Upwind 20MW Wind Turbine Pre-Design

Blade design and control

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Abstract
In the integrated wind turbine design project Upwind a 20MW wind turbine is designed using the aerodynamic and control expertise of ECN and the expertise of WMC on structural blade design.

In this report starting with an introduction on the design process, the design details on the aerodynamics, the structural blade design and the controller design is presented.

The data of the final wind turbine design is available in the appendices.

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1. Introduction

The Upwind project looks toward the design of very large wind turbines, both onshore and offshore. A lighthouse vision is developed for a 20MW offshore wind turbine. Using the Upwind 5MW reference wind turbine as a starting point a 20MW wind turbine is designed using the ECN/WMC design tools in Focus6. Focus is on the aerodynamic and structural design of the rotor including the design of the controller.

This report presents the final 20MW wind turbine and the design steps needed to come to the design. The classical upscaled 20MW wind turbine, based upon the Upwind 5MW reference wind turbine, is used as a starting-point for the design. Using the ECN/WMC design tools the aerodynamic and structural blade design is done. The control design is performed using the aerodynamic blade design as an input. The blade and control design was done in two design iterations. In the first iteration the absolute (scaled) blade thickness is applied. In the second iteration the relative blade thickness is applied together with a Reynolds correction for all the airfoils. The aeroelastic model of the wind turbine is a mixture of upscaled wind turbine data and the output of the rotor and control design.

This report starts in section 2 with a general description of the upscaling and design process for the Upwind 20MW turbine. In section 3 the effect of upscaling for the aerodynamic blade design is discussed. Section 4 presents the structural blade design. The controller is dealt with in section 5. For the controller the tower eigenfrequencies are important. The tower cannot be scaled using classical scaling rules. The air-gap between the blade tip and free sea surface will not change due to an increase of turbine scale.
To check the sanity of the design a load set according to IEC61400-1 edition class IIB is performed. The results are discussed in section 6.

2. Upscaling and design of 20MW

Design in general starts with the formulation of the design basis. What should the design look like and what is the functionality of the design. Will the wind turbine be two-bladed or three-bladed? What drive train concept should be used? Should the turbine be a downwind turbine because of the expected increased blade flexibility? For a 20MW wind turbine there is no example of a wind turbine having the same power output.

The design of the 20MW wind turbine described in this report has the following design basis:
- Based on Upwind 5MW reference version 8 (Jonkman, et al., 2007)
- 3 bladed
- Upwind rotor
- Drive train includes a gearbox and a generator with a full converter
- WP4 environmental design conditions
- Tower height and thus the hub height depend on the airgap between the free surface and the blade tip.

The Upwind 5MW reference wind turbine is scaled to a 20MW wind turbine applying classical simularity rules (Chaviaropoulos, 2006). As a consequence the 20MW design has the same tip-speed ratio en power density as the Upwind 5MW reference wind turbine. This scaled 20MW wind turbine is used as a starting-point in the design and used to improve the design by using the design tools of WMC and ECN available in the Focus6 suite. The main focus in the design is on the rotor nacelle assembly (RNA) and the controller design.

Figure 2.1 shows the design process starting with scaled 20MW turbine base on similarity rules. Having the principle dimensions first the aerodynamic blade design is done. The results of the aerodynamic blade design are input for both the structural blade design and controller design. The blade design is a trade off of the aerodynamic performance, the blade loads and the strength requirements. This determines the size and shape of the blade. For the controller design besides the aerodynamic input also a description of the generator curve is needed.

Having the aerodynamic and structural design 20MW blade and the controller an aeroelastic model can be created for the load set calculations. The scaled 20MW turbine supplies the remaining wind turbine parameters. The tower height and thus the hub height depend on the airgap of the blade tip and not on the size of the wind turbine. This means that the hub height needs to be determined separately.

Using ECN's aeroelastic code PHATAS a load set is calculated according to IEC61400-1 edition 2 Class II B. The fatigue and ultimate loads calculated are used to check the strength of the blade. Additional the buckling is checked. The blade is modified if necessary.

First the scaled absolute blade thickness is used as a constraint in the aerodynamic blade design. The blade thickness is an important parameter for the blade strength. For the aerodynamic blade design the same airfoil families are used as for the Upwind 5MW reference wind turbine.

WMC starts the structural blade design with the thickness and chord distribution of the aerodynamic blade design. First estimate values for mass and stiffness distribution are the values found by classical scaling. Glass fiber reinforced plastics are used.

The controller is designed using ECN's control design tool. As an input for the controller design the Cp-lambda curves are needed.

During the design the following difficulties were encountered:

- The aerodynamic coefficients need to be determined for higher Reynolds numbers.
- The control design tool is not ready for 20MW turbines. New strategies are needed.
- A third shear web was needed to avoid buckling. This increased the blade mass.

For the aerodynamic blade design the airfoils need to be corrected for the higher Reynolds number. A controller was designed and the first load cases were run in Focus6. The controller showed difficulties in handling the low tower eigenfrequency. Based on the classical scaled mass- and stiffness distribution, the aerodynamic blade design and the aeroelastic calculations the WMC did the structural blade design. Because of the large chord length for the 20MW turbine, a third shear web was added.

Based on the first design results it is decided that:
- The aerodynamic coefficients for higher Reynolds numbers are applied to all airfoils.
- The relative blade thickness, blade thickness to chord length ratio, is kept the same as for the Upwind 5MW.

A new aerodynamic and structural blade design was done together with a new controller design for these constraints.

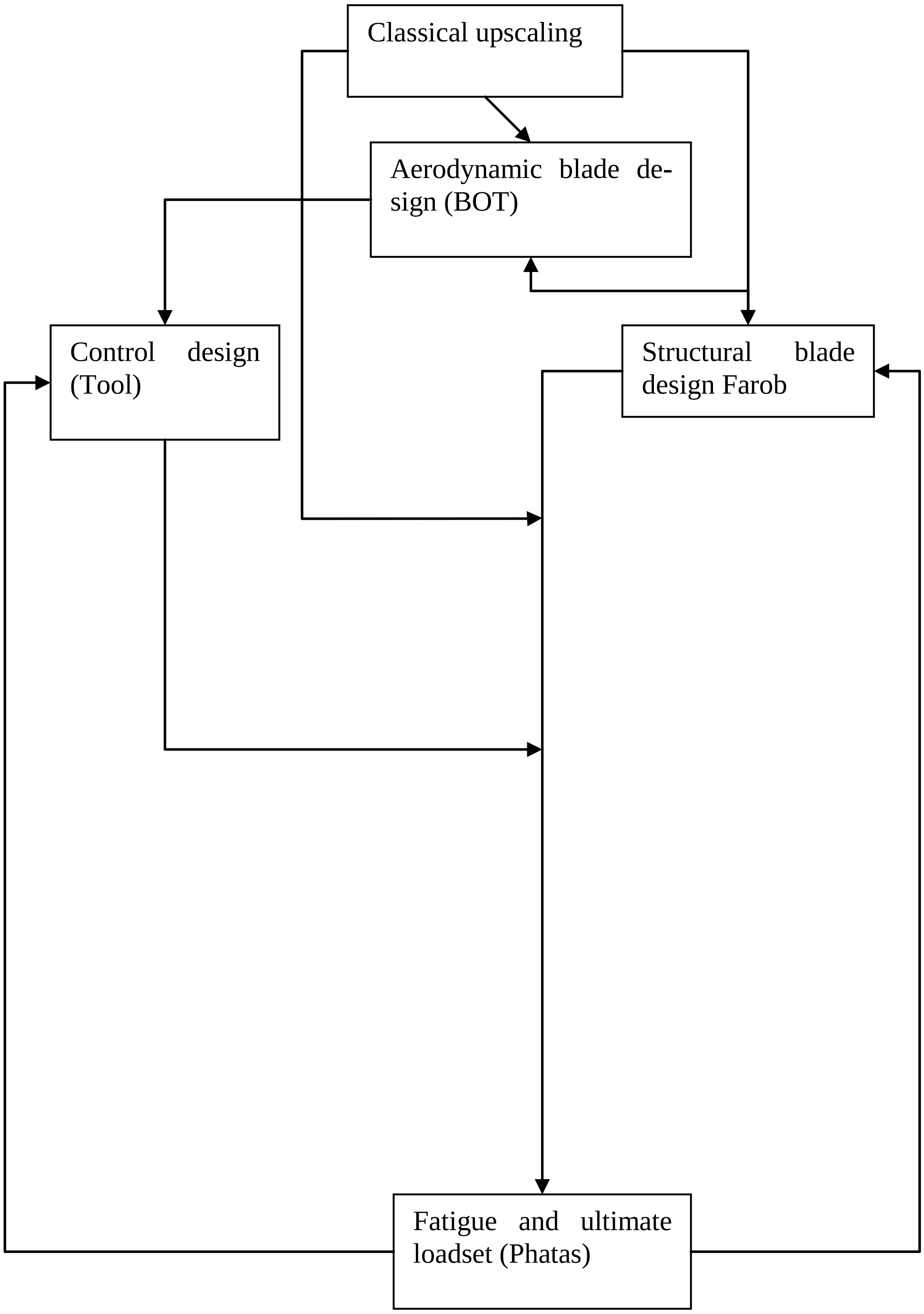


Figure 2.1 *Flow diagram of design process.*

3. Investigations of the Upscaling Effects on the Aerodynamic Blade Design

A blade design for a 20MW wind turbine rotor is an entirely new concept. It is not possible to clearly define the restrictions or requirements of the design from the beginning. Especially the restrictions and limitations coming from the structural design or manufacturing processes are not known since there is no build 20MW wind turbines, yet. Therefore, with this conceptual aerodynamic design study it is aimed to highlight the most important impacts and suggest possible methods for the real design.

3.1 Introduction

In the UPWIND project, it is decided to investigate the effects of 20 MW up-scaling. This investigation has been performed by two ways. First way is to use a 20MW wind turbine which is just scaled by using classical upscaling methods (i.e. power density is constant) (Chaviaropoulos, 2006). This wind turbine is called as “upscaled” or “classically upscaled” from now on. Second way is to design a 20MW wind turbine. At the end a comparison between the two wind turbines is done in order to find the differences and/or even benefits of designing the wind turbine instead of direct upscaling.

In this section the aerodynamic design of this 20 MW wind turbine is summarized. The aim is to compare the design with the classical upscaled design. In order to have 2 comparable designs at the end, some decisions have been made which bring some restrictions to the aerodynamic design during this task. This decisions and restrictions will be discussed in the next section. Moreover, two aerodynamic designs have been performed for this task. The reason for two designs or so called two iterations mainly lies in the fact that since there is no example of a 20MW wind turbine, it is not possible to use previous experiences to predict potential problems in the process. Therefore, the first design iteration has been used to learn what the potential problems are in the design of a large and complete system. The second design iteration can be considered as the real design practice. Since the first iteration has been used as a “Warming-Up-Case” for the design, it has not been described in this report.

3.2 Requirements and Restrictions

The main restriction in this 20MW design is to stay comparable with the upscaled 20MW wind turbine as much as possible. In order to keep this characteristic of the design, some parameters have been chosen. The parameters have been selected based on the design information of the reference wind turbine and the classically upscaled 20MW wind turbine.

3.2.1 Geometry restrictions

Rotor Diameter (m):	252
Hub Diameter (m):	6
Max. Chord (m):	9.3
Position of Max. Chord (m):	-
Tilt Angle (deg):	5
Forward Cone Angle (deg):	2.5

Besides these parameters only the airfoils in the reference wind turbine have been used for the design. The reason is to keep the number of variables in the design as few as possible. It has been decided to design a better wind turbine later by using the most suitable airfoils after the early stage.

In the beginning of the task, the absolute thickness distribution has been restricted to be equal to the upscaled 20MW blade in the beginning of the process. This decision has been made in order to stay on the safe side in the structural design and manufacturing, since there are no known (or potential) restrictions coming from the structural design or manufacturing at this stage of the 20MW design. Afterwards, it has been concluded that this does not give a high performance design in terms of aerodynamic characteristics and annual yield. Therefore, instead of absolute thickness, relative thickness (i.e. airfoil distribution) has been kept constant. By this way, the aerodynamic characteristics are still kept comparable with the classically upscaled wind turbine while the best performance possible can be obtained.

3.2.2 Operational parameters

Cut in (m/s):	3
Nominal (m/s):	10
Cut Out (m/s):	25
Rotational Speed (rpm):	0.5-6.05
Max. Tip Speed (m/s):	80
Max. Power (MW):	20
Power Control:	pitching to vane
Design Tip Speed Ratio (TSR):	8.5
Fixed Mechanical and Electrical Losses (kW):	50
Variable Mechanical and Electrical Losses (%):	6

3.3 Airfoils and Characteristics

The airfoils and the distribution of the airfoils used in this study design are:

Between 87-126m	: NACA 64618
Between 67-83m	: DU93-W-210
Between 55-64m	: DU91-W2-250
Between 43-52m	: DU97-W-300
Between 37-43m	: DU00-W2-350
Between 23-35.5m	: DU00-W2-401
Between 13-22m	: Cylinder2
Between 3-9m	: Cylinder

The distances are measured from the hub center. The sections which stay in these intervals have to be interpolated. The distribution is based on the reference wind turbine. For the design, the flow conditions due to the upscaling have been investigated instead of working on the selection of the best airfoils for this condition.

The local wind speeds stay the same as the reference wind turbine since the tip speed has been kept the same. Therefore, there is no change in the compressibility (i.e. no Mach number effects due to the upscaling). However, the local chord values are larger in the upscaled case. This indicates an increase in the operational Reynolds numbers of the spanwise sections. To figure it out, the above conditions have been modeled by using the classically upscaled wind turbine geometry in BOT (Bot and Ceyhan, 2009). The Reynolds number distribution for different wind speeds is shown in Figure 3.1.

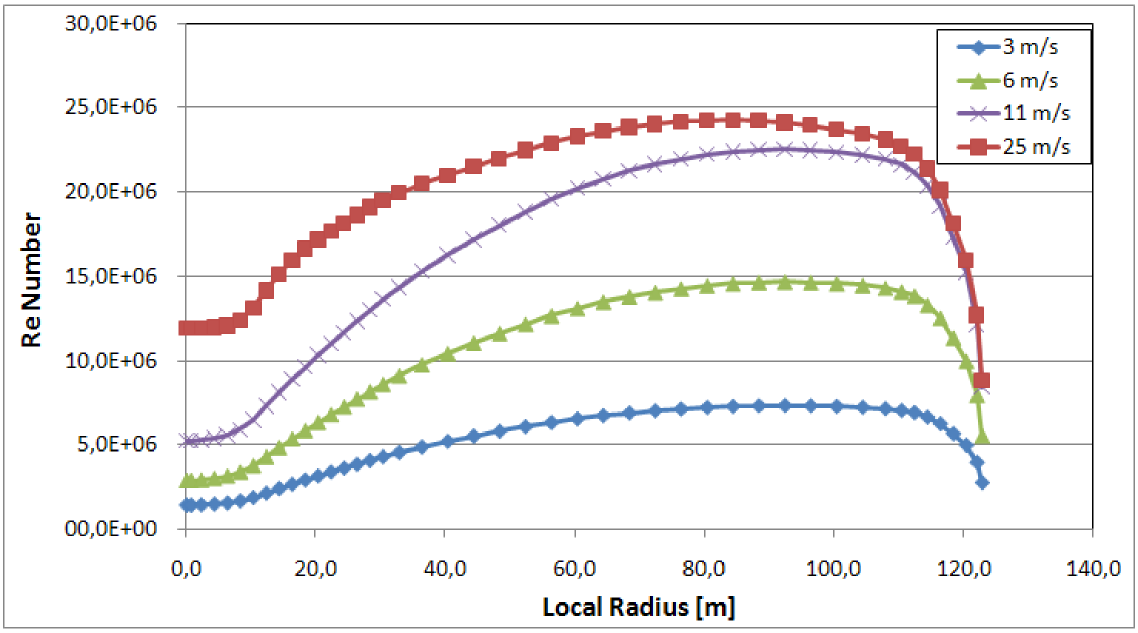


Figure 3.1 Reynolds number distribution along the blade for different wind speeds

According to this figure, for most of the wind speeds, the Reynolds numbers are higher than 10 million except for a few sections at the tip and the root. The wind tunnel test data of the wind turbine airfoils are usually around 3-6 million Reynolds numbers and 9 million Reynolds number wind tunnel test results are available only for a few NACA profiles. Still even with 9 million Reynolds numbers data, it is only possible to cover 3 and 4 m/s wind speed operations and a few sections at the tip. Therefore, there is a clear necessity of investigating very high Reynolds number performance of the airfoils used for this study.

