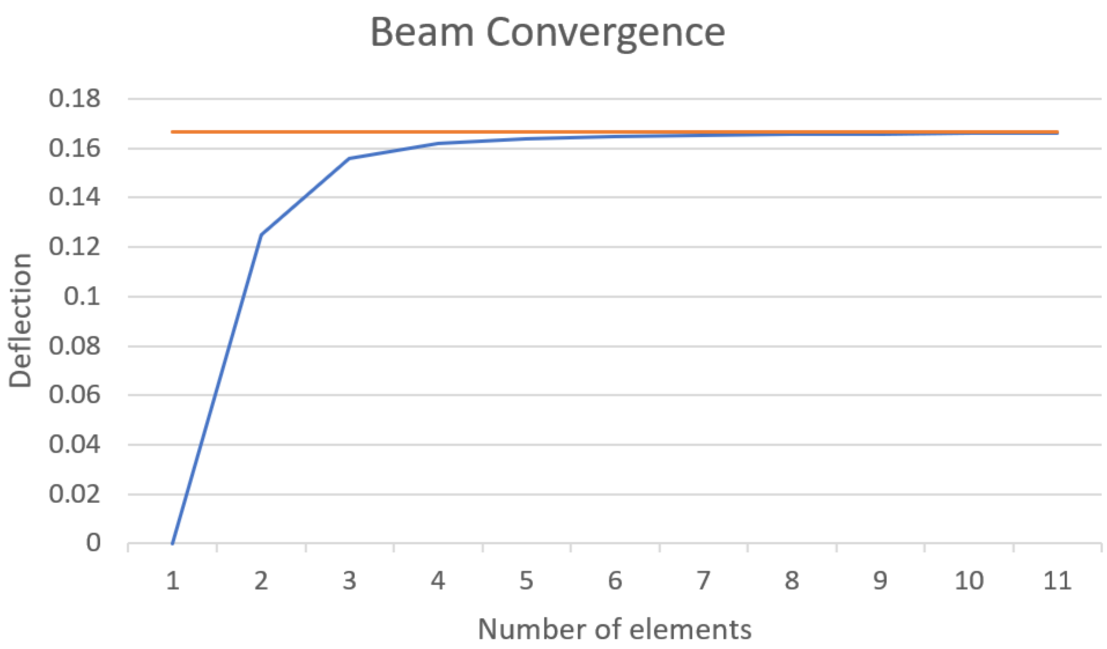

Figure 4.4: Beam deflection convergence study under point load at the tip

A study of eigen frequencies also showed good agreement between the discretized beam and analytical beam vibration calculations.

The torsional spring stiffness is derived by

$$\phi = ML/GI_p \tag{4.4}$$

Where L is the beam element length, G is the shear modulus and I_p is the second polar moment of area. Combining equations 4.1 and 4.4 gives the torsional spring stiffness:

$$c_t = GI_p/L \tag{4.5}$$

4.5 Nacelle

The nacelle component, figure 4.5, consists of a drive train including the mechanical and electrical system and an inertial body, positioned at the center of mass of the nacelle.

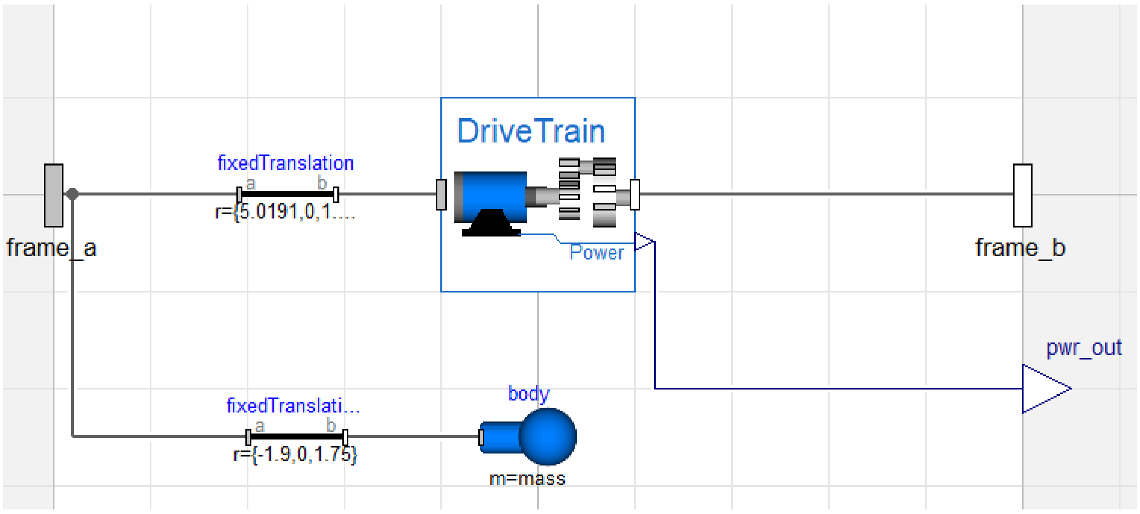

Figure 4.5: Nacelle model in Dymola

4.5.1 Drive Train

The drive train component, figure 4.6, is modelled by a rotational bearing that represents the generator. The torque of the generator is controlled according to a torque/speed curve such as the one seen in figure 2.2. If the rotation speed reaches a certain cut-off value, the torque is set to zero. The generator may be connected to a gearbox which in turn connects to the turbine hub, with a direct drive system, the generator is connected directly to the turbine hub. The electrical power output is calculatde by multiplying the rotational speed with the generator torque and efficiency.

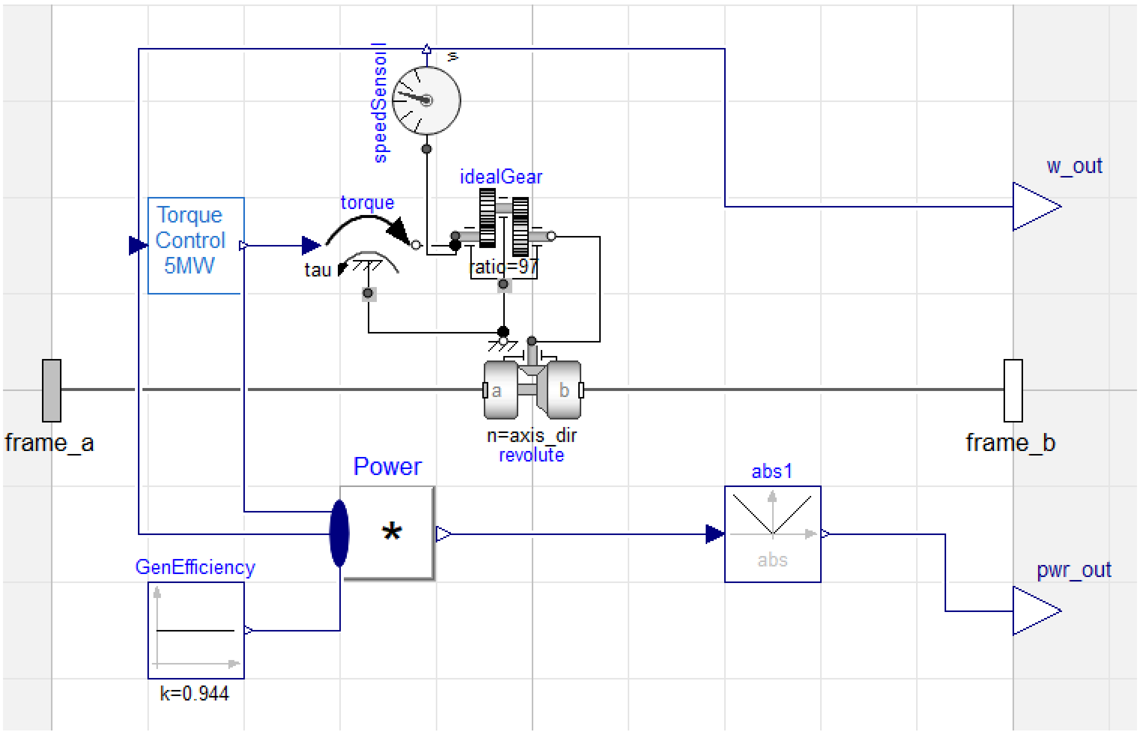

Figure 4.6: Drive train model in Dymola

4.6 Rotor

The rotor component, seen in figure 4.7, is made up of a hub, three blades and a pitch control unit. At wind speeds above rated wind speed, the rotational speed of the rotor is controlled by pitching the blades which limits the amount of energy extracted form the wind.

The pitch angle is controlled by a PI-regulator, which aims to hold the turbine at the rated rotational speed. In the Dymola there are predefined components for P-, PI-, and PID-regulators which are used in this project.