In order to investigate the effects of these very high Reynolds numbers the airfoils used in the design have been analyzed by using RFOIL (Montgomerie,1996). Several analyses have been performed to compare the results between different Reynolds number regimes including the ones that have been tested.

According to the airfoil distribution presented above, NACA 64618 covers 30% of the blade radius, therefore it has been selected for being the first airfoil for this investigation. Several RFOIL analysis have been performed to be able to cover all angle of attack regimes for the negative and positive and post stall behaviour. All the analysis have been performed with free transition for N=9 (N is a parameter in the boundary layer and it represents the turbulence level. For the details of this parameter, see Montgomerie (1996)). In Figure 3.2, RFOIL predictions for the lift of the NACA64618 airfoil for three different Reynolds numbers are compared and the experimental data obtained from ATG software (ECN’s airfoil database software (Bot, 2001)) of the same airfoil for 6 million Re numbers is included to this comparison. According to these results, there is a clear effect of the higher Reynolds number especially on the highest C_l by 13% increase. Also the linear C_l region is extended to the larger angles of attack. The similar character even more pronounced can be seen for the negative angles of attack region. Minimum C_l is decreased by 24% and the linear region is also extended. The lift curve slope, the performance on the linear lift region and post stall behaviour stays almost the same. The slope of the linear region of the lift curve stays almost unchanged except that the linear region is extended. In Figure 3.3, C_d is compared for the same conditions as C_l. There is a decrease in the drag as expected except for the angle of attack around 5 degree. Especially the drag decrease around the stall angles is quite pronounced.

Similar analysis have been performed for all the airfoils for this study. For example, in the Figure 3.4 and Figure 3.5, DU93-W-210 airfoil analysis results are shown. The same behaviour on C_l and C_d with increasing Reynolds numbers is also seen in these results. DU93-W-210 and NACA64-618 cover half of the blade span. Therefore, the Reynolds number effects have to be included in the design process for the 20MW wind turbine. In addition to these, DU00-W2-401 airfoil analysis results for different Reynolds numbers compared with test results obtained from ATG are shown in Figure 3.6 and Figure 3.7. This airfoil covers the blade from 20m to 35m blade span. This part of the blade usually operates closer to stall (or even in stall) therefore it is assumed to be not very effective in the power production. However, the effect of high Reynolds numbers improves the performance of the blade in this section due to the increase in maximum lift and maximum lift angle of attack. Therefore, some improvement in the overall performance can be obtained according to the results shown in the figures.

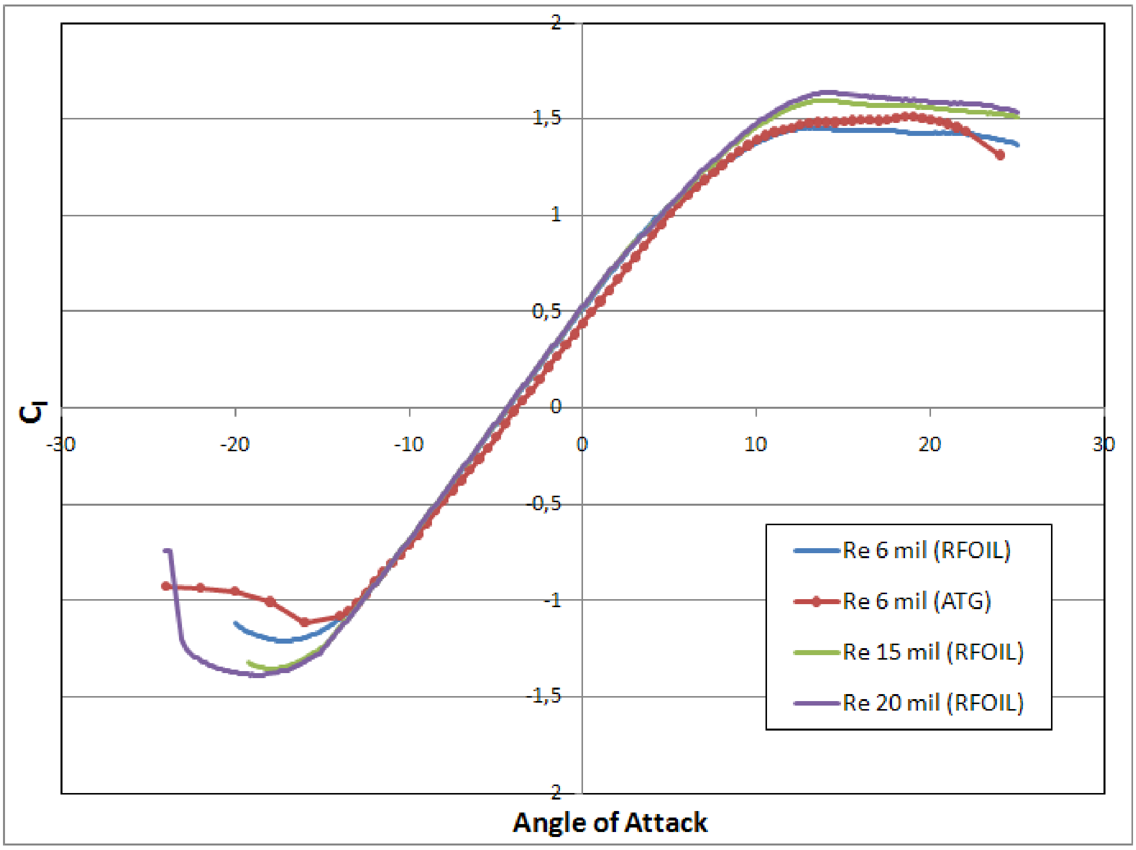


Figure 3.2 *C_l versus Angle of Attack curve of NACA 64-618 airfoil for different Reynolds numbers*

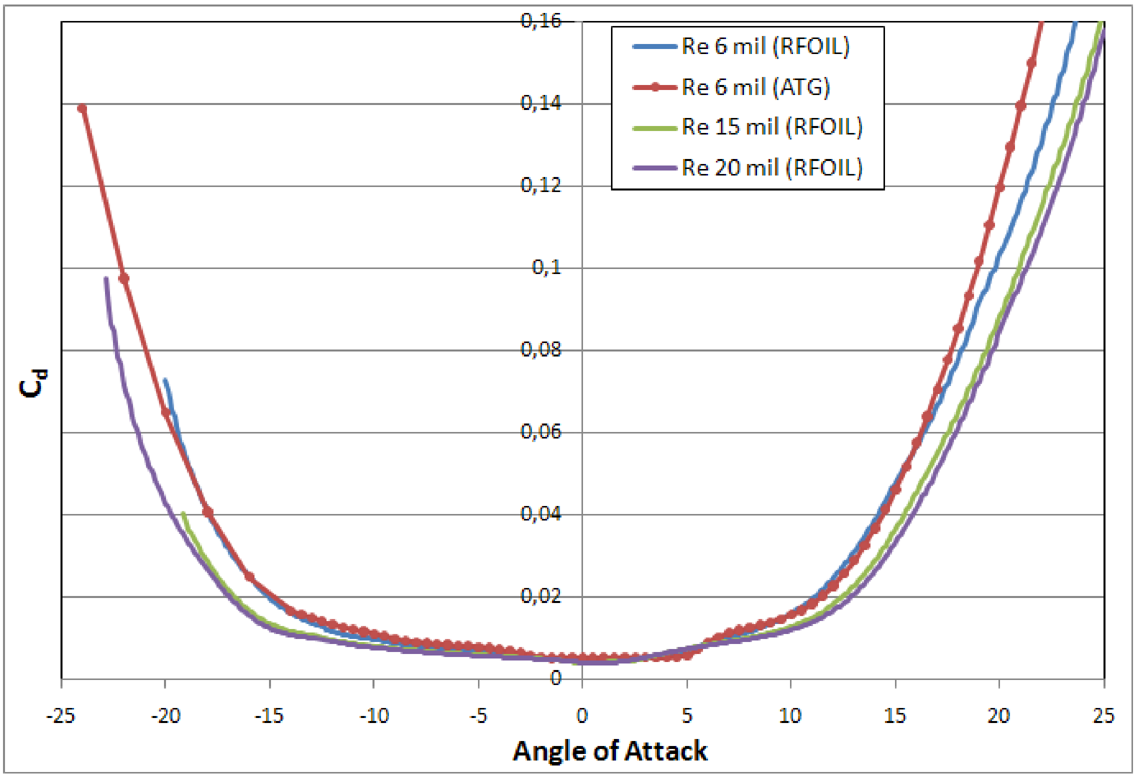


Figure 3.3 *C_d versus Angle of Attack curve of NACA 64-618 airfoil for different Reynolds numbers*

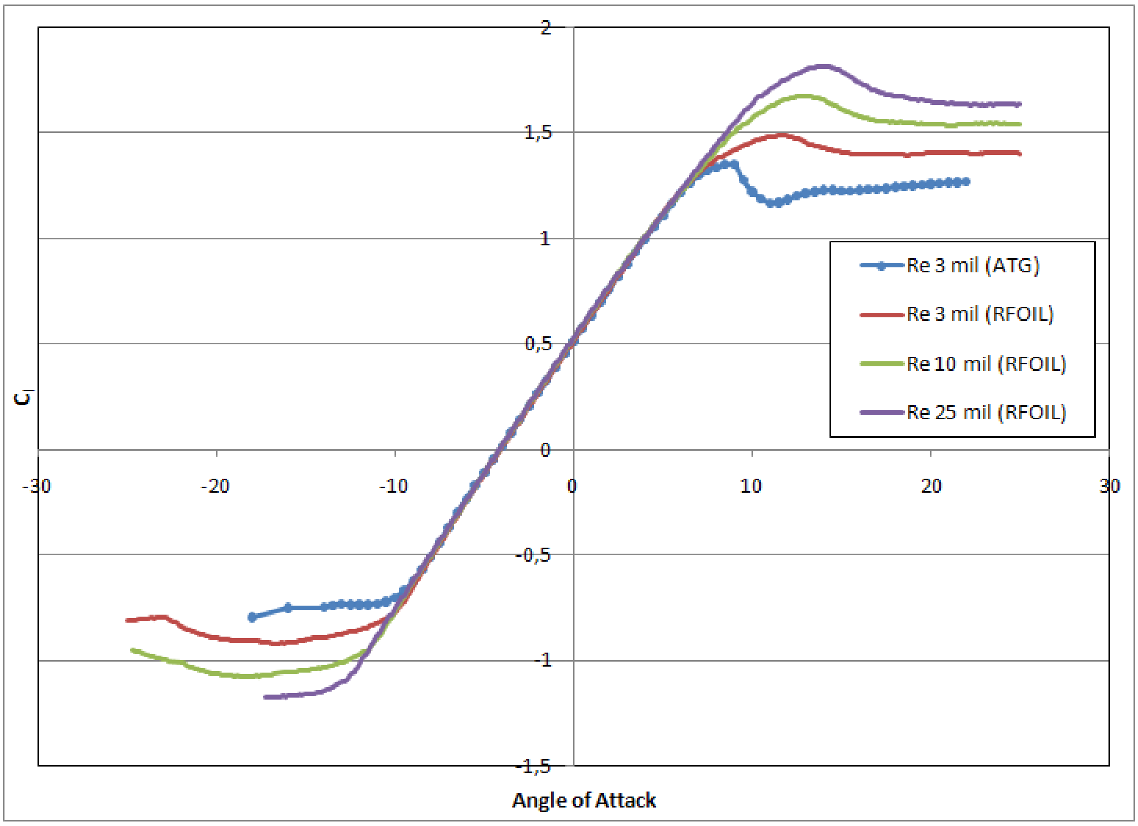


Figure 3.4 *C_l versus Angle of Attack curve of DU93-W-210 airfoil for different Reynolds numbers*

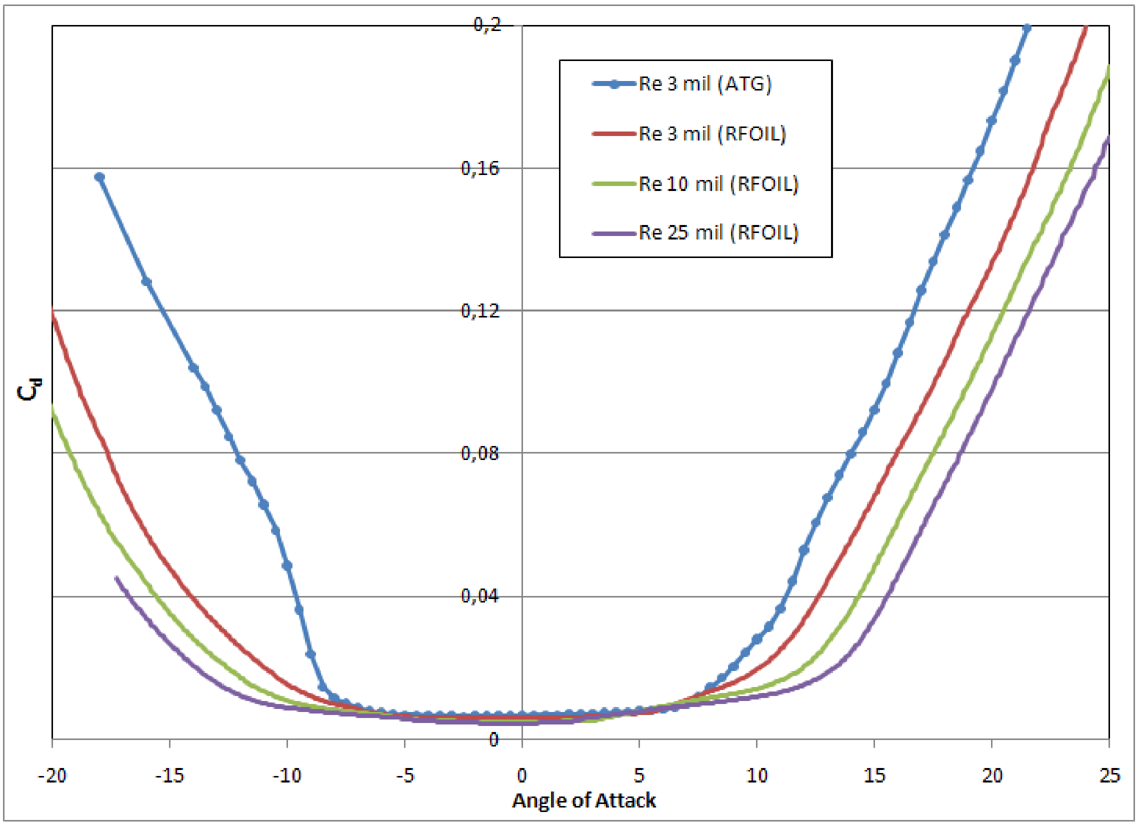


Figure 3.5 *C_d versus Angle of Attack curve of DU93-W-210 airfoil for different Reynolds numbers*

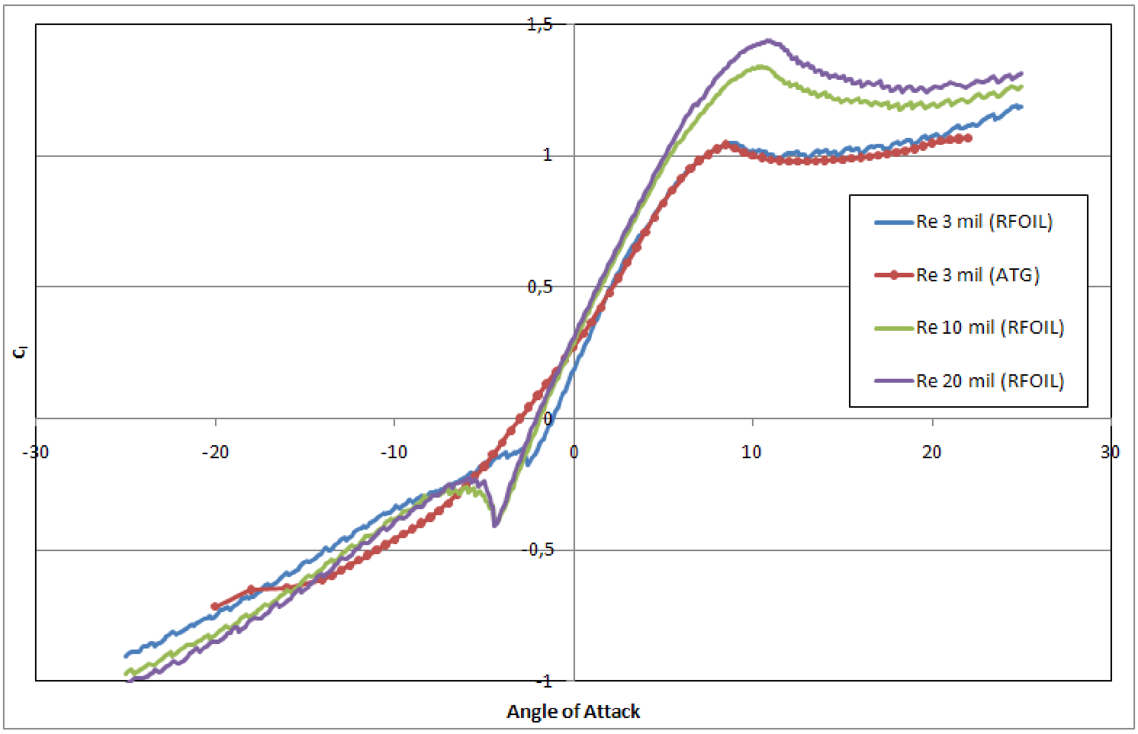


Figure 3.6 *C_l versus Angle of Attack curve of DU00-W2-401 airfoil for different Reynolds numbers*

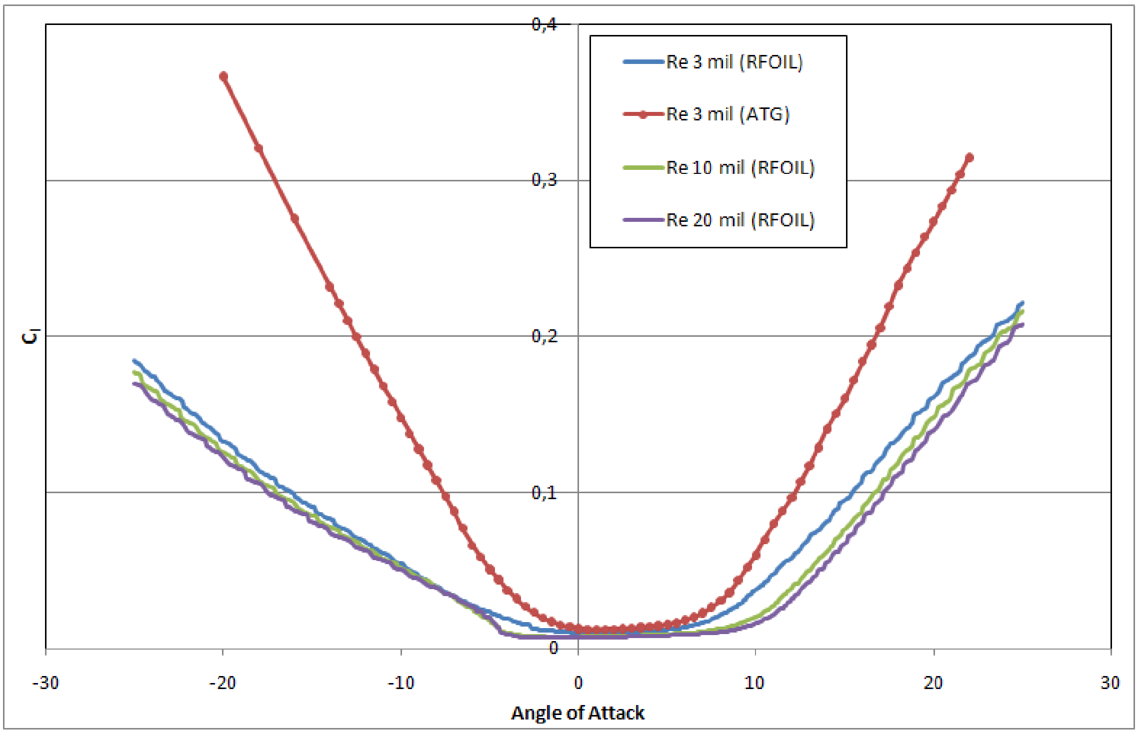


Figure 3.7 *C_d versus Angle of Attack curve of DU00-W2-401 airfoil for different Reynolds numbers*

As a result of the Reynolds numbers investigation, it is decided to design 20MW wind turbine by considering the Reynolds number effects. For this purpose, all the test results are corrected by using the results from RFOIL analysis for higher Reynolds numbers. RFOIL has just been used for the correction of the test results for higher Reynolds numbers instead of directly using the numerical simulation results for the design. The airfoil database in the BOT software is updated for the Reynolds numbers until 25 million Reynolds numbers referring to the results in Figure 3.1.

3.4 Blade Design

The aerodynamic blade design of the 20MW wind turbine has been performed by using ECN's software BOT (Bot and Ceyhan, 2009). The design has been carried out by using the optimization strategy in BOT to maximize the annual yield and C_p for the given design condition. The existing airfoil database in BOT has been updated with the higher Reynolds number analysis results of the airfoils. And the design has been carried out with the same design wind speeds as 5MW reference wind turbine by using Weibull scale parameter k=2 and for an average wind speed of 9.5 m/s.

The design has been performed for a tip speed ratio of 8.5. For the wind speeds under rated conditions, the pitch angles that gives the maximum C_P and the rotational speed of the wind turbine for the chosen tip speed ratio are calculated. The optimum conditions are found for every blade section by selecting the optimum angle of attack (i.e. the angle of attack where l/d is maximum) and the optimum axial induction factor (i.e. a=1/3). In practice, in order to take into account the load reductions, the tip noise reductions, etc. a reduction in aerodynamic performance has to be considered. In this design study, the tip noise has not been considered since the wind turbine is aimed to be operational in an offshore environment.

3.4.1 Design Results and Performance

The design of 20MW wind turbine has been compared with the 20MW classically upscaled wind turbine. The chord and twist distribution comparisons are shown in Figure 3.8 and Figure 3.9. The chord values are reduced quite a bit compared to the upscaled wind turbine except for the root part which is kept the same. Moreover, in the design, the twist angles are smaller than the upscaled wind turbine especially in the middle part of the blade. The main reason for these reductions is the effect of the modifications on the airfoil characteristics due to the high Reynolds numbers. A detailed discussion about the effect of high Reynolds number on the blade design is given by Ceyhan (2012). In addition to these, the absolute thickness distribution has not modified enormously. Due to the decrease in chord values (and the relative thickness is kept constant), the absolute thickness of the blade is also decreasing but not more than half a meter locally at most around the mid-span locations.

A smooth local angle of attack distribution has been kept for the design which can be found in Figure 3.11 and these values are far from the stall angles of attack. Also in Figure 3.12, the annulus averaged axial induction distribution for different wind speeds are shown and the optimum value of the axial induction of 0.33 has been maintained along the span except for the tip and the root regions in case the wind speeds are close to the design wind speed.

When the power production performances of the designed wind turbine and the upscaled wind turbine are compared for the different wind speeds as in Figure 3.13, the difference is not visible. It is more pronounced in the C_P performance curve in Figure 3.14. There is some improvement of C_P for the wind speeds smaller than rated wind speed. For these wind speeds, the turbine is able to operate with a constant C_P. For the wind speeds above rated, C_P is reduced due to the activation of the pitch control, but in this area, both the upscaled wind turbine and the designed wind turbine have the same performance. In Figure 3.15, the blade root bending moments of the two wind turbines are compared. There is a small reduction in the root bending moments for the rated and higher than rated wind speeds. However, for the wind speeds below rated wind speed, there are not much changes. All these comparisons have been performed by using the same airfoil database (i.e. corrected for higher Reynolds number effects) for the designed and upscaled wind turbine performance calculations.

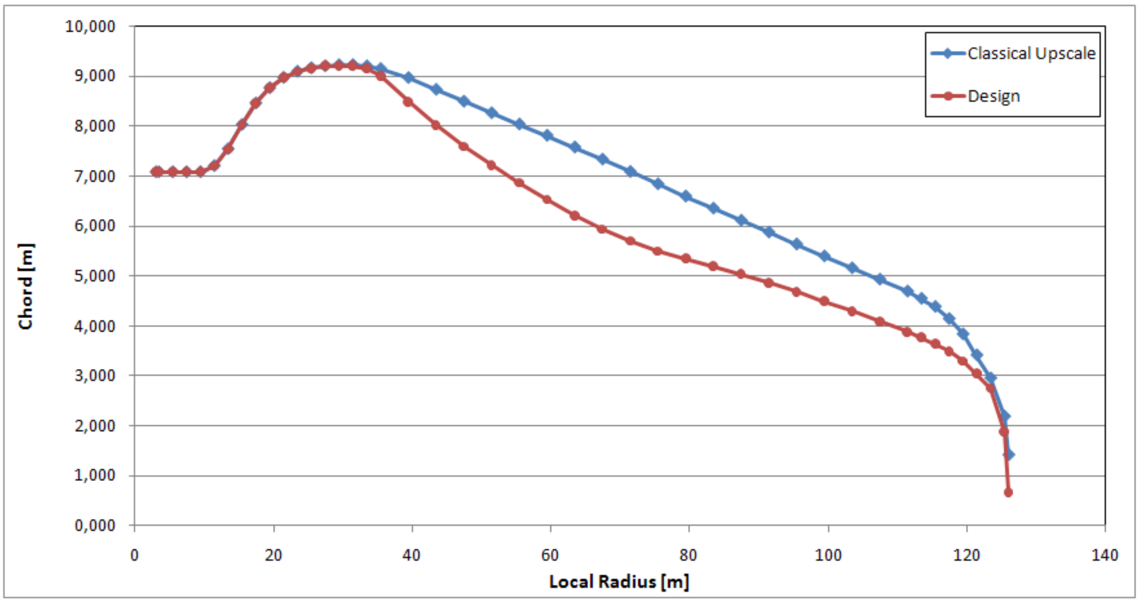


Figure 3.8 *20MW wind turbine chord distribution compared with the upscaled 20MW chord distribution*

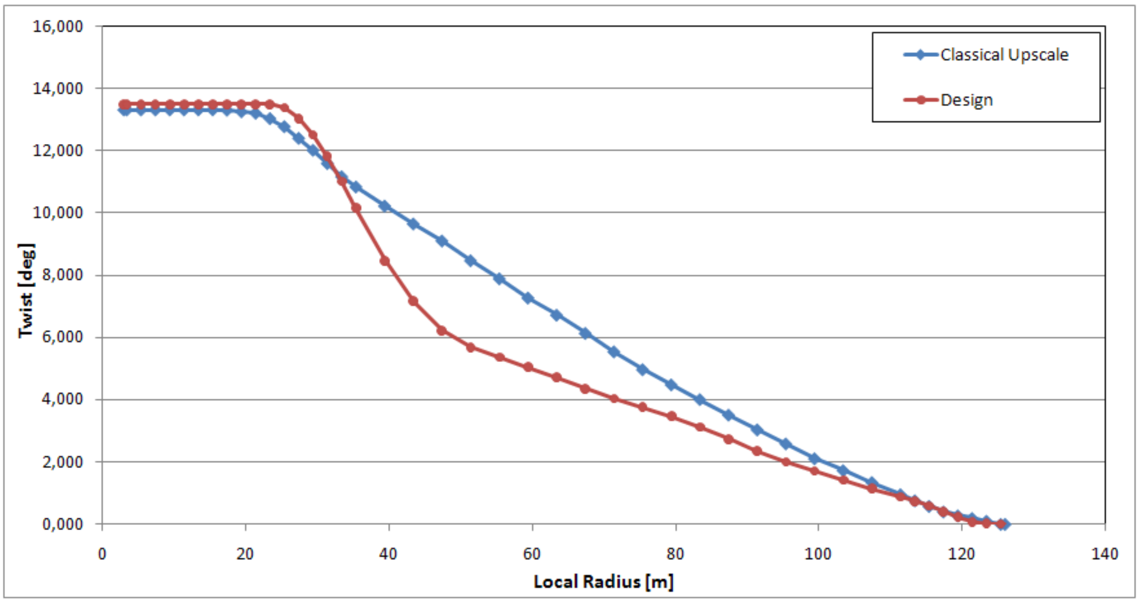


Figure 3.9 *20MW wind turbine twist distribution compared with the upscaled 20MW twist distribution*

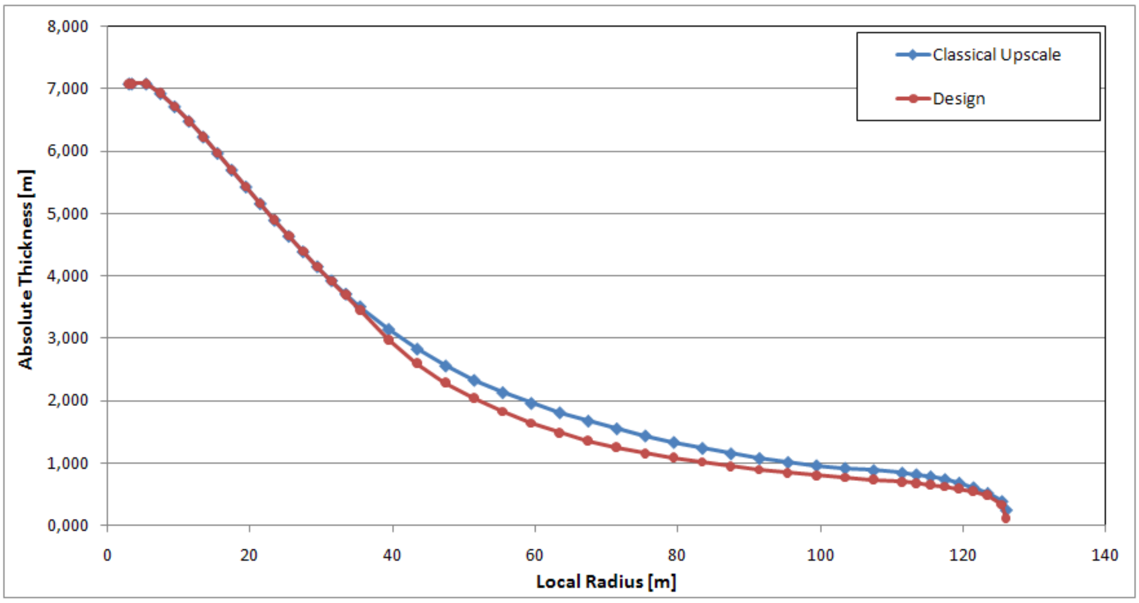


Figure 3.10*20MW wind turbine design absolute thickness distribution compared with the upscaled 20MW absolute thickness distribution.*