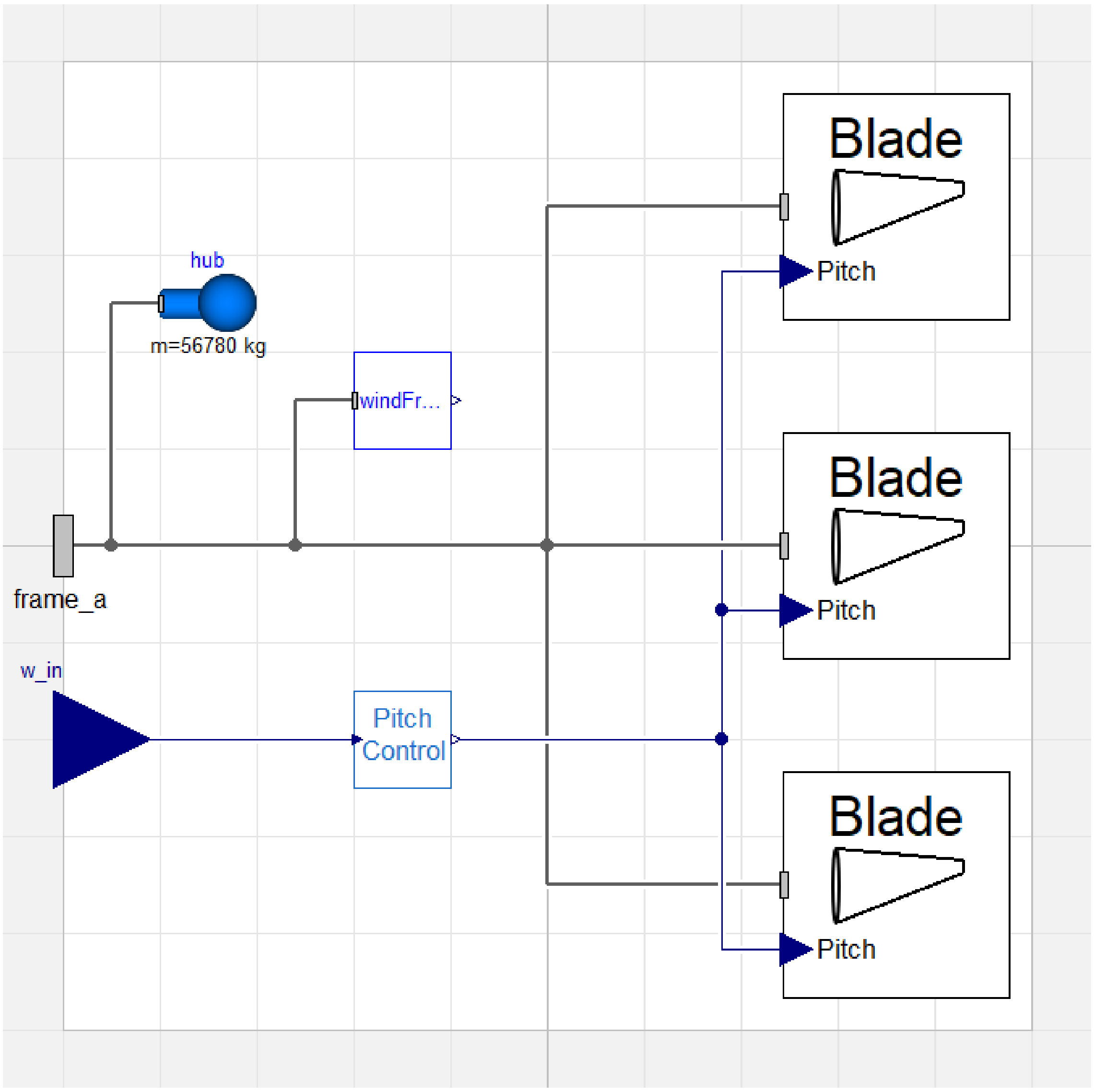

Figure 4.7: Rotor model in Dymola with the hub represented by an inertial body, the three blades are connected to the hub and the pitch control has the rotational speed as an input and outputs the pitch angle which is read by the blade components.

4.7 Blades

The blades are made up of a number of blade elements that are in turn built up by three types of components, beam elements, wind source components and BEM components. The beam elements, described in detail in section 4.4.1, represent the mechanical properties with mass, stiffness and damping. The wind source components contain wind vectors in tabulated form, which have been generated outside of the Dymola tool either using matlab or turbsim, the wind vectors vary in space and time and their value is continuously extracted from the tables based on time and the position of the blade element. The BEM component calculates the forces acting on the blade element according to the theory describedin section 3.2, the Modelica code of this component can be seen in appendix A. The airfoil properties, lift, drag and torque coefficients as functions of the angle of attack are stored in tables. Limits are set to the induction factors a and a' in order to make the simulation more stable, the limits make up a simplified approach to the Glauert correction used in FAST [14] The number of blade elements cannot be too high, or the model will be very computationally heavy. Figure 4.8 shows an example of a blade component in the Dymola tool.

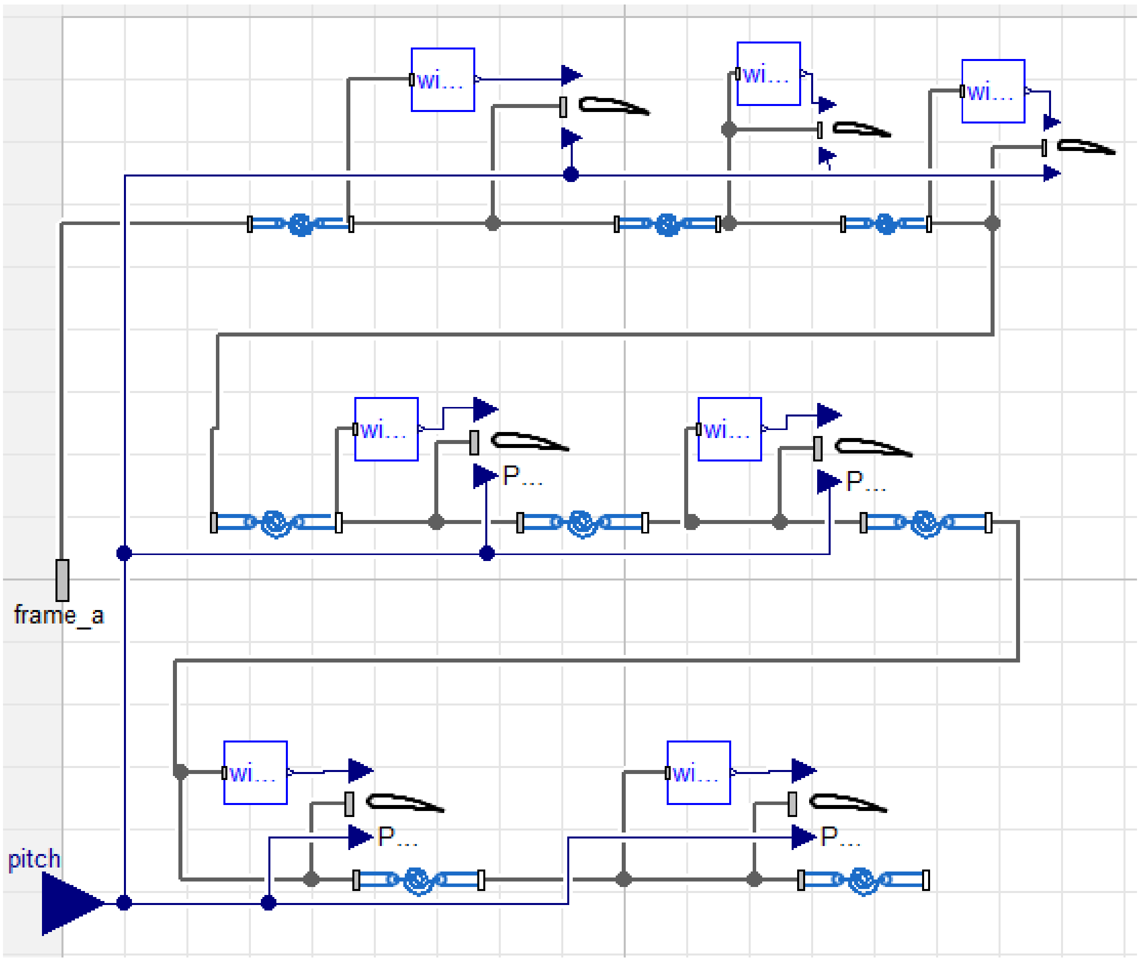

Figure 4.8: Blade model in Dymola with seven blade elements, each consisting of a beam element, a BEM element and a wind source component.

4.8 Wind field

A frozen field approach is used, as described in section 3.1. The frozen wind fields are stored as large tables of vectors, which have been generated outside of the Dymola environment.
Turbulent wind fields have been generated using the software turbsim and then formatted to nd-tables readable by Dymola using a matlab script. The Ramp and EOG wind fields have been generated directly in matlab according to the wind turbine standard [4].

5
Tool Verification

In this chapter, the accuracy of the tool is evaluated, since no field measured data is available for the turbines in question the verification is made by comparing the results of identical simulations made with the acknowledged software FAST [17] and Vidyn [18].

5.1 Models

Two different wind turbine models have been studied in this project, they have been chosen due to the availability of information about their design.

5.1.1 Chalmers Research Wind Turbine

The Chalmers Research Wind Turbine on Björkö, is a small wind turbine with a rated power of 45 kW. The turbine has a rotor diameter of 16 meters and is supported by a 30 meters tall wooden tower constructed by Modvion. This model has been used for the comparison between the Dymola tool and Vidyn

5.1.2 NREL 5MW Turbine

The second turbine that has been studied is the NREL 5MW reference turbine which is a benchmark model often used in wind turbine research. The turbine has a rotor diameter of 126 meters and is supported by a 89 meters tall steel tower [9]. This model has been used for the comparison between the Dymola tool and FAST.

5.2 Load cases

Three types of load cases have been selected for the studies, there are many more relevant load cases for wind turbines but the studies need to be limited and the selected load cases are useful for comparisons and are often critical for the design of the structural components of a wind turbine.

5.2.1 Ramp case

To verify a good behaviour of the models in different wind speeds, the Ramp case is used. This case starts with a wind speed just above the cut in speed, it is kept constant until the model has stabilized from the initiation event. The wind is then increased linearly up to the cut of speed, which is the wind speed where the turbine is shut off to prevent high loads on the structural components. As the wind speed increases, so does the rotational speed of the rotor and the torque of the generator as the different torque regions are passed. When the rated speed is reached, the turbine blades start to pitch and the rotational speed and torque are kept constant. This load case is used for comparison between the Dymola tool and both Vidyn and FAST.

5.2.2 EOG case

The Extreme Operating Gust [EOG] case is often critical for ultimate limit state of the structural components of a wind turbine. Therefore, it is important to make sure that the dymola tool is able to simulate such a load case. The case is defined in the wind turbine standard [4] and is characterized by a steady wind which suddenly changes by first decreasing and then increasing rapidly over a few seconds and then return to the original speed.

In this load case, the wind speed increases so rapidly that the pitch mechanism of the blades is unable to keep the turbine at rated speed. When a certain cut-off speed is reached, the generator shuts off and the torque goes to zero. This causes the turbine rotation speed to increase even faster and when the wind speed starts to decline rapidly, the turbine keeps rotating due to the angular momentum built up in the rotating parts, and the rotor starts to propel the turbine in the upwind direction which in combination with the front heavy turbine and nacelle structure causes a large negative bending moment in the tower base. This load case is used for comparison between the Dymola tool and Vidyn.