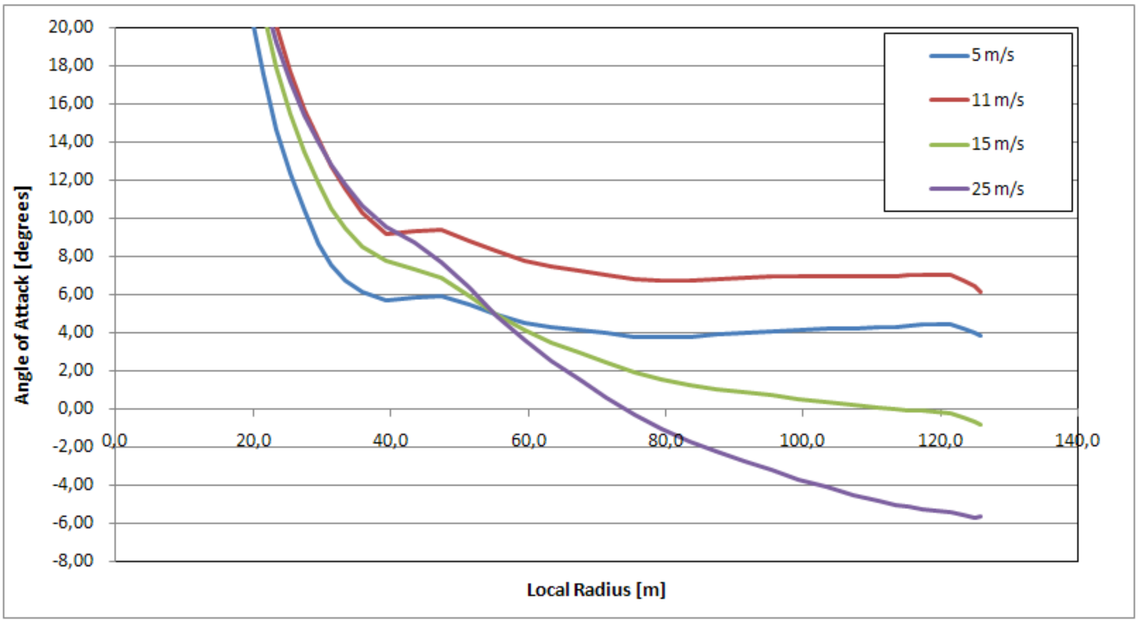


Figure 3.11 *Local angle of attack distribution along the blade span for different wind speeds.*

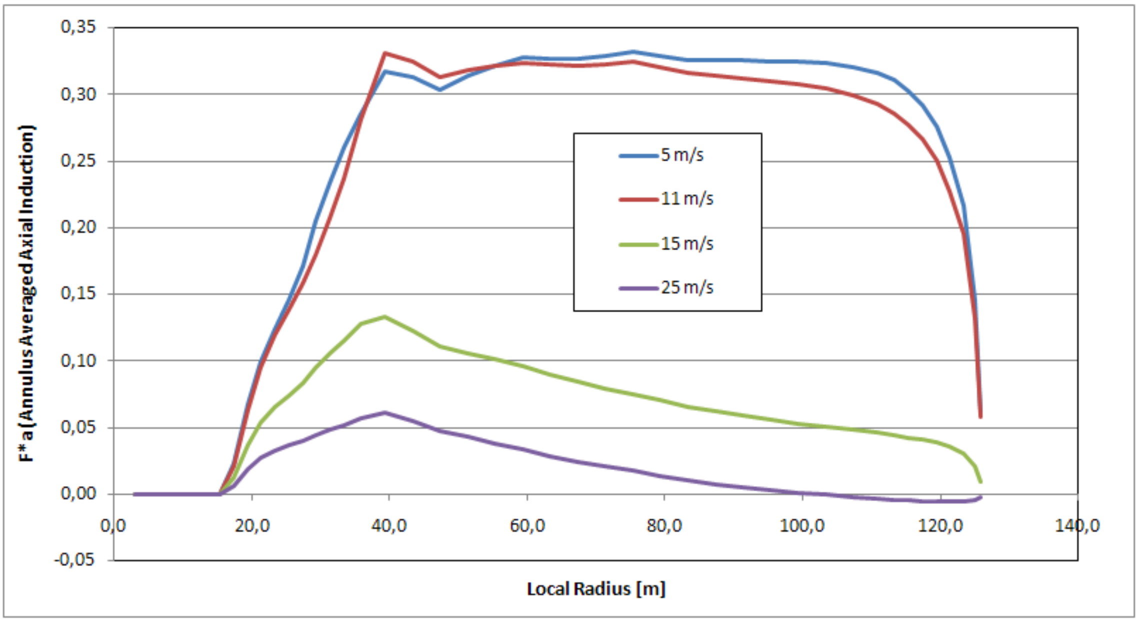


Figure 3.12 *Axial induction distribution along the blade span for different wind speeds.*

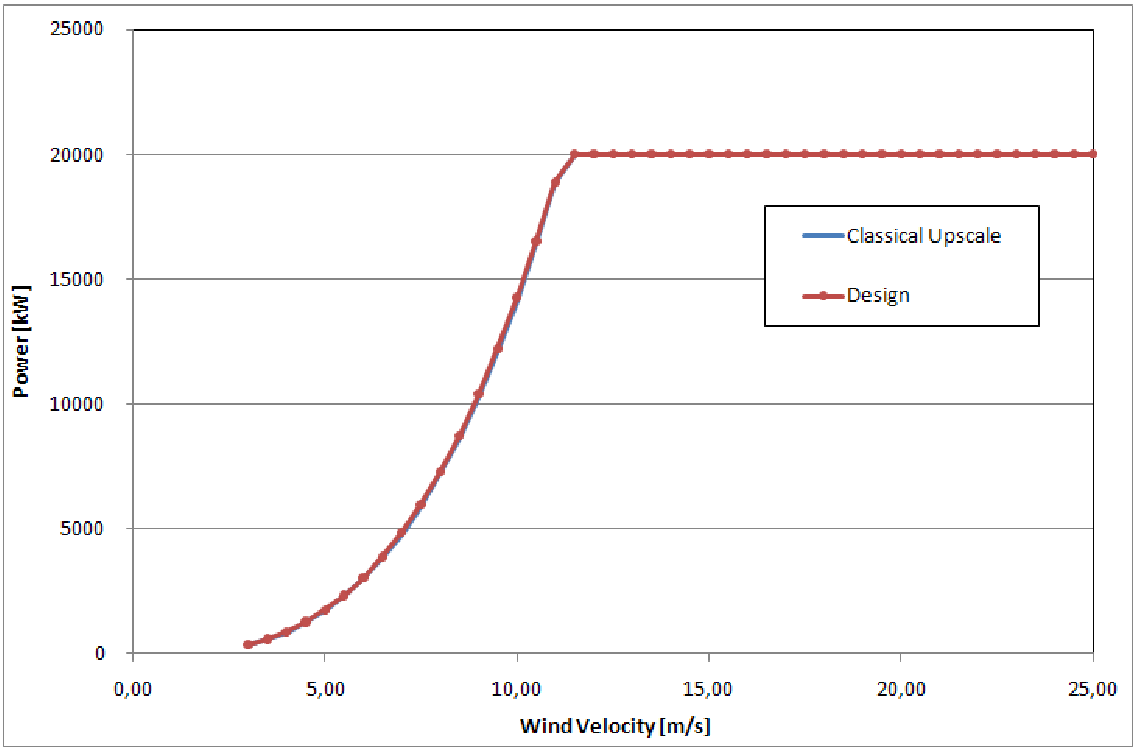


Figure 3.13 *The power production of the 20MW design for different wind speeds compared with the 20MW upscaled wind turbine*

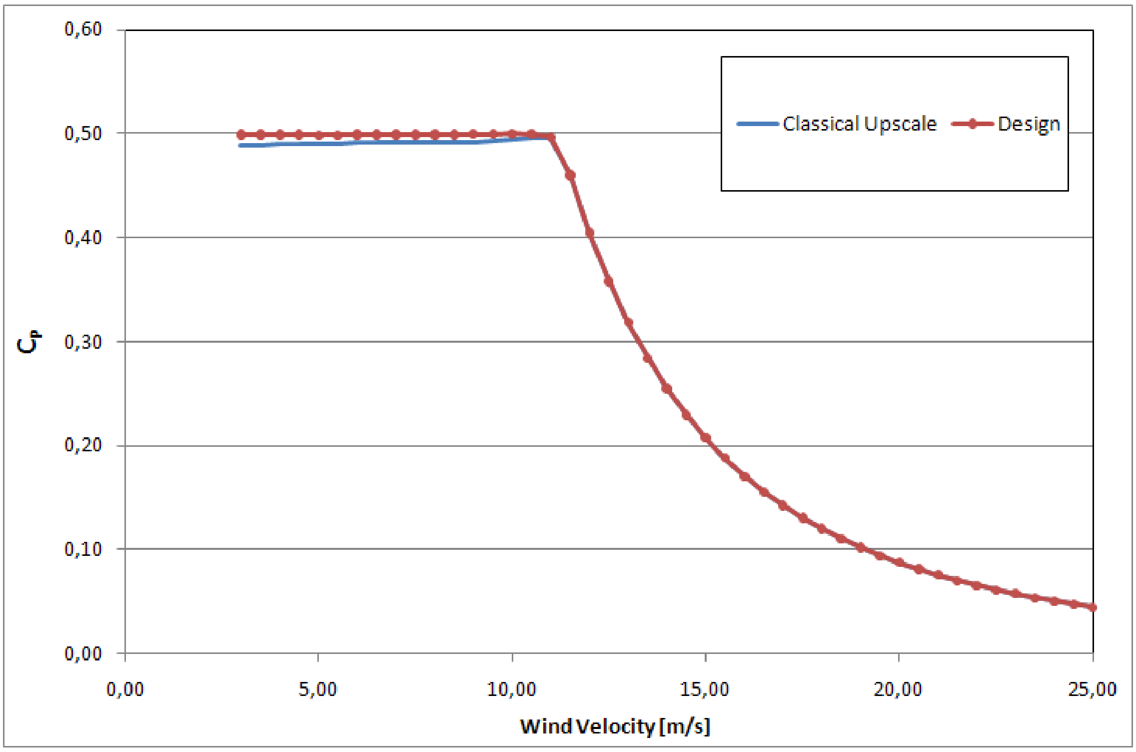


Figure 3.14 C_P *performance of the 20MW design for different wind speeds compared with the* C_P *of the 20MW upscaled wind turbine*

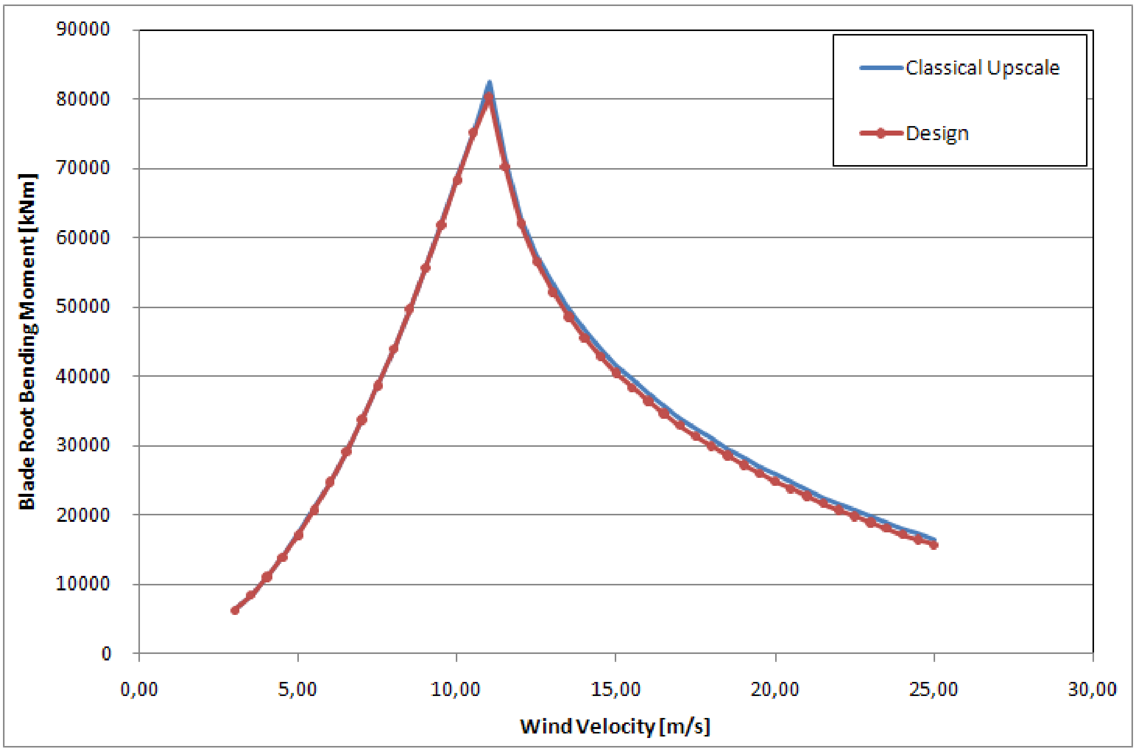


Figure 3.15 *Blade root bending moment of the 20MW design compared with the 20MW upscaled wind turbine for different wind speeds*

3.5 Discussions

As a result of this design study, there are a few points that should be highlighted:

- The design has been performed under some limitations to be comparable with the upscaled wind turbine. The overall power performance has not improved enormously, although the CP values of 0.5 is achieved. Within these limitations, this wind turbine is , so to say, a conservative design. In the real design applications, these limitations have to be reconsidered and especially a proper airfoil selection and thickness distribution have to be determined.
- Since the efficiency of the airfoils are increased due to the Reynolds number effects, the blade has smaller chords and less twists. The effects of the high Reynolds numbers are based on the numerical simulation results obtained from RFOIL predictions. In order to realize these effects, the wind tunnel tests for these Reynolds number regimes are obligatory.
- Considering the effects of the Reynolds numbers, more reductions on the loads is possible. The blade design can be improved more in order to reduce the loads. Still, as a result of this design study, it has been shown that it is possible to have a better performance wind turbine with smaller chords and twist angles with similar loads.

4. Structural blade design

Base of the structural design is the aerodynamic blade design. The airfoil distribution is given in Table 4.1. The blade is modelled using the chord twist distribution discussed in section 3 and given in Figure 3.8 and Figure 3.9.

Table 4.1 *The airfoil distribution of the blade*

Start radius [m]	Airfoil name
0	Cylinder_1
11.4	Cylinder_2
17.4	DU00-W2-401
36.4	DU00-W2-350
43.4	DU97-W-300
53.2	DU91-W2-250
68.4	DU93-W-210
83.4	NACA-64618

The layup of the blade is made to meet the bending stiffness as given in Table 4.2. These values are obtained following classical up-scaling rules (Chaviaropoulos, 2006).