5.2.3 Turbulent case

Since the wind is always more or less turbulent, turbulent load cases need to be studied in order to estimate the energy producing ability of a wind turbine. They are also of great importance considering the fatigue resistance and ultimate strength of all structural components.
The turbulent wind fields have been generated using turbsim, this has made it possible to run the exact same wind conditions in the Dymola tool as in the reference software FAST.
A few different turbulent cases have been studied but the main focus has been on a case with a reference wind speed of 10 meters per second since it varies around the rated speed of the turbines which is most critical and complex to simulate. This load case is used for comparison between the Dymola tool and FAST.

5.3 Verification results

The results from the verification study is presented and analysed in the following sections.

5.3.1 Chalmers turbine

The Chalmers turbine model in Dymola, was created based on information about the Vidyn model which included mechanical and aerodynamic properties of the different parts as well as parameters governing the generator and pitch control. Simulations with this wind turbine model have been made with the Dymola tool on the Ramp case and the EOG case, the results have been compared with the results from simulations made by Anders Wikström using the Vidyn software.

5.3.1.1 Ramp case

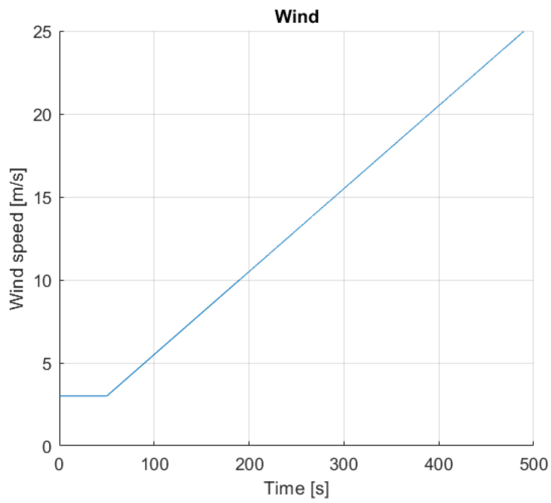

Figure 5.1: Wind speed for ramp case for the Chalmers turbine

In figure 5.1 we see the wind speed of the simulations of the ramp case run in both the Dymola tool and Vidyn. There is a constant wind speed of 3 m/s initially and after 50 seconds it begins to increase steadily up to 25 m/s.

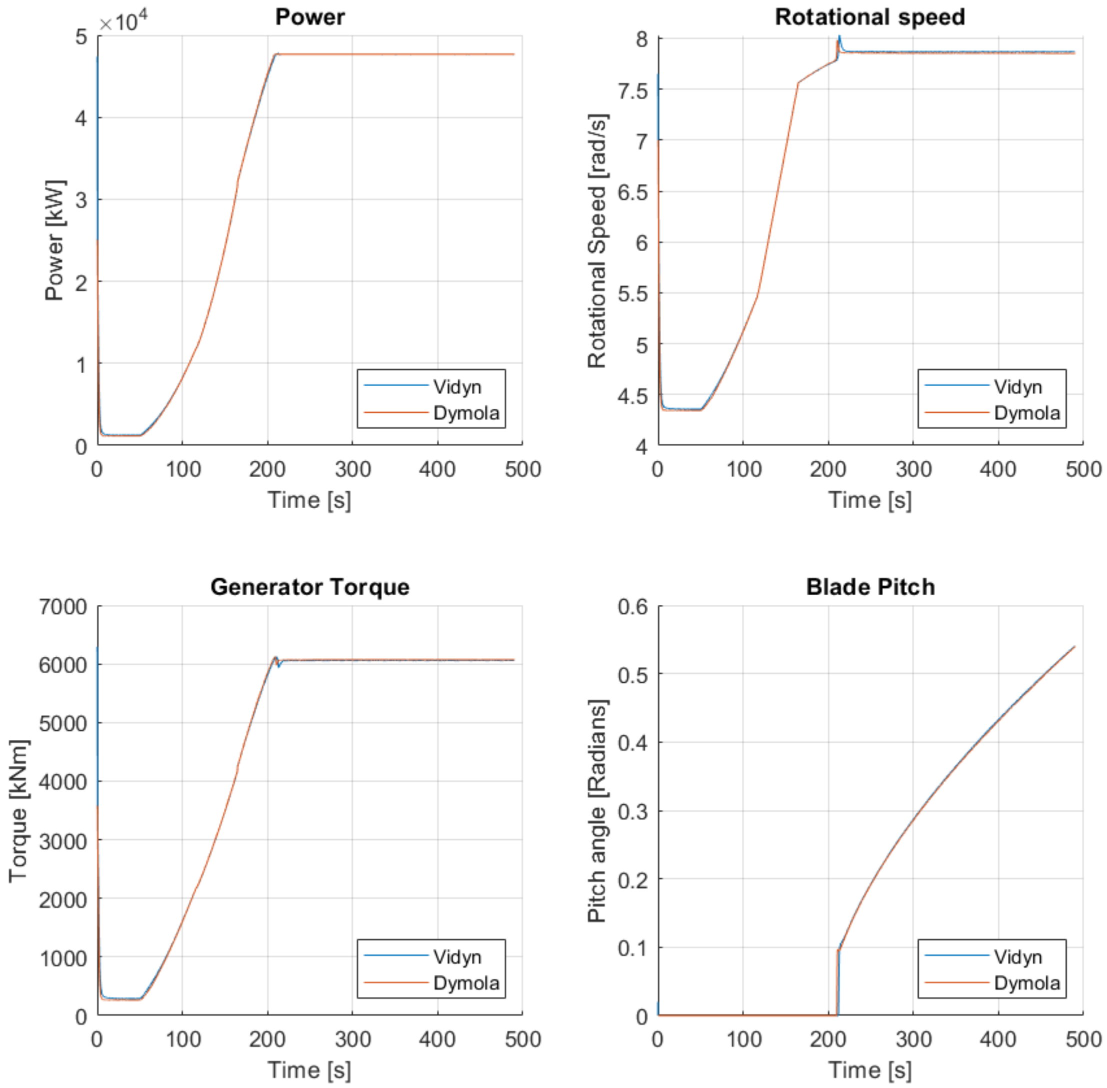

Figure 5.2: Results of machine parameters in ramp case for the Chalmers turbine

In figure 5.2 we can see the power in the upper left graph, after the initialisation event of about ten seconds it stabilizes at about 1 kW. After 50 seconds the power starts to climb as the wind speed increases, at around 120 seconds, the region 2 of the torque/speed curve is reached and the power climbs faster as the turbine is running at optimal tip speed ratio. After about 160 seconds, region 2.5 is reached, the generator torque is increased and the power climbs slightly slower up to rated power which is reached after about 210 seconds. We can see that the agreement between the two simulations is really good concerning the power output as well as rotational speed, generator torque and blade pitch angle, however, there is a small difference at 210 seconds when the rated power is reached, this difference is likely due to small differences in how the pitching of the blades is controlled by the PI-regulators in the simulations.

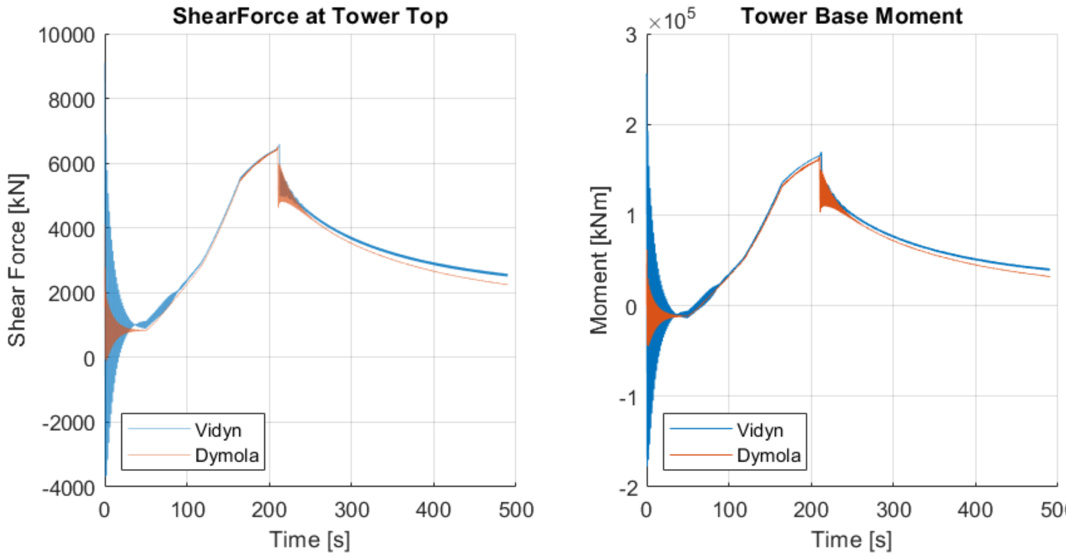

Figure 5.3: Results of machine parameters in ramp case for the Chalmers turbine

In figure 5.3 we can see the shear force at the tower top and the bending moment at the tower base. At the initiation event there is some oscillation of the forces which stabilize before the wind starts to increase. At 50 seconds, when the wind starts to ramp up, we can see how the loads on the structure increase, in region 2, the increase is most rapid and it slows in region 2.5. When the rated speed is reached after about 210 seconds, the pitching of the blades causes a clear drop in the thrust force which keeps decreasing as the blade pitch angle increases. The loads on the tower structure are similar for the two simulations, there are some differences in the initiation phase where the Vidyn simulation shows a much larger oscillation of the tower, this is likely due to differences in starting positions and since both simulations seem to stabilize at the same level, this difference is not of importance. There is also some difference between the simulations in the period between 50 and 80 seconds which could be connected to some excitation at the 3p frequency of the turbine that is present in the Vidyn simulation. At 210 seconds, where the rated speed is reached and the blades start pitching, there is also some differences which are likely connected to the PI-regulators as described above.

In general, good agreement between the two models was found for the ramp load case indicating that the dymola tool is capable of useful simulations for this wind turbine.

5.3.1.2 EOG

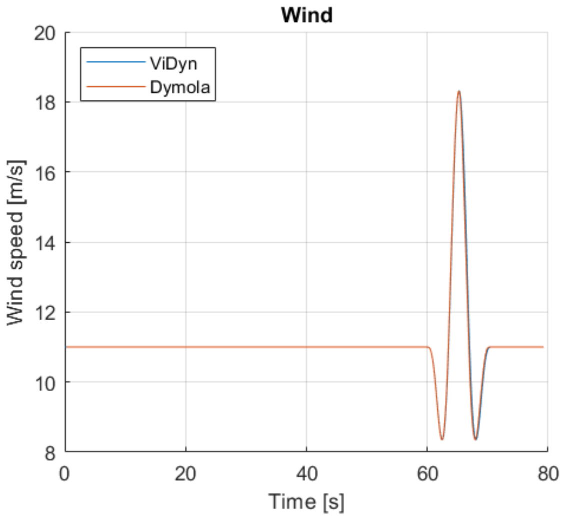

Figure 5.4: Wind speed at hub height for EOG case for the Chalmers turbine

In figure 5.4 we see the wind speed of the simulations of the EOG case run in both the Dymola tool and Vidyn. There is a constant wind speed of 11 m/s initially and at 60 seconds, it starts to decrease down to about 8 m/s before it rapidly increases up to 18 m/s and decreasing again to about 8 m/s before it returns to 11 m/s.

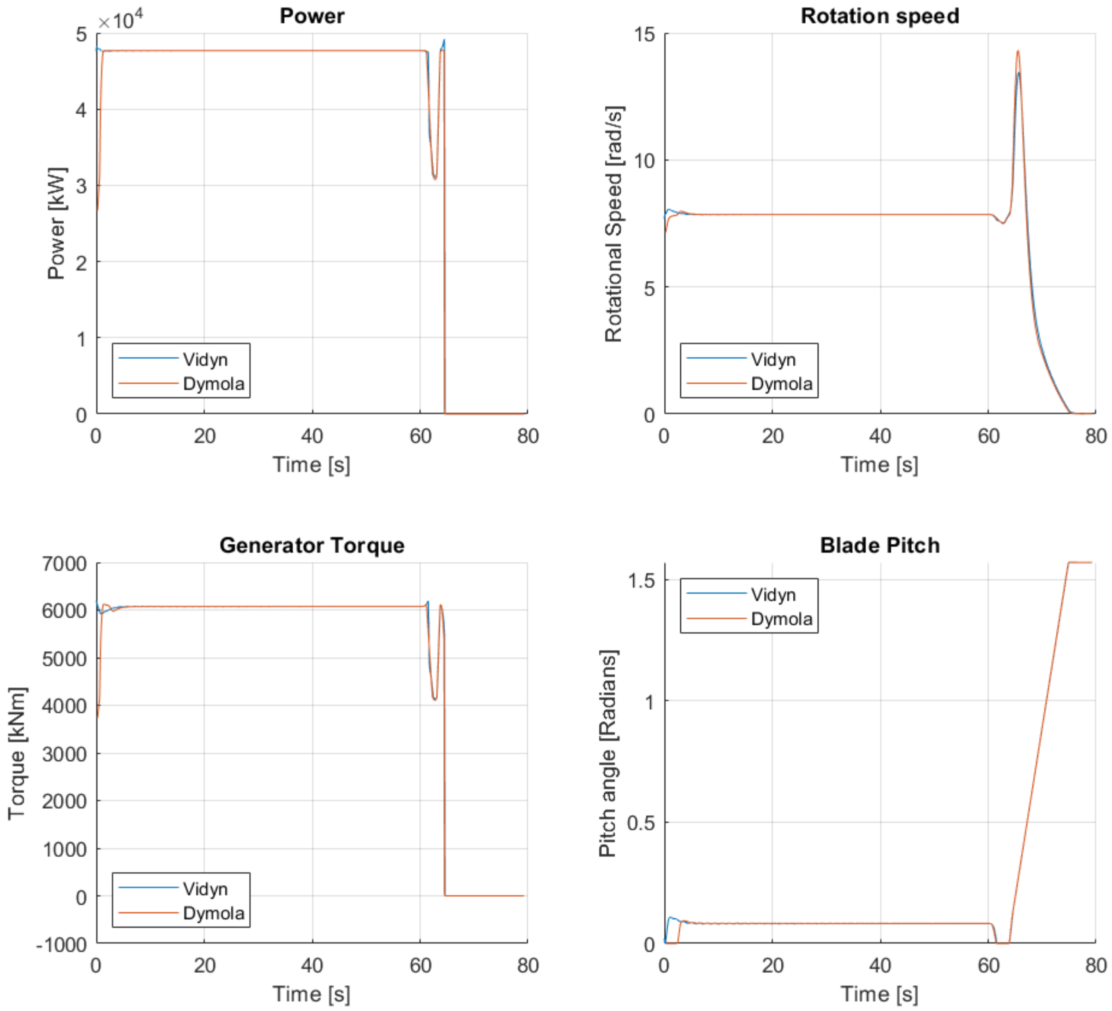

Figure 5.5: Results of machine parameters in EOG case for the Chalmers turbine

In figure 5.5 we can see that the power stays a constant level of 48 kW while the blades are slightly pitched at around 0.1 radians. The gust event begins at 60 seconds when the wind speed decreases, the power decreases to about 30 kW and the blade pitch is turned to zero for a few seconds until the wind increases again and the power returns to 48 kW, the blades begin to pitch out. A few seconds later we can see that the rotational speed keeps increasing and at a certain level, the generator torque is set to zero, this off course results in output power of zero as well. When the torque is set to zero, the rotational speed starts to increase drastically since the rotor is free to rotate, the emergency shut down procedure is initiated and the blade pitch angle keeps increasing in order to stop the rotor, however, the pitch mechanism is quite slow and the blade pitch angle remains quite low for a few more seconds while the rotational speed keeps increasing drastically up to about 14 radians per second. At this point the wind speed has started to decrease and the rotor begins to slow down due to aerodynamic drag.
We can see that the agreement between the two simulations is quite good concerning the turbine performance and machine control system. The Dymola tool shows a slightly higher maximum rotational speed, but considering the very dynamic char-

acteristics of this load case, the difference can be considered small.

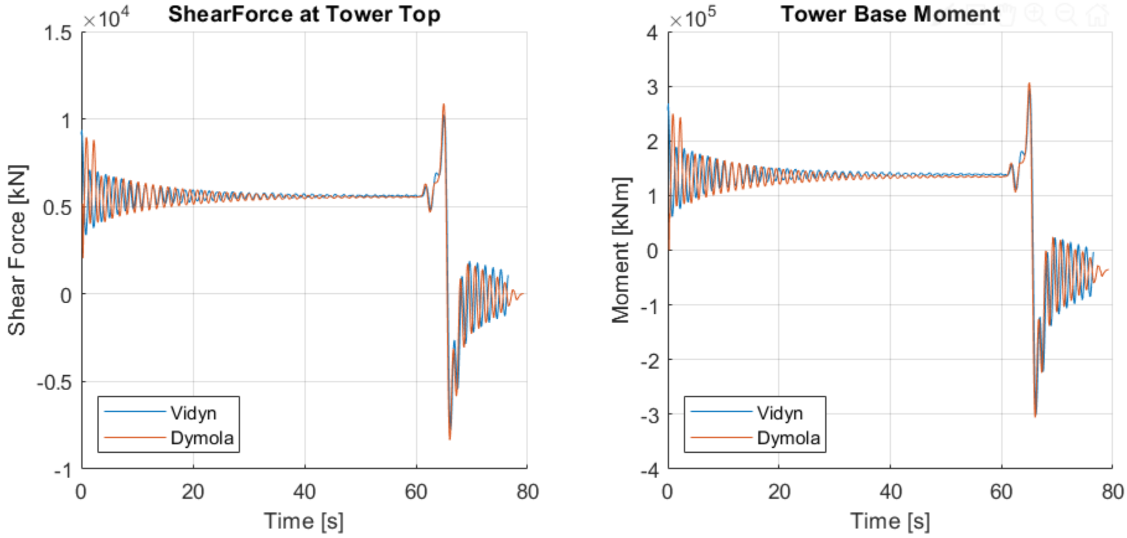

Figure 5.6: Results of structural parameters in EOG case for the Chalmers turbine

In figure 5.6 we can see that there are some oscillations from the initiation event that stabilize after about 40 seconds. There is a constant thrust force of about 5.6 kN during the steady wind of 11 m/s. The thrust force is clearly affected by the gust and peaks at about 11 kN when the highest wind speed is reached at 65 seconds.
At this point, the rotational speed is high and the wind speed decreases rapidly, the angle of attack of the blades will be negative which causes the rotor to propel the turbine in the upwind direction. This causes a large thrust force in the opposite direction of about 8 kN.
The Bending moment at the tower base is largely coupled to the force at the tower top but is also affected by the front heavy nacelle as well as the inertia of the tower mass.
Again we can see similar results from the two simulations, there is a slightly higher shear force and base moment which correlates with the higher rotation speed of the turbine.

5.3.2 NREL 5MW turbine

The 5MW NREL turbine model in the dymola tool was created based on information about the same model in the FAST software which is available on the NREL web page [10]. Simulations with this wind turbine model have been made with the dymola tool on the Ramp case and turbulent cases, the results have been compared with the results from simulations made using the FAST software which is also provided by NREL.

5.3.2.1 Ramp case

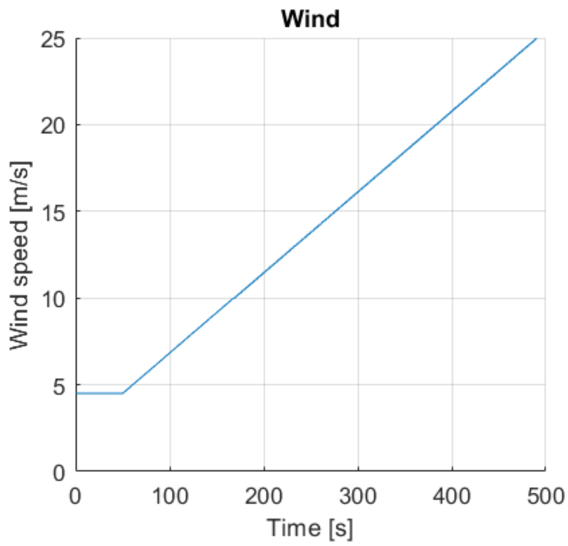

Figure 5.7: Wind speed for ramp case for the FAST 5MW reference study

Figure 5.7 shows the wind speed of the simulations of the ramp case run in both the Dymola tool and Vidyn. There is a constant wind speed of 4 m/s initially and after 50 seconds it begins to increase steadily up to 25 m/s.