Table 4.2 *Bending stiffness according to classical scaling rules for 20MW turbine*

bending_span [m]	bending_EIflat [Nm2]	bending_EILag [Nm2]
0	2.90E+011	2.90E+011
0.4	2.90E+011	2.90E+011
2.4	3.11E+011	3.13E+011
4.4	2.79E+011	3.12E+011
6.4	2.45E+011	3.17E+011
8.4	1.73E+011	2.38E+011
10.4	1.16E+011	1.64E+011
12.4	1.01E+011	1.46E+011
14.4	88453760000	1.29E+011
16.402	79680960000	1.10E+011
18.4	78989440000	1.12E+011
20.4	75066560000	1.15E+011
22.4	63191360000	1.16E+011
24.4	54184320000	1.13E+011
26.402	46939840000	99912480000
28.4	41103360000	80783360000
30.4	38218400000	79175840000
32.4	36351840000	76928320000
36.402	32800800000	72022400000
40.4	29252000000	67905120000
44.4	25419360000	63924480000
48.4	21790880000	60012160000
52.4	17638080000	55154240000
56.402	14012848000	50225120000
60.4	10900800000	43747840000
64.4	8555552000	40877920000
68.4	6542416000	37344480000
72.4	5032656000	29259680000
76.402	3818048000	25345600000
80.4	2814000000	21173760000
84.4	2016160000	18938880000
88.4	1716224000	16322560000
92.4	1454147200	12765008000
96.402	1220966400	11353728000
100.4	976776000	8290976000
104.4	791716800	7277968000
108.4	629742400	6321968000
110.4	554758400	5659504000
112.4	486616000	4875680000
114.4	424352000	4502672000
115.4	381385600	4187312000
116.402	314107200	2541024000
117.4	256038400	2206080000
118.4	205200000	1900704000
119.4	161323200	1626016000
120.4	120735040	1361115200
121.4	73673440	1028099200
122.4	3921424	105732320
123	2793232	80204000

4.1 Blade layout

For the blade layout glass fiber reinforced plastics are used. Along the blade the blade layout differs. In short, the basic layout of the blade interior is:

- Between 0 and 8.4 meter full triax shell
- Between 8.4 and 14.4 first part of transition area
- Between 14.4 and 71m, three shear webs.
- Between 71m and tip at 123 meter two shear webs.

A shear web consists out two layers (2 * 1.33 mm) of biax, web foam and two layers of biax.
A foam panel consists out of three layers (3 * 0.94mm) of triax, skin foam and three layers of triax. . The material properties used, are obtained from the 5 MW Upwind reference blade (Nijssen, 2007).

Table 4.3 *UD spar caps thickness distribution*

Span [mm]	Thickness [mm]
8400	55
16400	50
20400	68
26400	56
56400	200
68400	150
84400	90
115400	46
120400	24
123000	15

Table 4.4 *UD edge thickness distribution*

Span [mm]	Thickness [mm]
8400	120
12400	80
16400	45
24400	40
30400	25
68400	40
100400	20
123000	15

First part is a root section with a triax layup. See Figure 4.1 and Figure 4.2.

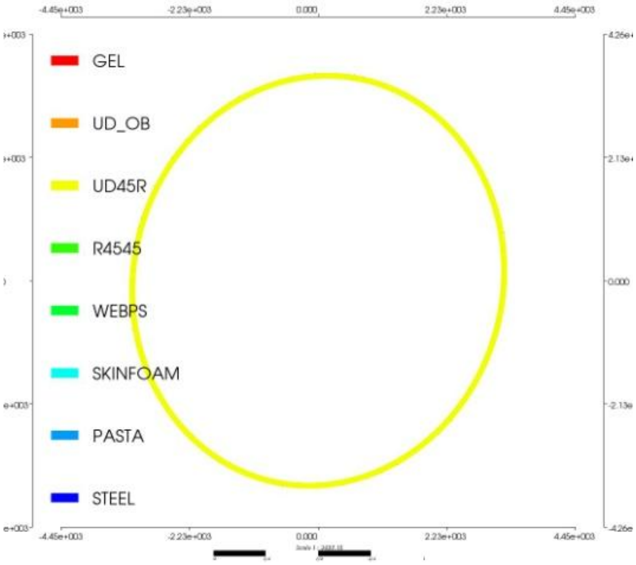


Figure 4.1 *Cross section at 0 m.*

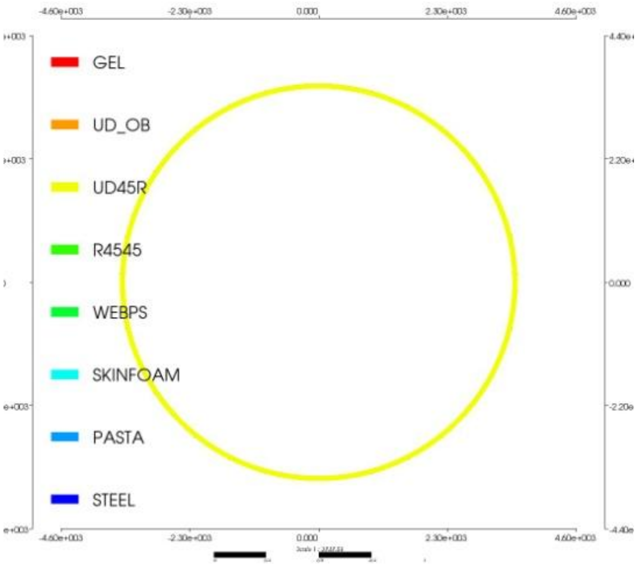


Figure 4.2 *Cross section at 8.399 m.*

Second part is a transition part, with UD spar caps and UD strips in the leading and trailing edge, Figure 4.3 and Figure 4.3. The distribution of the thickness along the blade for the UD spar caps and the UD strips is given in Table 4.3 and Table 4.4 respectively. The two shear webs consist of sandwich panel with a biax (R4545) facing and a foam core (“web foam), the leading and trailing edge panels consist of a sandwich of triax, skin foam and triax.

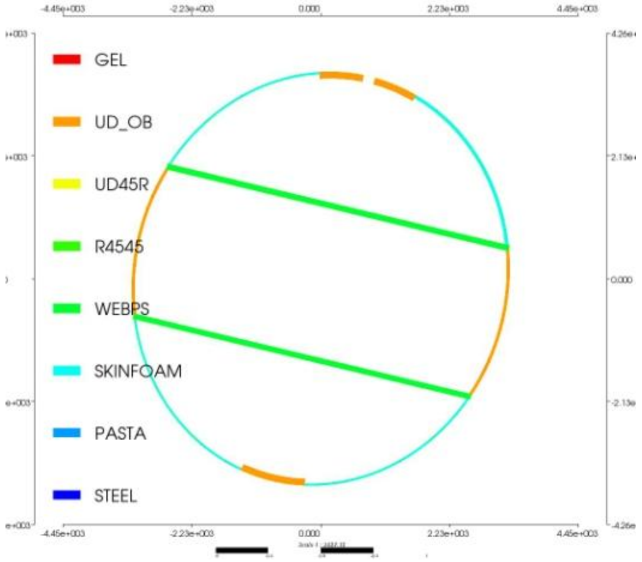


Figure 4.3 *Cross section at 8.4m*

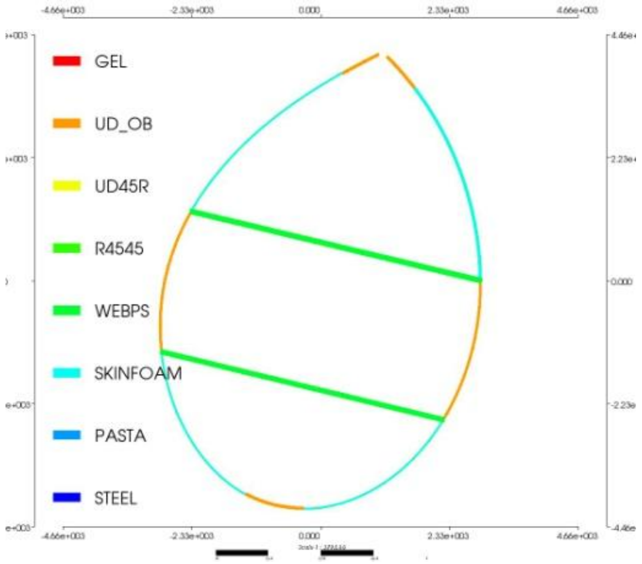
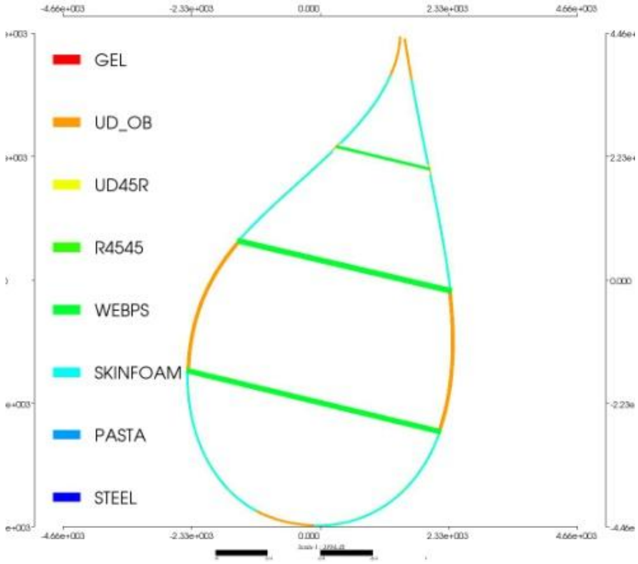


Figure 4.4 *Cross section at 14.399 m*

Due to the large chord length a 20MW wind turbine blade is sensitive to buckling. To avoid a too large foam thickness a 3rd shear web is added at the trailing side of the largest chords. See to Figure 4.7



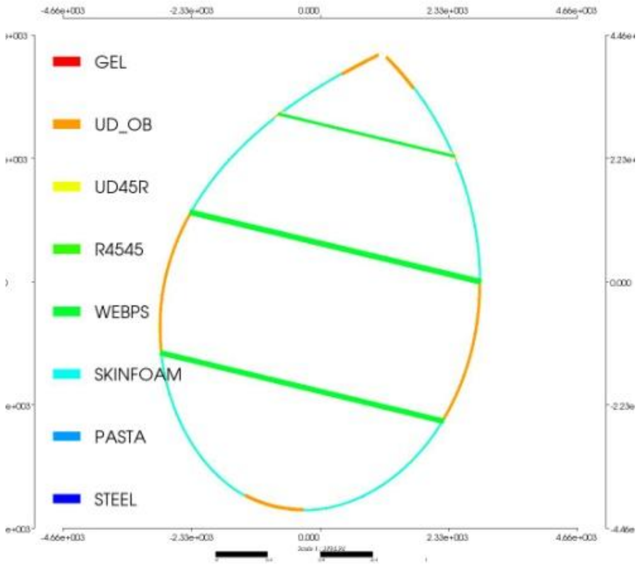


Figure 4.5 *Cross section at 14.4 m*

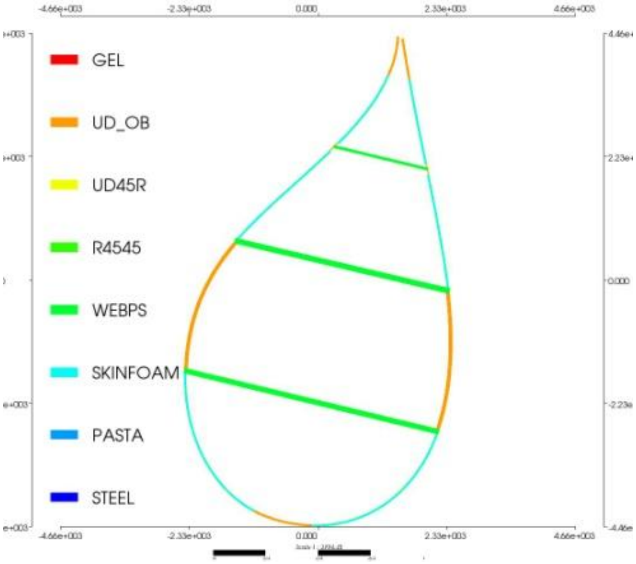


Figure 4.6 *Cross section at 20.4 m*

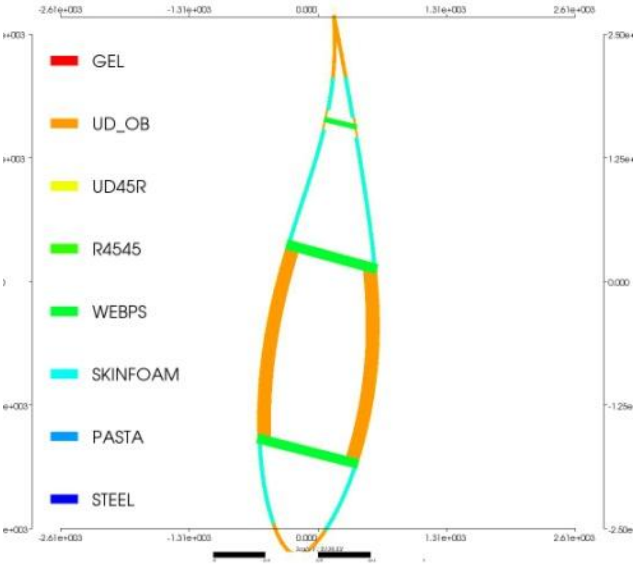


Figure 4.7 *Cross section at 49.4 m*

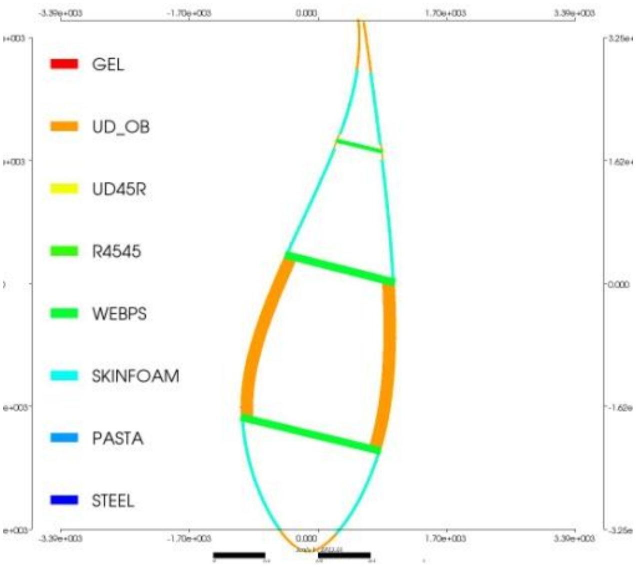


Figure 4.8 *Cross section at 70.999 m*

After 71 meters, see Figure 4.9 to Figure 4.11 two shear webs are sufficient.