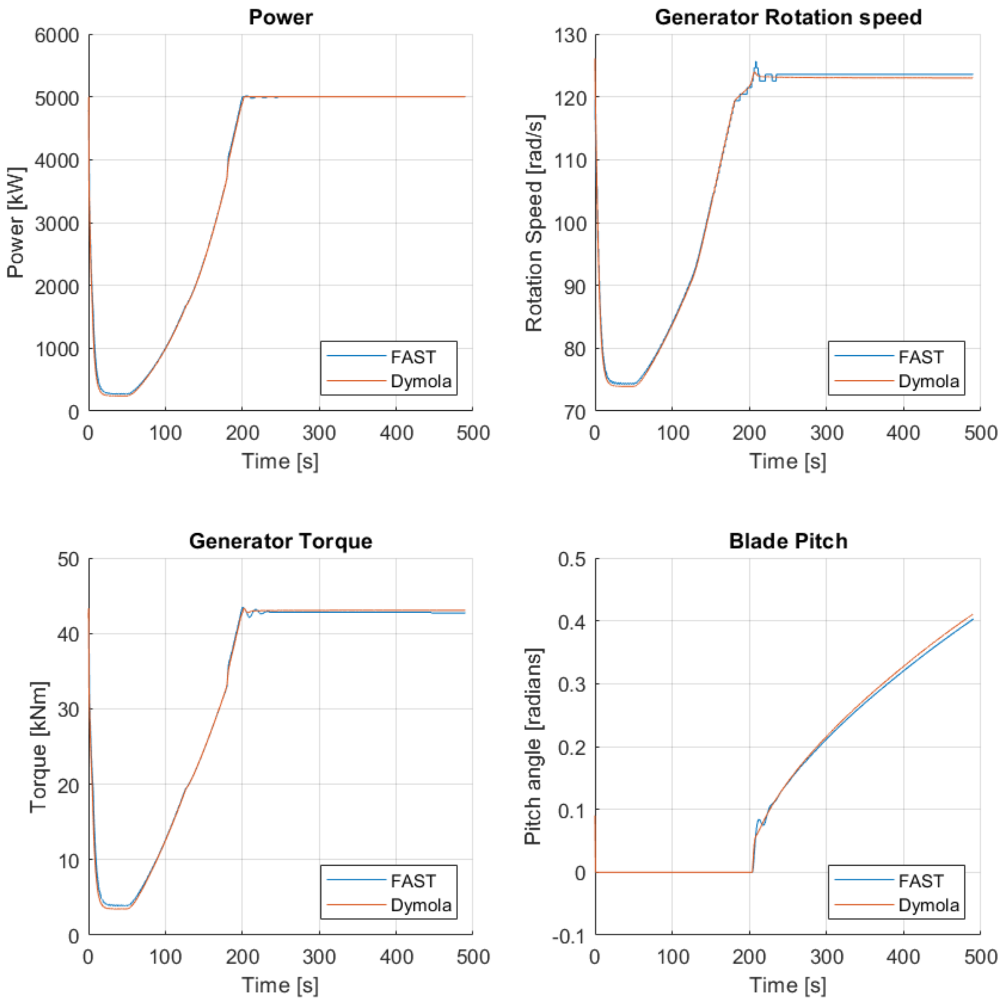

Figure 5.8: Results of machine parameters in ramp case for the FAST 5MW reference study

In figure 5.8 we can see that there is very good agreement between the two models concerning the turbine performance and machine control system. As with the Ramp case simulation for the Chalmers turbine, see section 5.3.1.1, we can see how the different regions of the torque/speed curve are passed as the wind increases from 4 up to 25 m/s, we also see how the power increases up until the rated speed is reached, it is then kept constant while the blade pitch angle is increasing. There is a mismatch at 210 seconds when the rated speed is reached, this is due to that the PI-regulators controlling the blade pitch, have not been modelled identically, the PI-regulator in the dymola model has been calibrated independently for optimal behaviour.

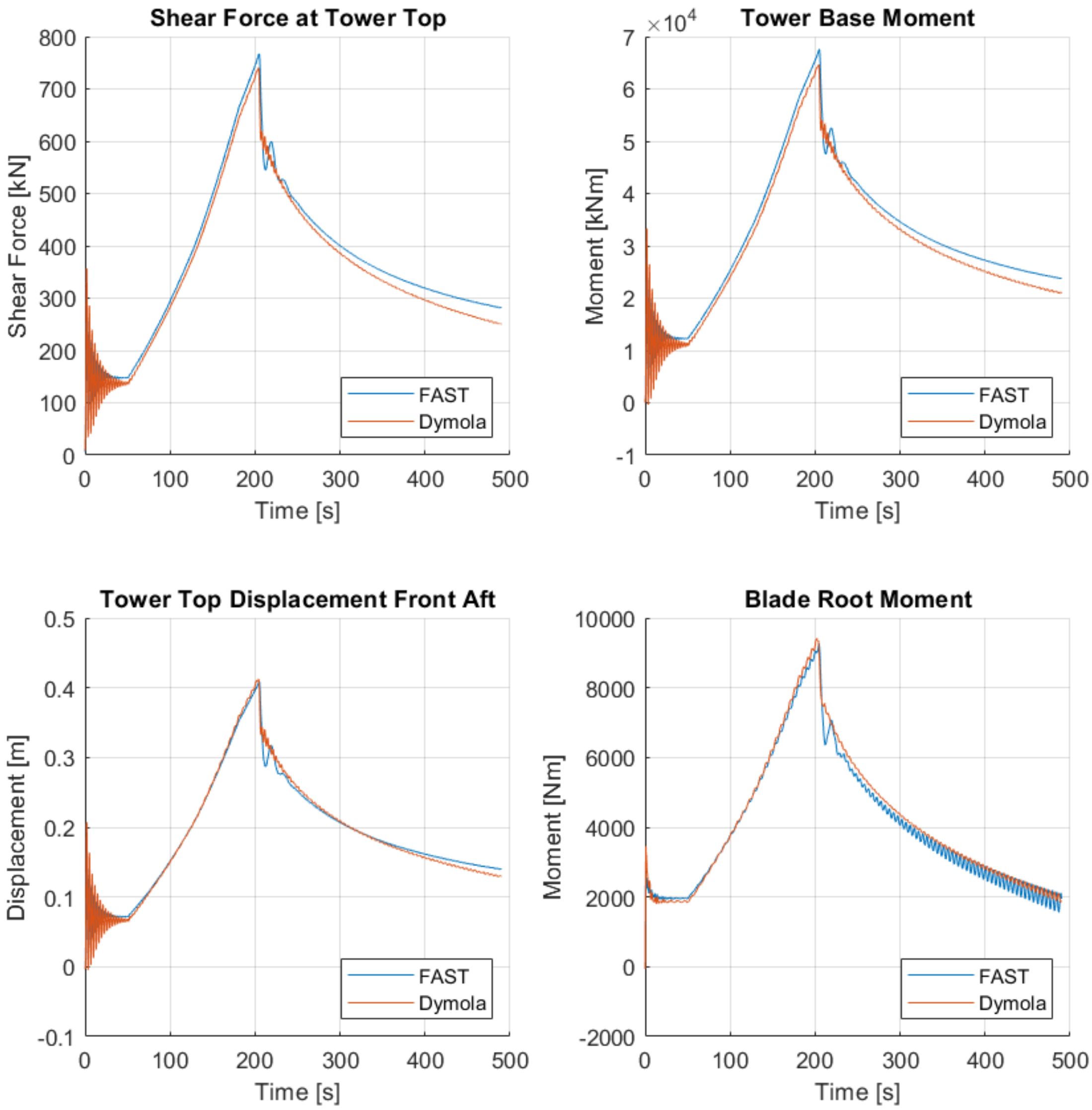

Figure 5.9: Results of structural parameters in ramp case for the FAST 5MW reference study

In figure 5.9 we can see that the forces acting on the tower are following a similar pattern as with the smaller Chalmers turbine but with different magnitude. We can also clearly see how the tower displacement and the blade root bending moment follow the same pattern.
There is good agreement between the two simulations concerning the structural loads and displacements. The shear force and bending moment on the tower are slightly lower in the Dymola tool simulation. The difference at 210 seconds is related to the PI-regulator settings as described above. We can see that the FAST simulation show some blade vibrations at high wind speeds that are not described by the vidyn tool simulation, this is likely due to a different damping setting in the blades.

5.3.2.2 Turbulent case

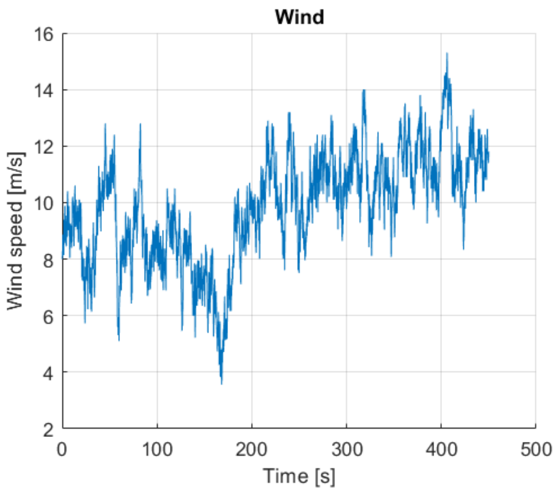

Figure 5.10: Wind speed for turbulent case for the FAST 5MW reference study

In figure 5.10 we see the wind speed at the rotor hub for the turbulent case. The reference wind speed is 10 m/s and we can see that the wind speed varies significantly with the lowest value below 4 m/s and the highest at 14 m/s. We can also see that the wind speed changes quite rapidly, between 55 and 60 seconds into the simulation, the wind speed drops by around 7 m/s.

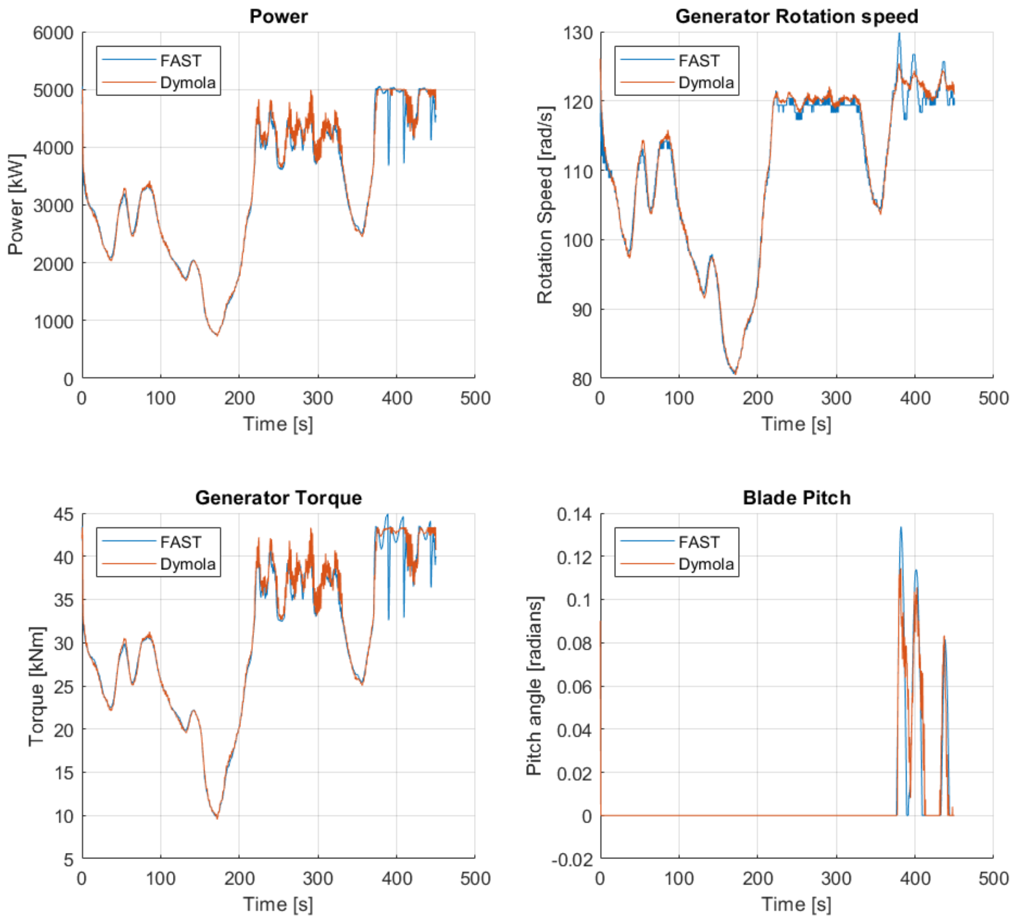

Figure 5.11: Results of machine parameters in turbulent case for the FAST 5MW reference study

In figure 5.11 we can see how the power, torque and rotational speed curves follow the wind curve while they are significantly smoother due to the angular momentum of the rotor. We can also see how the power stabilizes at a value of 5 MW when the general wind speed exceeds 11 m/s and the blade pitch system is activated. There is good agreement between the two simulations, concerning the turbine performance and machine control system while there are some differences where the rated speed is reached due to the settings of the PI-regulators for the blade pitch as mentioned in section 5.3.2.1.

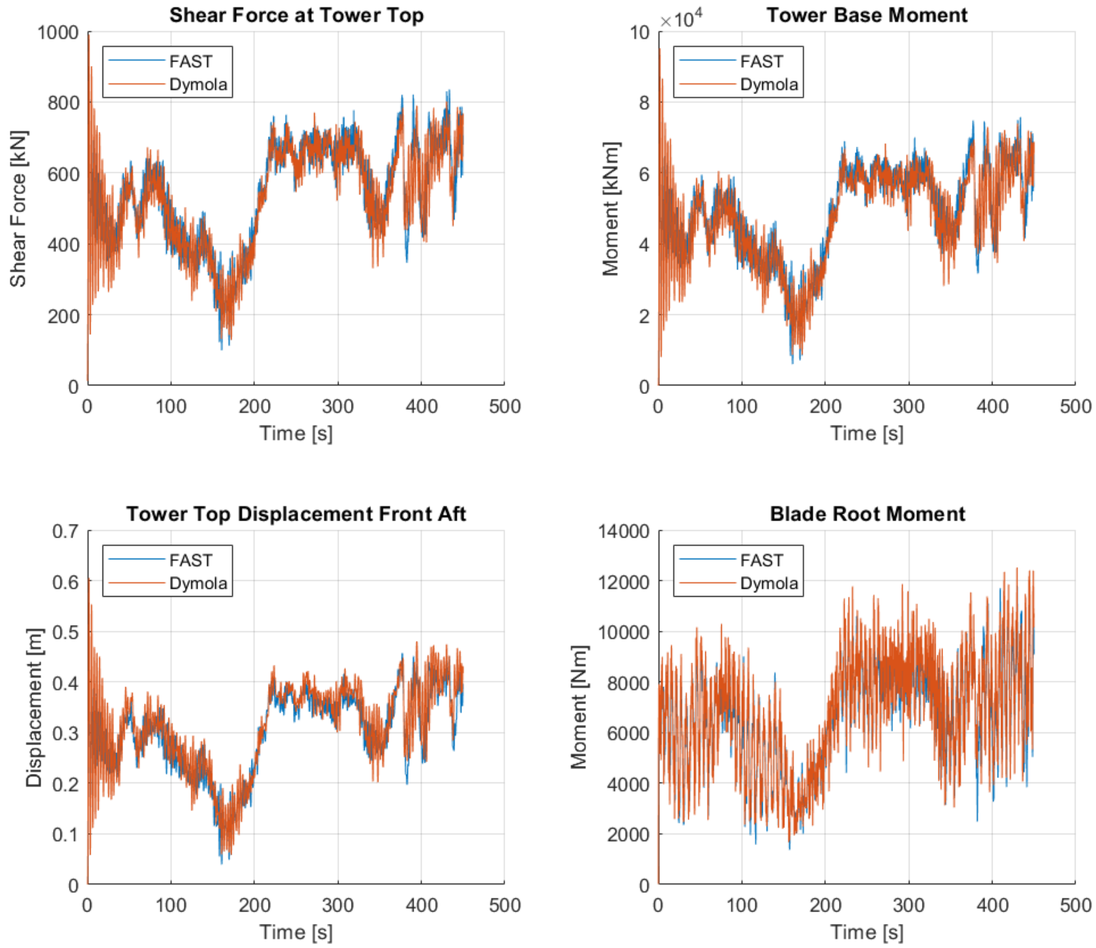

Figure 5.12: Results of structural tower parameters in turbulent case for the FAST 5MW reference study

In figure 5.12 we can see how the forces on the tower fluctuates quite rapidly but not quite as much as the wind, while the root moment on the rotor blade varies even more than the wind, likely due to some vibrations in the blade structure.
There is good agreement between the two simulations concerning the structural loads and displacements. The results are not trivial to compare, but the general forces and displacement are of the same size and the vibrations are of the same magnitude.

6

Example Studies

A few case studies made with the Dymola tool to give examples of how its usage are presented in this chapter. The same models and load cases as in the verification studies are used but with slight modifications. The studies are focused on how different design changes and parameters affect the loads on the tower structure.

6.1 Tower damping

The wind turbine towers of timber developed and built by Modvion have significantly higher material damping than steel towers, it is of interest to find out if higher damping in the tower might have a positive effect on the structural loads and the dynamical behaviour of a wind turbine. Other simulation software describe the damping properties by a damping ratio. A steel structure like traditional wind turbine towers normally has a damping ratio around 0.25% while a timber structure without mechanical joints has a damping ratio around 1% [11]. In vidyn, the damping ratio is "hard coded" to 1% while in FAST, it can be set to a desired value. In the Dymola model, the damping property can not be set as a damping ratio but must be set as spring damping in the beam components. In order to achieve the right damping value, it is necessary to study the decline of oscillations in the results and derive the damping ratio from there.