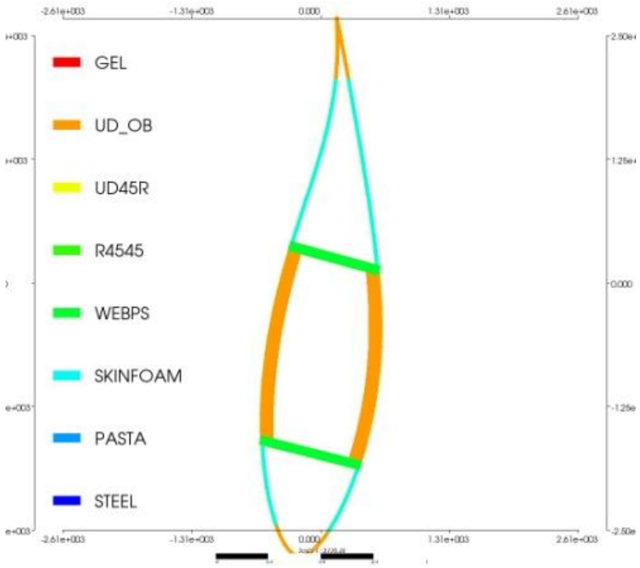


Figure 4.9 *Cross section at 71 m*

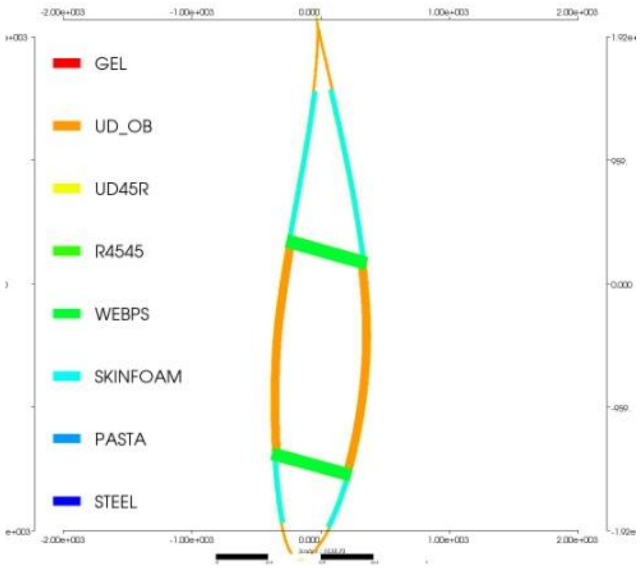


Figure 4.10 *Cross section at 100.4 m*

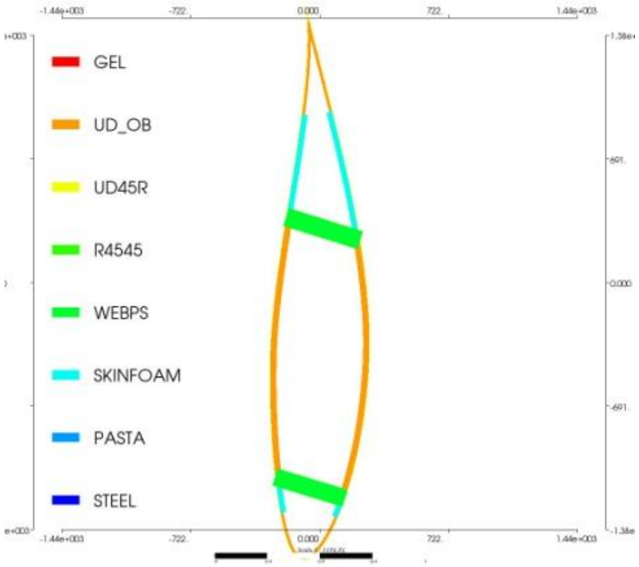


Figure 4.11 *Cross section at 118 m*

In
Table 4.5 the contribution of the blade material to the blade mass is given. The total weight of the blade is 161 ton compared to 142 ton using the classical scaling rules (Chaviaropoulos, 2006). The structural blade properties are given in 0.

Table 4.5 *Mass in kg*

GEL	UD	UD45R	R45	WEB Foam	Skin Foam	Total
291	103000	44800	4580	2030	6490	161000

5. Control design

The design of the controller must be done in two stages: first a controller must be designed for the 5 MW upwind turbine and then a controller can be designed for the 20 MW turbine. Because the drive train itself was not a concern, it was assumed stiff and no drive train damping controller was designed.

5.1 Concerns beforehand

The frequencies of the 20 MW turbine are about half of those of the 5 MW turbine. Because the controller's bandwidth is adjusted according to these frequencies, there is less bandwidth available for control as well. A controller with a lower bandwidth, as for the 20MW wind turbine, cannot react as quickly to a fast change in wind speed or direction. That means that the controller may not be able to parry loads due to fast variations or track variations in the wind well.

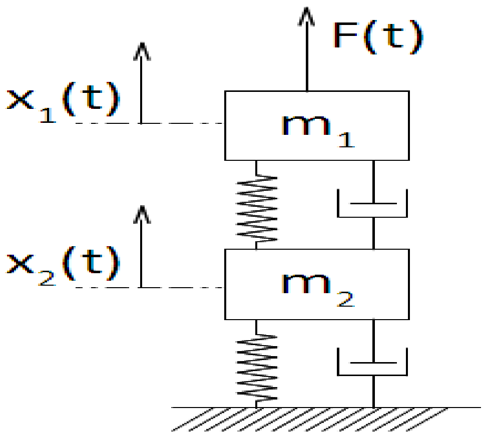
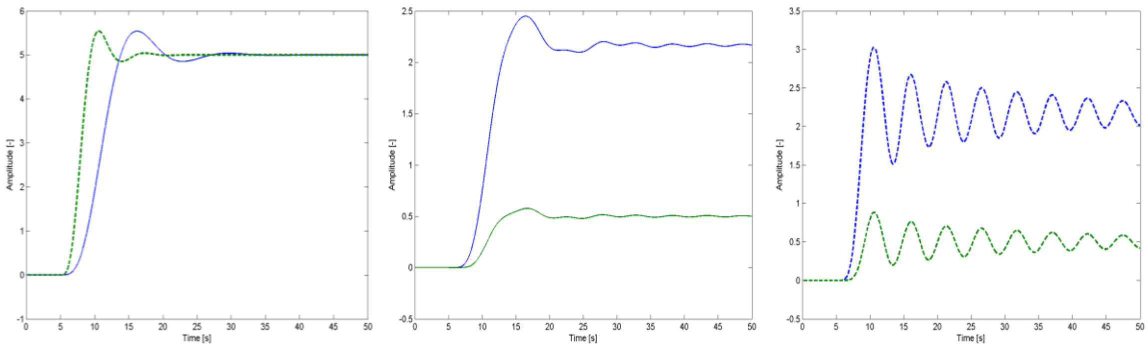


Figure 5.1 *A simple mass spring system*

To illustrate this, a simple mass-spring system such as the one in Figure 5.1 can be studied. The effect of an extreme operating gust acting on the 5 and 20 MW wind turbines, could be modelled by filtering a step signal in the force F(t) with two different filters. To simulate a large wind turbine, the force is filtered with a low pass filter with a higher frequency than for a smaller wind turbine. This means that the force will reach its final value relatively quicker, in the same way that a gust would reach its final value in fewer rotations of the rotor.

Figure 5.2 shows the two differently filtered disturbances acting on the mass spring system, as well as the response of the system. The system responds a lot stronger when the frequency content of the step-disturbance is higher. In this case this effect is strong because the disturbance has a larger frequency content at the eigenfrequency of the system.

It should be noted that the opposite is also possible: if there is a variation that passes relatively quickly and has no constant offset (e.g. a 'Mexican hat' excitation), the frequency content of the wind could be less at the eigenfrequencies and the disturbance could pass without exciting the system.



(a)
Filtered step force, low pass frequencies at 0.5 (solid blue) and 1 (dashed green) rad/s

(b)
Response for 0.5 rad/s filtered force with x1 solid blue and x2 dashed green.

(c)
Response for 1.0 rad/s filtered force with x1 solid blue and x2 dashed green.

Figure 5.2 *Disturbances and according responses of a mass-spring damper system*

This would mean that on the one hand, the controller does not have to react to a fast variation, but on the other hand, it might mean that the wind turbine is to slow at following trends in the wind. Either way: the frequency content of the wind excitations relative to the eigenfrequencies will change and its effect should be studied.

5.2 5 MW controller

To design the 5 MW controller, ideally we would use the reference controller that was designed for the turbine (Jonkman, 2009). However, because we will be designing our own controller for the 20 MW turbine, it is decided to design our own controller for the 5 MW reference turbine such that we can compare the performance and design for both turbines.

The design is done in several steps:

1) appropriate Cp and Ct data are gathered first
2) based on analysis of this data an appropriate generator curve Qn is chosen. Electrical losses were estimated to be 5.6% and mechanical losses 2.8%.
3) the ECN control design tool is used to design a controller that includes:
    a. tower filter
    b. 3p filter and low-pass filter
    c. dynamic Qn shift
    d. peak shaving

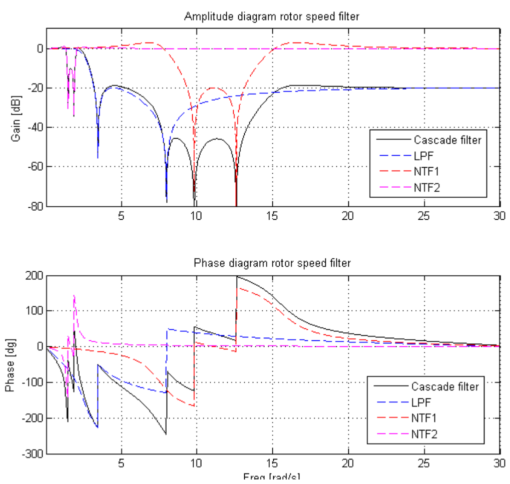


Figure 5.3 *Rotor speed filter of the controller for the 5MW controller*

Drive train damping was not included in this controller. Gain scheduling was implemented as a pitch angle dependent scheduling only. Dynamic Qn shifting is aimed at preventing dips in power when average winds are above rated.

Figure 5.3 shows the filters applied to the rotor speed signal. The figures show that the filtering is composed of three separate filters: LPF is the combined 3p and low-pass filter, NTF1 is the filter for the collective lead/lag frequencies and NTF2 is the tower filter. The tower filter is designed to filter out any tower frequency components from the control signals. This means the controller does not attempt to control the tower motions, but also will not cause any additional tower excitation.

The control parameters are first designed to obtain good performance in the 5 MW reference design, before they were adjusted further to obtain good performance for the 20 MW design.

Figure 5.4 shows the Qn curve as designed originally for the 5 MW wind turbine and the design that was made for the comparison. Because the ECN control design tool handles the transition from below rated to above rated conditions differently than the NREL 5MW controller, a slightly less steep transition was designed to ensure stability.

Peak shaving through pitching was also included in the controller and started at a rotor speed of 9.4 rpm to reach a pitch angle of 2 degrees at rated rotor speed.

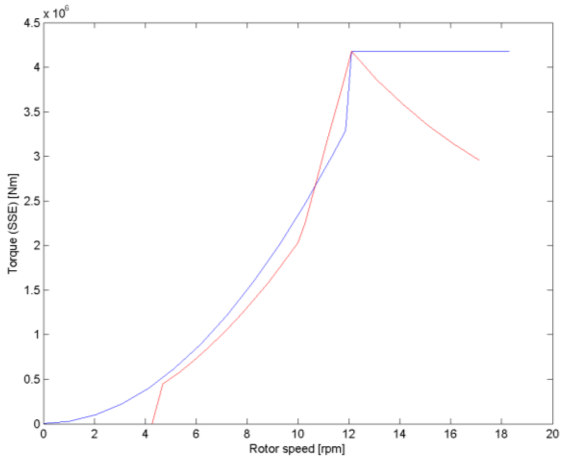


Figure 5.4 *Qn curve for the reference 5MW turbine as designed originally (blue) and the new design (red)*

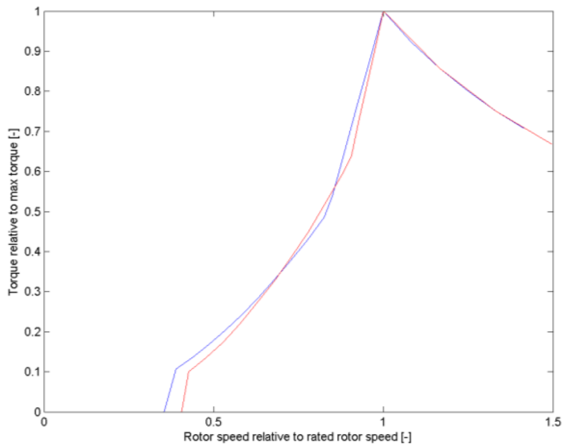


Figure 5.5 *Normalised Qn curves as designed for the 5 MW reference turbine (blue) and the 20 MW turbine (red)*

5.3 20 MW Controller

The 20 MW controller was adapted in two ways, first the low-pass filtering was reduced, i.e. the high pass amplification was adjusted from -20 dB to -10 dB. Additionally, the sample frequency for the generator was reduced to 10 Hz.
Figure 5.5Figure 5.2 shows the Qn curve of the 20 MW turbine in comparison to the 5 MW turbine, while **Error! Reference source not found.** shows the filter designed for the 20 MW wind turbine.
Peak shaving through pitching started at a rotor speed of 4.7 rpm to reach a pitch angle of 2 degrees at rated rotor speed.

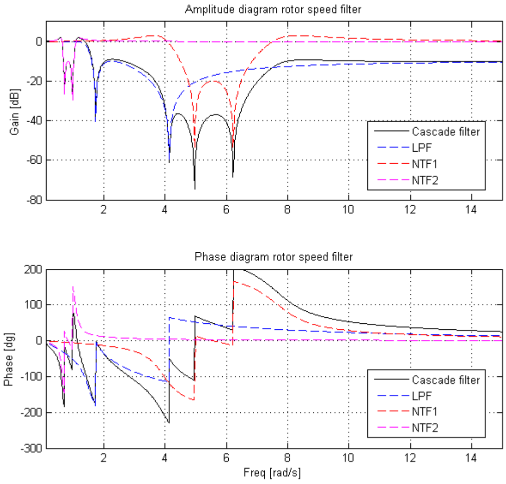


Figure 5.6 *Rotor speed filter of the controller for the 20MW turbine*

5.4 Comparison of selected load cases

For the analysis of this turbine, IEC 61400-1 edition 2 (IEC,1998) was used to define the load cases. In both edition 2 and edition 3 (IEC, 2005) of this standard, the amplitude of the wind speed variation for the extreme operating gust (EOG) and extreme direction change (EDC) are inversely related to the size of the rotor; the amplitude one can take into account becomes smaller for larger rotor diameters.

The wind speed in the extreme wind speed model (EWM), the extreme coherent gust (ECG) and the extreme coherent gust with direction change (ECD) is invariant with respect to the rotor size. For the extreme wind shear (EWS), the magnitude of the variation of the rotor is related to the size of the rotor. The time scales described in these load cases are time independent, i.e. the frequency content of the wind is not dependent on the size of the rotor.

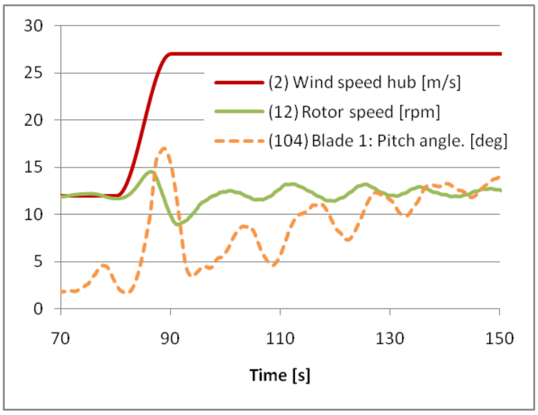
A small selection of extreme load cases is examined. In particular load cases 1.3, 1.6 and 1.7. These load cases describe extreme transients that are unaffected by the rotor size (1.3, ECD), inversely related to rotor size (1.6, EOG) and related to rotor size (1.7, EWS).

5.4.1 Load case 1.3: Extreme coherent gust with a direction change

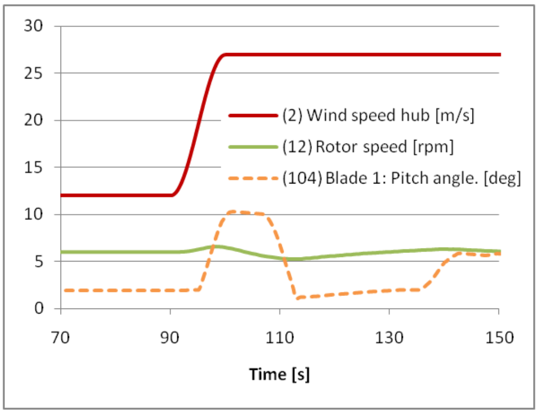
Load case 1.3 (part of load case 1.4 in IEC 61400-1 ed. 3) describes the occurrence of an extreme coherent gust in combination with a direction change at normal operation at rated wind speed. The direction change can be in either direction. 10 seconds after the direction change occurs, the turbine starts to yaw in the direction of the wind at 0.3 degrees per second.
Figure 5.7shows some results for the 5 MW turbine, while Figure 5.8 shows results for the 20 MW turbine.

It can be seen that:

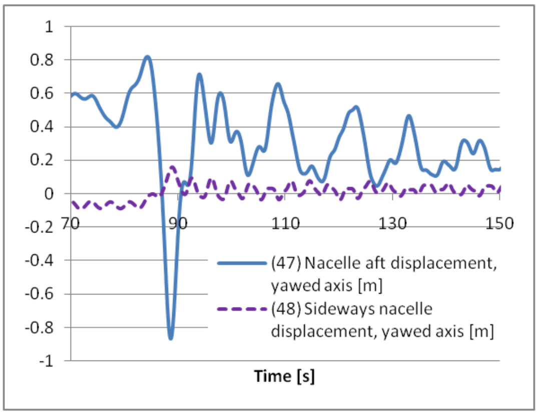
- The pitch controller of the 5 MW turbine has difficulty dealing with the steady state disturbance.
- The rotor speed (and thus the pitch angle) of the 20 MW wind turbine reacts very slowly to the changed circumstances.
- The variation in the lead wise moments in the blades is relatively large, compared to the variations in the flap wise bending moment. This is to be expected, as the forces that cause that moment are mainly due to gravity acting on the mass of the blade. The mass scales as D^3 and the arm of the moment as D; the total lead wise moment will therefore scale as D^4. The aerodynamic torque only increases as D^3.



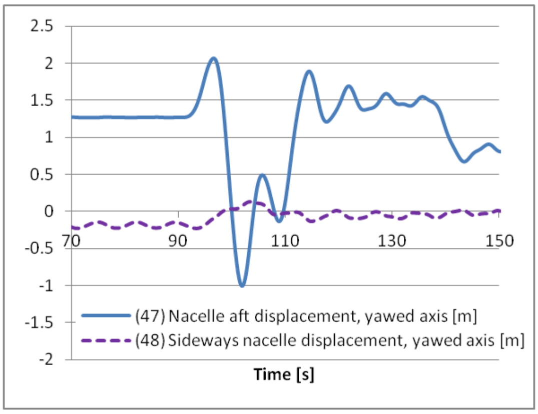
(a)



(a)



(b)



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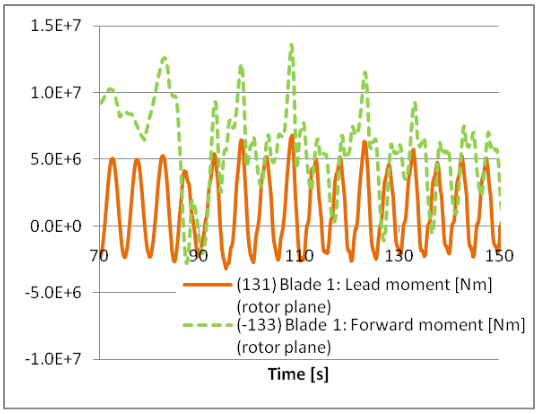
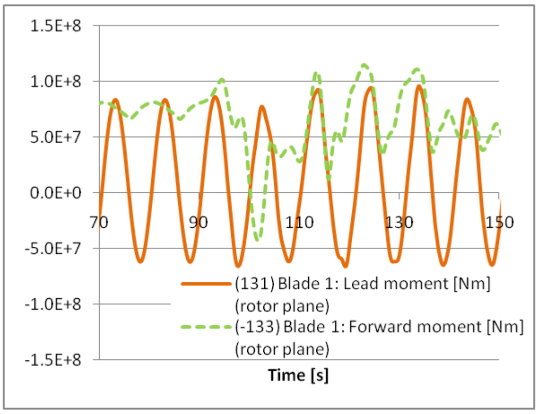


(c)



(c)

Figure 5.7 *Load case 1340 for 5 MW turbine*

Figure 5.8 *Load case 1340 for 20 MW turbine*

5.4.2 Load case 1.6: Extreme operating gust

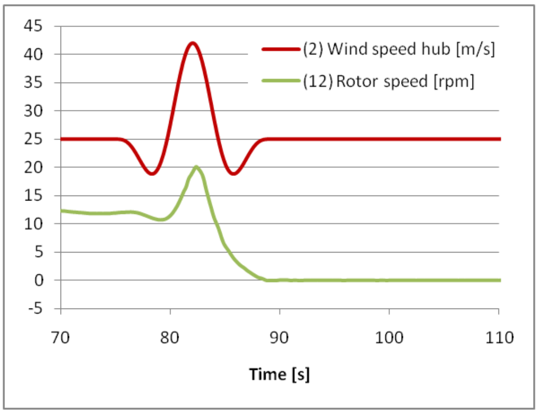
For load case 1.6, the response must be calculated to a 50 year extreme operating gust at sub-rated, rated and cut-out wind speeds. Figure 5.9 shows the gust and rotor speed for the 5 MW and 20 MW turbine, while Figure 5.10 shows the displacement of the nacelle. This load case is not used in edition 3 of IEC 614001-1.

It can be seen that:

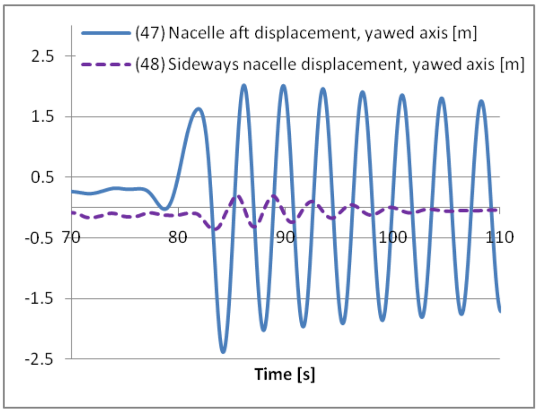
- The amplitude of the gust is a lot smaller for a 20 MW wind turbine. This is due to how the gust is calculated according to the standard. The amplitude of the gust depends on the turbulence and the rotor diameter.

- The 5 MW turbine shuts down due to an over speed situation. The increase in rotor speed of the 20 MW turbine is small, only 0.6 rpm. There is a significant time difference between the peak in wind velocity and the peak in the rotor speed.

- The nacelle response of the 20 MW turbine in rotor speed and nacelle displacement is relatively small when compared to rotor size, although larger in absolute terms. One should consider that the excitation is also a lot smaller.

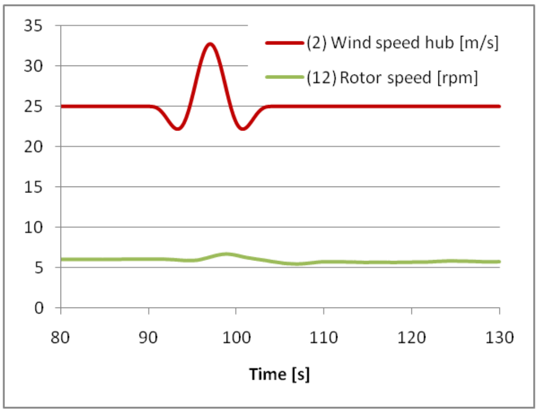


(a)

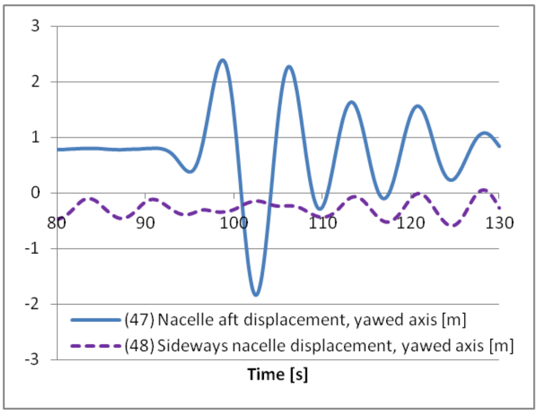


(b)

Figure 5.9 *Load case 1690 for 5 MW turbine*



(a)



(b)

Figure 5.10 *Load case 1690 for 20 MW turbine*

5.4.3 Load case 1.7: Extreme wind shear

Load case 1.7 describes extreme wind shear. This load case does not test the reaction of the controller because the effects of wind shear are not influenced much by collective pitch or torque control.

Figure 5.11 shows the resulting yaw and tilt moments on the tower of the 5 MW turbine, due to wind shear in various conditions. Figure 5.12 shows the resulting yaw and tilt moments for the 20 MW turbine, for the same load cases.

The figures show that the rotor moment increase substantially. Not only does it increase more (a factor 20-24) than could be expected on the basis of simple scaling rules (one would expect a factor 8 increase: the forces would increase as D^2, the arm as D), but it also increases relative to steady state variations.

The turbine model used here did not allow for yawing due to wind loads, where the rotor loads drive the yawing motion of the wind turbine because they exceed the friction of the brake pads. Whether this is a realistic assumption given the moments acting on the structure, is not examined here.

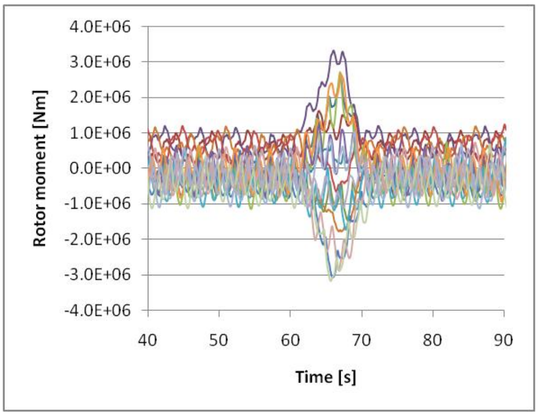


Figure 5.11 *Rotor moments for various extreme wind shear conditions, 5 MW turbine*

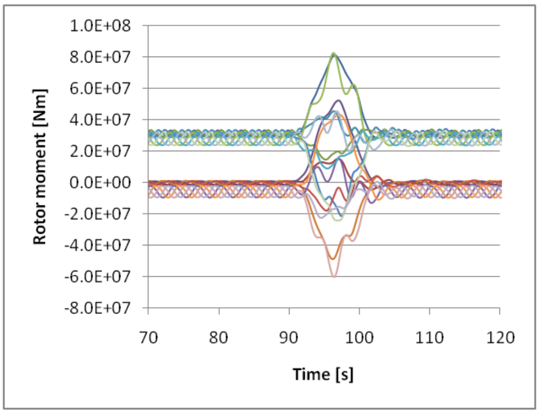


Figure 5.12 *Rotor moments for extreme wind shear conditions, 20 MW turbine*

5.5 Conclusions

The comparison of the two turbines is difficult based on this selected set of extreme load cases, because the amplitude of the wind speed variation in the load cases depends in a different way on the rotor size. Also, the time scale of the excitations does not change with rotor size. That means that the frequency content of the excitation relative to the frequencies of the structure changes.
The load cases do allow for some conclusions:

- With this aerodynamic design, the rotor speed of the 20 MW wind turbine is relatively insensitive to changes in the wind. This is certainly an advantage in that the rotor speed limits are rarely reached, but it also makes it considerably more difficult to track the optimal lambda in wind speed variations. If the pitch angle is not adjusted accordingly, this may result in power loss.

- As expected, normal wind shear affects the 20 MW wind turbine design more strongly than the 5 MW design, because of the relatively lower tower.

- Extreme wind shear affects this wind turbine much more than one might expect on the basis of simple scaling rules.

5.6 Discussion

Load case 1.7 (Extreme wind shear) resulted in some very large moments acting on the support structure. The controller designed for the 20 MW turbine is a controller with collective pitch control and can do little to alleviate such loads. An individual pitch controller may be able to counter such loads more effectively.

6. IEC61400-1 edition 2 load set calculations

In the preceding sections the blade and controller design was discussed in detail. Here the results of a load set calculation according to IEC61400-1 edition 2 class IIB is presented. The complete 20MW turbine is modelled in PHATAS (Focus6-AeroelasticityII). The general characteristics of the 20MW wind turbine are summarized in Table 6.1.

Table 6.1 *General wind turbine properties*

Variable	**Unit**	**20 MW ref turbine**
Nominal power	MW	20
Rotor diameter	m	252
Hub height	m	153
Number of blades	-	3
Blade span	m	123
Tower height (incl. monopile)	m	168.2
Water depth	m	20
Rated tip speed	m/s	80
Rated rotor speed	rpm	6.05
Cut-in rotor speed	rpm	2.58
Gearbox ratio	-	194
Cone angle	°	-2.5
Rotor tilt	°	5

More details of the 20MW wind turbine can be found in Appendix A to Appendix C. In Appendix A the main differences between the 5MW and 20MW wind turbine is shown. Most 20MW properties are scaled according to the classical scaling rules.

Apart from the blade and controller designs, there is one change that is not according to the scaling rules: the increase in tower height. The tower height was increased such that hub height increases by 63m (the additional blade length). This should keep the airgap (blade tip - wave distance) at least equal[1]. Because it is assumed that the dimensions of the nacelle increases as well, that means that the increase in tower height is less than the increase in blade length. Furthermore, it is assumed that a monopile is used up to the same height as for the reference design. If all other dimensions were scaled according to classical scaling criteria, a relatively high tower frequency would be obtained. It was therefore chosen to adjust the wall thickness such that an eigenfrequency is obtained that is nearly half of the 5 MW turbine.

Another effect of this lower tower will be that load variations due to wind shear will be more pronounced (**Error! Reference source not found.**).

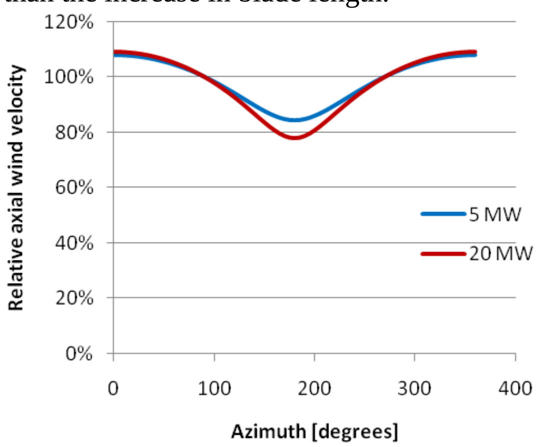


Figure 6.1 *Wind shear is stronger for a relatively shorter tower*

[1] Actually there will be some change, because the cone-angle and blade bending are not taken into account here.

For the 20MW wind turbine a full IEC 61400-1 Edition 2 (IEC, 1998) load set was done using FOCUS6 - Aeroelasticity II (PHATAS).

Summary IEC load set:

- IEC class IIB
- Annual average wind speed 8.5 m/s
- Reference wind speed 42.5 m/s

The following subsections will discuss the results of the load set calculation.

6.1 Fatigue

For fatigue analyses, the fatigue loads from the load set were used. The GL 2003 Goodman diagram was used for the fatigue analyses. The material properties used, are obtained from the 5 MW Upwind reference blade (Nijssen, 2007). For the interpretation of the fatigue results the Fatigue Safety Factor FSF is used.

The FSF is the factor by which the load or stresses have to be multiplied to arrive at the allowable damage rate D (normally one).