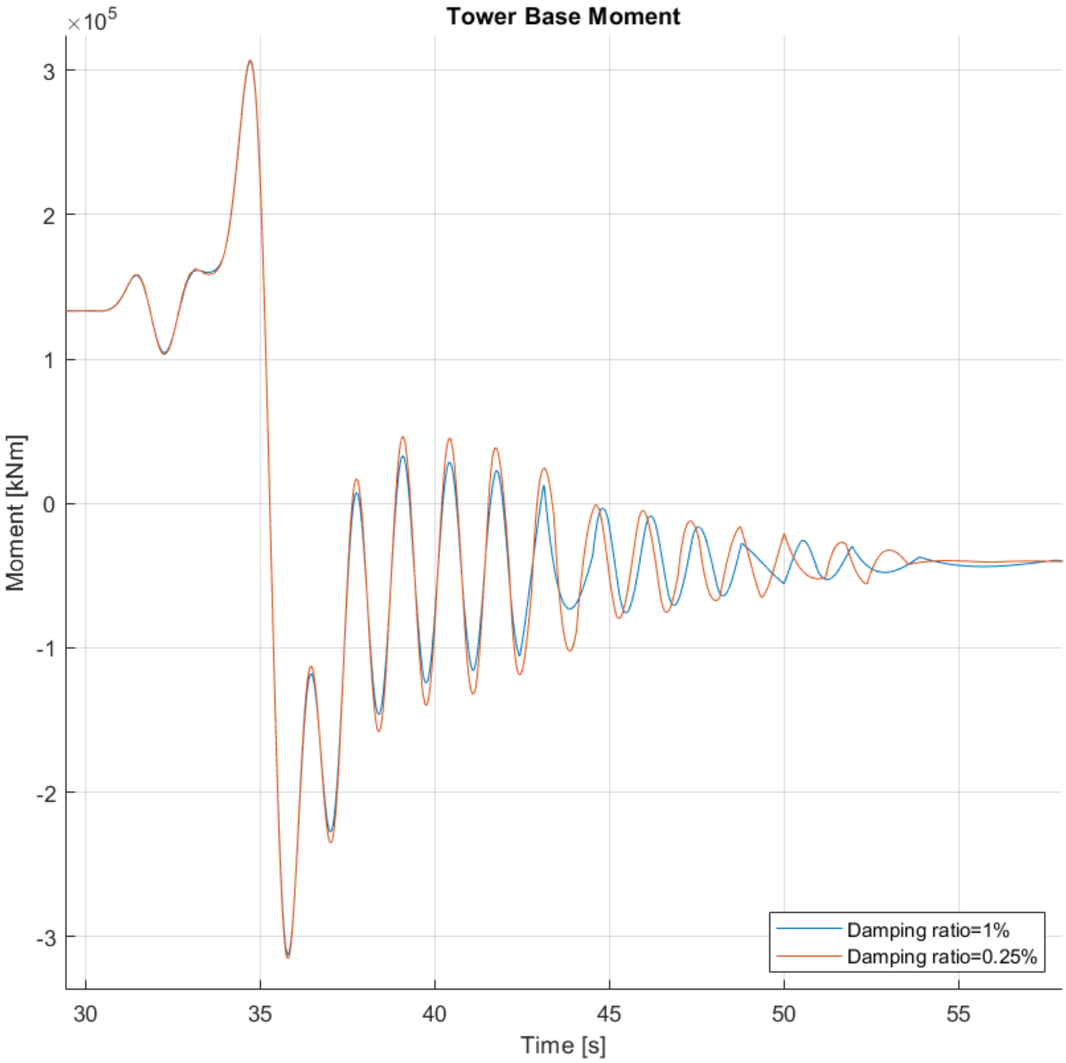

Figure 6.1: Bending moment at tower base during EOG load case with damping ratios of 1% and 0.25% in the tower structure.

In figure 6.1 we see the bending moment at the tower base during the EOG load case with two different damping ratios, 1% and 0.25%. It is clear that, concerning the ultimate load, there is practically no difference. In fact, the highest value of the bending moment is 315 kNm with a 0.25% damping ratio and 312 kNm with 1% damping ratio, which is a difference of about 1%.

6.2 Tower inclination

In the construction of the tower, unintentional inclination may appear due to inaccuracies in the manufacturing. Such inclination will cause higher loads primarily on the tower itself and the foundation structure. One way to handle this, in the simulation, is to calculate a static moment caused by an assumed inclination, this will give a good estimate of the additional loading, but will not capture any dynamic effects that may augment the forces caused by tower inclination. A study has been made with leaning towers of two and four degrees, both upwind and downwind on the EOG case for the Björkö turbine. This study illustrates in a good way the flexibility of the Dymola tool since this type of analysis would be cumbersome to perform with many other software.

6.2.1 Björkö turbine

The static moments for the Björkö turbine was calculated to 102 kNm with 2 degrees inclination and 203 kNm with 4 degrees.

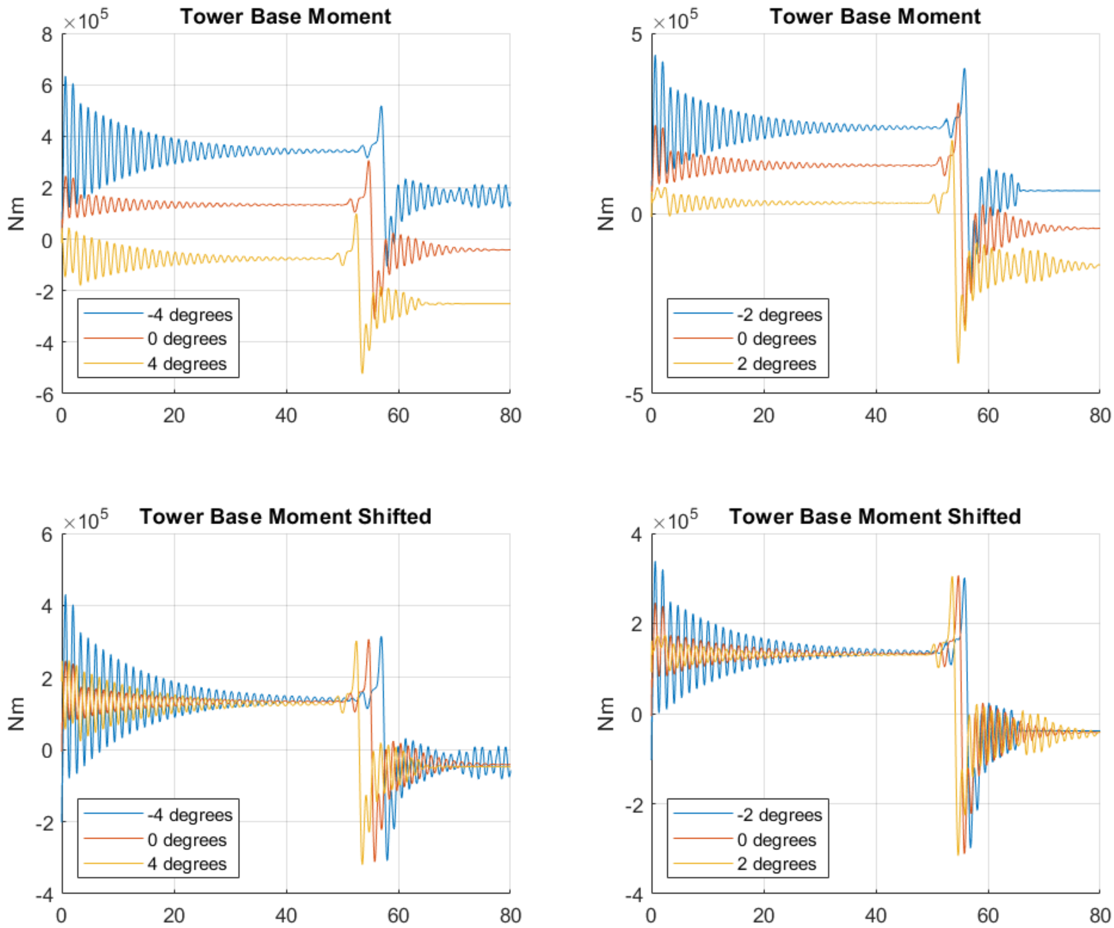

Figure 6.2: Bending moment at tower base under EOG load case with different inclination angles. The top graphs show the real moments while in the bottom graphs, the results have been shifted by the calculated static moments in order to enable the comparison.

In figure 6.2 we can see the results from the dynamic simulations with tower inclination. The estimated bending moment from static calculations, gives a good estimation for the 2 degrees inclination, but with 4 degrees, the dynamic effects results in a slightly higher increase in the critical bending moment of about 212 kNm.

6.3 Light weight generator

Implementation of new technology for low mass generators, could result in a lower nacelle mass which would affect the eigen frequencies of the turbine and the dynamic loads on the tower and foundation structures. A study has been performed where the nacelle mass was reduced by about 70% on the Chalmers research turbine studying the EOG case and on the NREL 5MW turbine studying the turbulent case.

6.3.1 EOG

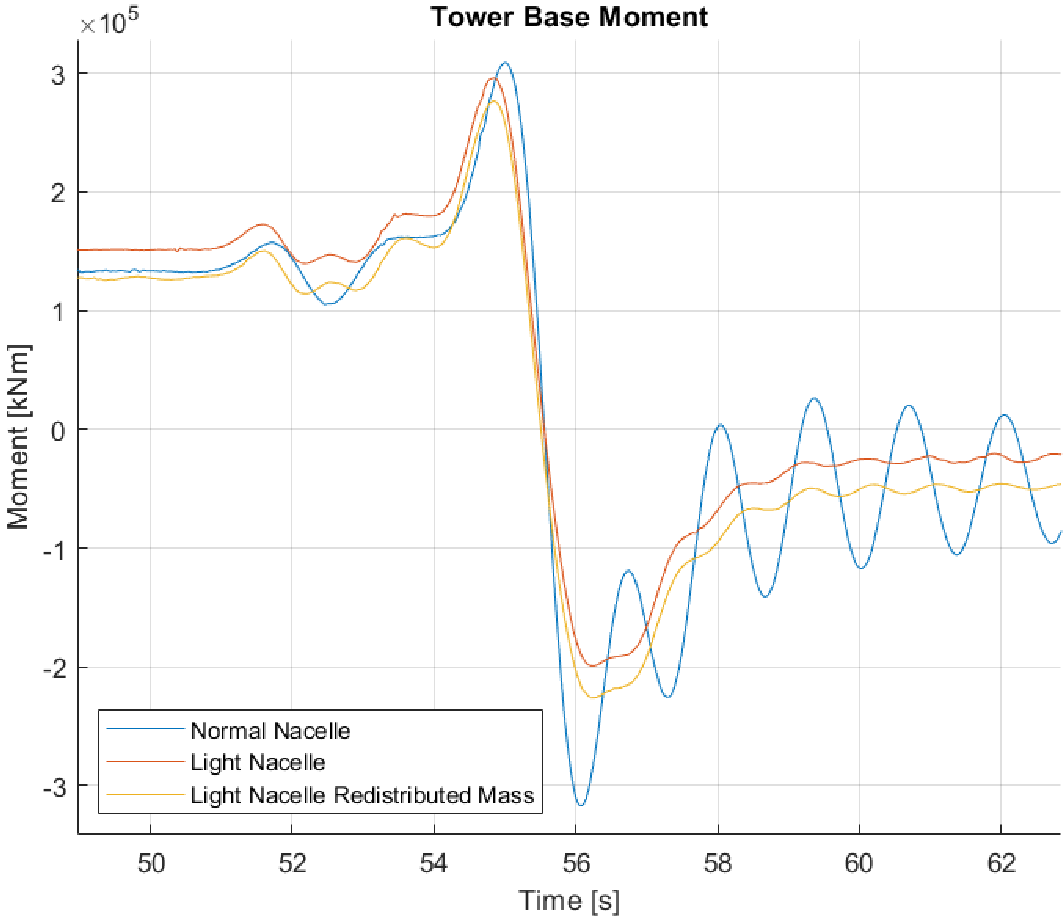

Figure 6.3: Bending moment at tower base under EOG load case with low mass nacelle

In figure 6.3 we can see that for the EOG case the negative bending moment is reduced when the nacelle mass is reduced, but the highest bending moment remains at a similar level. This is due to the front heavy mass distribution of the nacelle which causes a negative moment in the entire tower that cancels out some of the bending moment caused by the wind load, by simply reducing the nacelle mass, this negative moment is reduced. When the mass distribution of the nacelle is changed in order to maintain the negative bending moment, the bending moment at the tower base is reduced by about 10%. It should be noted that in practice, it may not be possible to adjust the mass distribution of the nacelle freely to reduce loads on the tower.

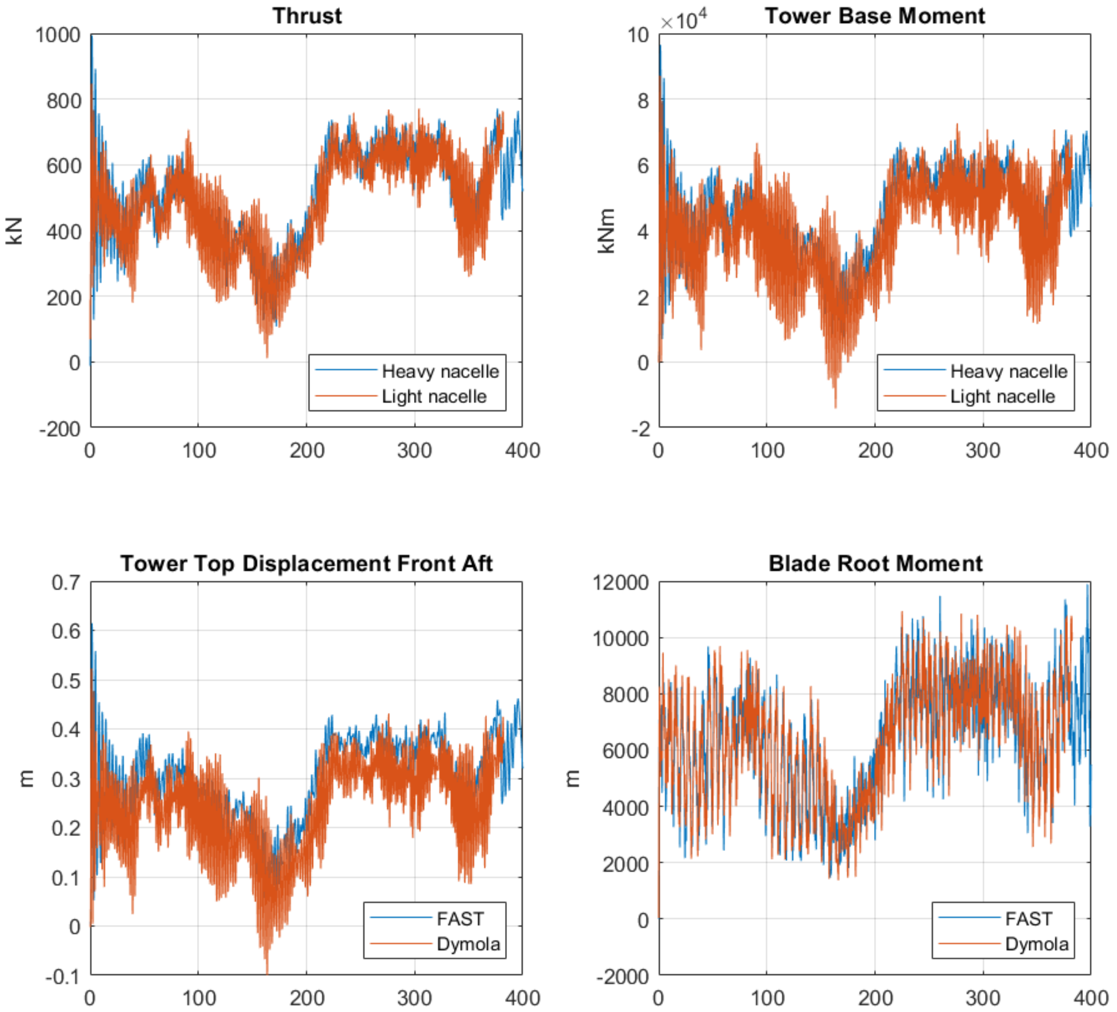

Figure 6.4: Results of structural tower parameters in turbulent case for the NREL 5MW turbine with light nacelle

On the turbulent case with the 5MW turbine we can see in figure 6.4 that the loads fluctuate significantly more compared to the results presented in section 5.3.2.2, this is due to that the lower nacelle mass affects the eigenfrequency of the tower and turbine structure in such a way that it comes close to the 3p frequency and therefore some resonance is occurring. The average load levels appear slightly lower with the low mass nacelle which is a positive effect, however, it is clear that having a generator with substantially lower mass affects the entire structure in such a way that significant redesign is needed in order to have any beneficial effects on the structural loads.

7
Conclusion and Outlook

The aim of this project was to create a tool for aero-elastic simulation of horizontal axis wind turbines in the Dymola modelling environment. This was achieved by creating components for wind turbine models using the open Modelica library and programming in the Modelica language. Verification was made against acknowledged software such as FAST and Vidyn and it could be shown that the tool is capable of accurate simulation of wind turbines for a set of different load cases. The study of the Extreme Operating Gust case showed that the tool can handle highly dynamic scenarios and that the control system for shut down sequence can be modelled. A severe turbulent case was chosen where the simulation is running close to the rated wind speed, this indicated that most turbulent load cases could be simulated. A few case studies demonstrated the usability of the tool. One benefit of having a tool for aero-elastic simulation in Dymola is that it enables large freedom for modification of the simulation, this is exemplified by the tower inclination study. Another benefit is the potential for adding more complex models for different sub-components, for example, a sophisticated model for the gear box or the generator could be incorporated into the tool. Future work on the tool can be put on adding complexity to the models, improve the computation speed as well as the user-friendliness of the tool. At Modvion, the tool can be a complement to consultancy services using commercial software, it can for example be used to verify tower designs at an early stage.

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A

Appendix 1

The Modelica code for the BEM component is showed below.

```
model BEM
  import Modelica.Constants;
  import Modelica.Math.Vectors;
  import Modelica.Math;
  parameter Real x_dir[3]= {1,0,0};
  parameter Real rho=1.25;
  parameter Real segmLen= 1;
  parameter Real chordLen= 1;
  parameter Real r_loc= 1;
  parameter Real R_hub= 1;
  parameter Real R=8 "Rotor radius";
  parameter Real N_blades= 3 "Number of blades in the turbine";
  parameter Real twistAngle = 3 "Number of blades in the turbine";
  parameter Real table[:, :] = [1,1,1,1];
  Real S;
  Real rel_flow[3];
  Real Beta;
  Real W;
  Real angleOfAttack;
  Real angleofattack_deg;
  Real CL;
  Real CD;
  Real CT;
  Real trq[3];
  Real lift[3];
  Real drag[3];
  Real LSF = N_blades*chordLen/(2*Modelica.Constants.pi*r_loc) "Local solidity factor";
  Real a "Axial induction factor";
  Real a_prim "Tangential induction factor";
  Real ftip;
  Real fhub;
  Real Ftip;
  Real Fhub;
  Real F "Tip and hub loss factor";
  Real lamb_r "Speed ratio";
  Real Wind_Vel;
  Real Blade_Vel;
  Real Blade_Vec[3];

equation
  Blade_Vec={absoluteVelocity1.v[1],absoluteVelocity1.v[2],absoluteVelocity1.v[3]};
  Wind_Vel=Vectors.length(Wind);
  Blade_Vel=Vectors.length(Blade_Vec);
  lamb_r=Blade_Vel/Wind_Vel*sign(cross(Wind,Blade_Vec)*x_dir);

  a=min(0.6,1/max(0.000001,(1+(4*F*sin(Beta)^2)/(max(0.000001,LSF*(CL*cos(Beta)+CD*sin(Beta)))))));
  a_prim=1/(-1+4*F*sin(Beta)*cos(Beta)/(max(0.0001,LSF*(CL*sin(Beta)-CD*cos(Beta)))));

  fhub=N_blades*0.5*(r_loc-R_hub)/(r_loc*sin(3.1415926*0.5-Beta));
  ftip=N_blades*0.5*(R-r_loc)/(max(0.001,(r_loc*sin(Beta))));
  Ftip=(2/3.1415926)*acos(Constants.e^(-ftip));
  Fhub=(2/3.1415926)*acos(Constants.e^(-fhub));
  F=Ftip*Fhub;

  rel_flow ={(Wind[1]-Blade_Vec[1])*(1-a),(Wind[2]-Blade_Vec[2])*(1+a_prim),Wind[3]-Blade_Vec[3]};
  Beta=atan2((1-a),lamb_r*(1+a_prim));
  W=Vectors.length(rel_flow);
  angleOfAttack=Beta-pitch-twistAngle;
  angleofattack_deg=Modelica.SIunits.Conversions.to_deg(angleOfAttack);
  AeroDynFoilCoeff.u = angleofattack_deg;
  CL=AeroDynFoilCoeff.y[1];
  CD=AeroDynFoilCoeff.y[2];
  CT=AeroDynFoilCoeff.y[3];
  S = segmLen*chordLen;

  lift=0.5*rho*W^2*S*CL*Vectors.normalize(cross(x_dir,rel_flow));
  drag=0.5*rho*W^2*S*CD*Vectors.normalize(rel_flow);
  trq =0.5*rho*W^2*S*CT*Vectors.normalize(x_dir);
  force1.force=lift;
  force2.force=drag;
  torque.torque=trq;

end BEM;
```