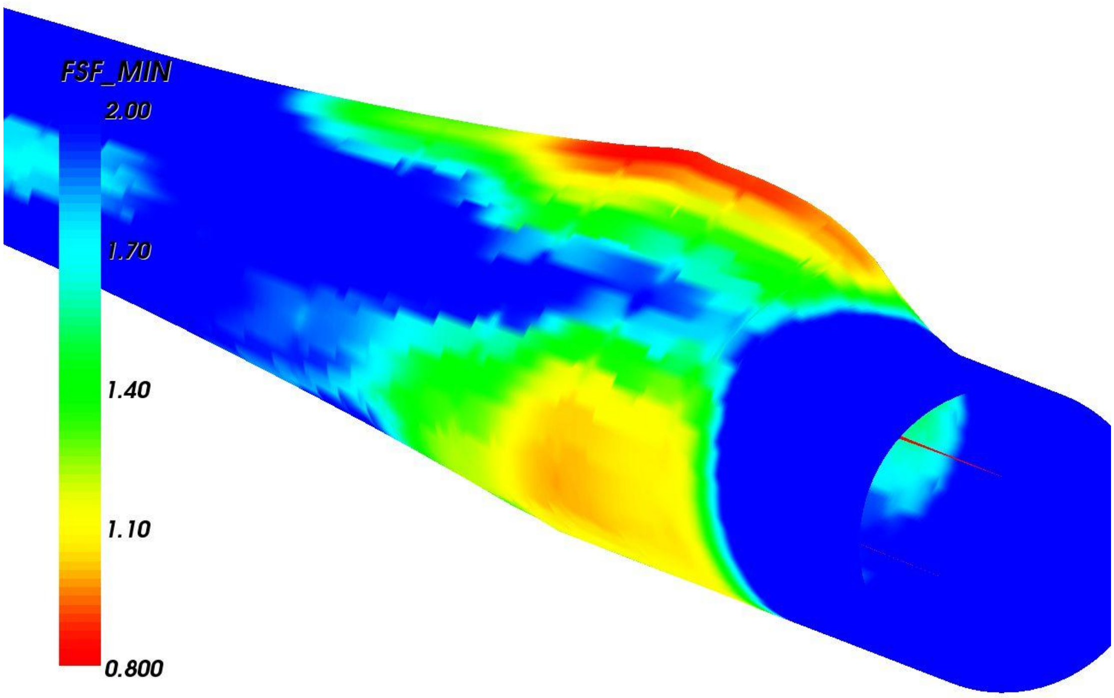


Figure 6.2 *Fatigue Safety Factor (FSF) on blade.*

In the current design a safety factor for fatigue at the trailing edge at the largest chord area of the blade is below 1. See Figure 6.2. This is the case for both TRIAX and for the UD material. In this area of the blade, the materials would need to be about 20% stronger to meet the design criteria.

6.2 Extreme

After calculation of the entire load set some calculations did not converge correctly. This was partly due to a sub-optimal controller setting. In the design process there is always in interaction between the results of the load set calculations and the finding the optimal controller settings. In this study the non-converging calculations were removed from the load set.

Figure 6.3 shows some plots of the combined load set minimum safety factors on strain for UD, TRIAX and BIAX. The upper left plot gives the Safety factor for the UD at the pressure side. Red means no material. The upper right plot shows the UD at the suction side. Again red means no material. The plot left below shows the Safety factor for the Triax pressure side, the right below the Triax suction side.

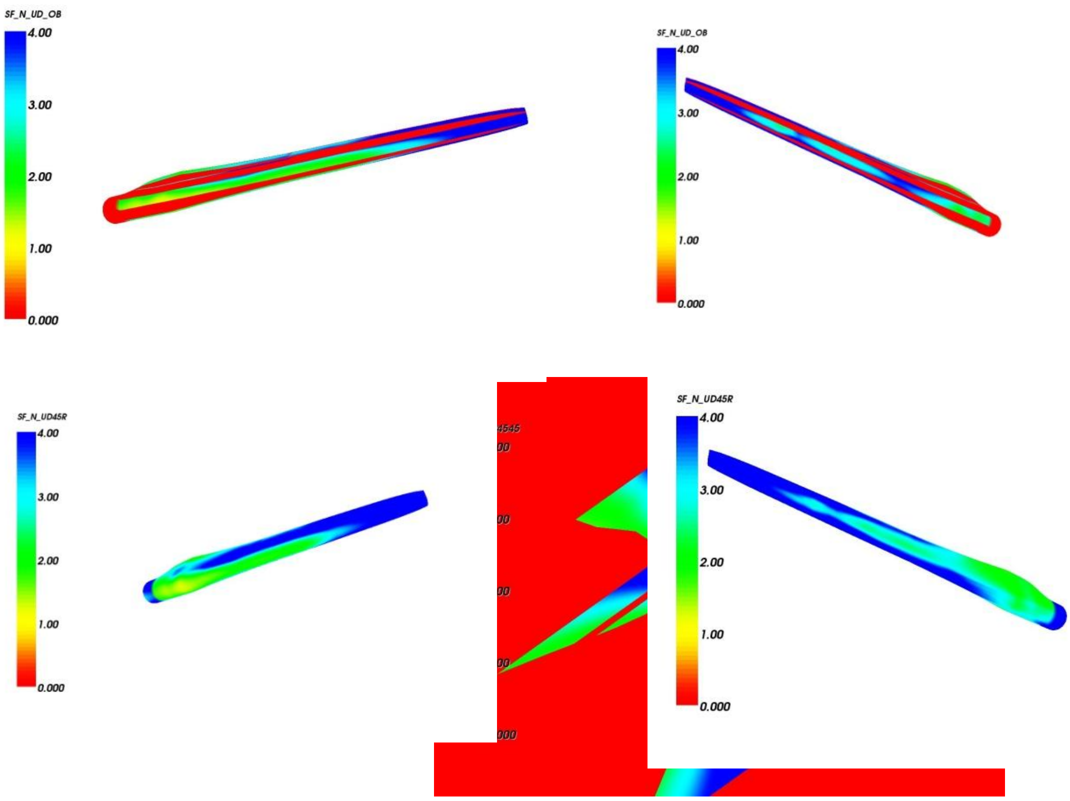


Figure 6.3 *Shear web seen from inside*

The strength of the blade against extreme loading is good.

6.3 Tip deflection

The maximum tip deflections as listed below, Table 6.2 , are including partial load factors (typical 1.35). For series only the highest tip deflection is shown. The maximum tip deflection corresponds with the deflection found by Wessels et al. (2010).

Table 6.2 *Tip deflection in x direction*

Load case	Description	m
1690	DLC1.6 EOG_50 at cut-out wind with positive misalignment.	12
1350	DLC1.3 ECD, at rated wind and positive direction change.	21
2204	DLC2.2 NWP, Pitch runaway of all blades, at rated wind.	24
3383	DLC3.3 EDC_1 Start with Extreme Direction Change, max-start	25
3277	DLC3.2 EOG Start with Extreme Operating Gust, max-start.	25
2208	DLC2.2 NWP, Pitch runaway of all blades, at cut-out wind.	28

The chord-wise deflection of the blade, Table 6.3, is in the order of (-3, 4) meters for production load cases. For some load cases this can increases.

Table 6.3 *Deflection in chord-wise direction*

Load case	Description	m
1340	DLC1.3 ECD, at rated wind and negative direction change.	4.8
3290	DLC3.2 EOG Start with Extreme Operating Gust, max-start.	5.3
2186	DLC2.1 NTM, Blade 2 blocks at cut-out wind	5.4

6.4 Buckling

Buckling analyses using a panel based method is performed on two load cases:

- DLC1.9 ECG, at rated wind and negative misalignment.
- DLC1.9 ECG, at rated wind and positive misalignment.

The panels analysed are the sandwich panels both on the skin as on the shear web.
The calculation resulted in a buckling safety factor greater than one.

A full load set buckling analysis is not performed.

7. Conclusions and Recommendations

This report describes the design of a 20MW wind turbine. The dimensions of the upscaled Upwind 5MW reference wind turbine are used as a starting point for the design. The scaling was done according to classical scaling rules. Focus in the 20MW design was on the aerodynamic and structural blade design and the controller design.

For the aerodynamic blade design it can be concluded that for a 20MW wind turbine the airfoils should be corrected for a higher Reynolds number. Wind tunnel tests are needed to further understand the airfoil performance at high Reynolds numbers. The design has been performed under some limitations to be comparable with the upscaled wind turbine. The overall power performance has not improved enormously, although CP values of 0.5 are achieved. Within these limitations, this wind turbine is , so to say, a conservative design. In the real design applications, these limitations have to be reconsidered and especially a proper airfoil selection and thickness distribution have to be determined.

The structural blade strength is good for extreme loads. For fatigue the safety factor at the trailing edge at the largest chord area of the blade is below 1. In this area of the blade, the materials would need to be about 20% stronger to meet the design criteria. The maximum tip displacement corresponds with other studies. A limited buckling analysis is performed for two load cases. The blade mass is 161 ton and about 20 ton more than the classical scaled 20MW blade.

To explain the behaviour of the controller three selected load cases are discussed. These load cases do allow for some conclusions:

- With this aerodynamic design, the rotor speed of the 20 MW wind turbine is relatively insensitive to changes in the wind. This is certainly an advantage in that the rotor speed limits are rarely reached, but it also makes it considerably more difficult to track the optimal lambda in wind speed variations. If the pitch angle is not adjusted accordingly, this may result in power that is lost.
- As expected, normal wind shear affects the 20 MW wind turbine design more than the 5 MW design, because of the relatively lower tower.
- Extreme wind shear affects this wind turbine much more than one might expect on the basis of simple scaling rules.

In this pre-design of a 20MW no flutter speed or aeroelastic stability analysis is performed. The emphasis was on the aerodynamic and structural blade design and the controller design. With increasing power the blade length and blade flexibility increases. Therefore for long slender and flexible blades like the one for a 20MW wind turbine it is recommended to perform a flutter speed and aeroelastic stability analysis first before continuing the design.

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Appendix A Turbine characteristics

A.1 General properties

Variable	Unit	5 MW ref turbine	20 MW ref turbine
Nominal power	MW	5	20
Rotor diameter	m	126	252
Hub height	m	90	153
Number of blades	-	3	3
Blade span	m	61.5	123
Tower height (incl. monopile)	m	107.6	168.2
Water depth	m	20	20
Rated tip speed	m/s	80	80
Rated rotor speed	rpm	12.1	6.05
Cut-in rotor speed	rpm	4.7	2.58
Gearbox ratio	-	97	194
Cone angle	°	-2.5	-2.5
Rotor tilt	°	5	5

A.2 Generator properties

Variable		5 MW ref turbine	20 MW ref turbine
Constant loss	Nm	50	24000
Fast shaft inertia	kgm^2	5.34E+02	17088
Gearbox inertia	kgm^2	0	0
Gear ratio	-	97	194
Generator model	-	5	5
Generator slope	-	0.02	0.02
Maximum torque	Nm	4.60E+04	36.8E+4
Proportional loss	-	0.028	0.028
Nominal generator power	MW	5.297	21.186
Rated rotor speed	rpm	12.1	6.05
Shaft stiffness	Nm/rad	8.68E+08	2.44E+10
Support damping	-	0.005	0.005
Support stiffness	Nm/rad	3.00E+20	3.00E+20

A.3 Nacelle

Variable	Unit	5 MW ref turbine	20 MW ref turbine
Cross inertia	kgm^2	0	0
Nacelle front area aerodynamic drag	m^2	36	144
Nacelle mass	kg	240000	1920000
Nacelle side area aerodynamic drag	m^2	108	432
Nacelle unbalance x	Nm	4.56E+5	7.296E+6
Nacelle unbalance z	Nm	4.20E+5	6.72E+6
Rolling inertia	kgm^2	9.75E+5	3.12E+6
Side drag location	M	0	0
Tilt angle	°	5	5
Tilting inertia	kgm^2	2.92500E+6	9.36E+7
Yawing inertia	kgm^2	2.60789E+6	8.345248E+7

A.4 Hub

Variable	Unit	5 MW ref turbine	20 MW ref turbine
Hub inertia	kgm^2	115926	3709632
Hub location	m	2.4	4.8
Hub mass	kg	56780	454240
Hub static moment	Nm	283900	4542400
Hub distance to yaw axis(horizontal)	m	-5.43	-10.86
Blade root radius	m	1.5	3

A.5 Tower segments

5 MW ref turbine

segment height	diameter low end	diameter upper end	wall thickness	Youngs modulus	shear modulus	mass density
[m]	[m]	[m]	[m]	[Pa]	[Pa]	$[kg/m^3]$
30	6	6	0.06	2.10E+11	8.08E+10	8500
30.001	6	6	0.027	2.10E+11	8.08E+10	8500
37.76	6	5.78	0.026	2.10E+11	8.08E+10	8500
45.52	5.78	5.58	0.025	2.10E+11	8.08E+10	8500
53.28	5.58	5.36	0.025	2.10E+11	8.08E+10	8500
61.04	5.36	5.14	0.024	2.10E+11	8.08E+10	8500
68.8	5.14	4.94	0.023	2.10E+11	8.08E+10	8500
76.56	4.94	4.72	0.022	2.10E+11	8.08E+10	8500
84.32	4.72	4.5	0.021	2.10E+11	8.08E+10	8500
92.08	4.5	4.3	0.021	2.10E+11	8.08E+10	8500
99.84	4.3	4.08	0.02	2.10E+11	8.08E+10	8500
107.6	4.08	3.88	0.019	2.10E+11	8.08E+10	8500

20 MW ref turbine

segment height	diameter low end	diameter upper end	wall thick-ness	Youngs modulus	shear modulus	mass den-sity
[m]	[m]	[m]	[m]	[Pa]	[Pa]	[kg/m^3]
30	12	12	0.08	2.10E+11	8.08E+10	8500
30.001	12	12	0.036	2.10E+11	8.08E+10	8500
37.76	12	11.56	0.034667	2.10E+11	8.08E+10	8500
44.04	11.56	11.16	0.033333	2.10E+11	8.08E+10	8500
59.56	11.16	10.72	0.033333	2.10E+11	8.08E+10	8500
75.08	10.72	10.28	0.032	2.10E+11	8.08E+10	8500
90.6	10.28	9.88	0.030667	2.10E+11	8.08E+10	8500
106.12	9.88	9.44	0.029333	2.10E+11	8.08E+10	8500
121.64	9.44	9	0.028	2.10E+11	8.08E+10	8500
137.16	9	8.6	0.028	2.10E+11	8.08E+10	8500
152.68	8.6	8.16	0.026667	2.10E+11	8.08E+10	8500

Appendix B Blade Geometry (as modelled in BOT)

r [m]	*C* [m]	*e* [°]	*t* [m]	*t/c* [-]	***Airfoil distribution***
3.0	7.0840	13.5000	7.0840	1.0000	Cylinder (100%)
3.4	7.0840	13.5000	7.0840	1.0000	Cylinder (100%)
5.4	7.0840	13.5000	7.0840	1.0000	Cylinder (100%)
7.4	7.0840	13.5000	6.9290	0.9781	Cylinder (92,7%); Cylinder2 (7,3%)
9.4	7.0840	13.5000	6.7190	0.9485	Cylinder (82,8%); Cylinder2 (17,2%)
11.4	7.2068	13.5000	6.4852	0.8999	Cylinder (66,6%); Cylinder2 (33,4%)
13.4	7.5461	13.5000	6.2344	0.8262	Cylinder2 (57,9%); Cylinder (42,1%)
15.4	8.0336	13.5000	5.9722	0.7434	Cylinder2 (85,5%); Cylinder (14,5%)
17.4	8.4644	13.5000	5.7038	0.6739	Cylinder2 (91,3%); DU00-W2-401 (8,7%)
19.4	8.7695	13.5000	5.4331	0.6195	Cylinder2 (73,1%); DU00-W2-401 (26,9%)
21.4	8.9756	13.5000	5.1645	0.5754	Cylinder2 (58,3%); DU00-W2-401 (41,7%)
23.4	9.0991	13.5000	4.9003	0.5385	DU00-W2-401 (54%); Cylinder2 (46%)
25.4	9.1693	13.3843	4.6431	0.5064	DU00-W2-401 (64,8%); Cylinder2 (35,2%)
27.4	9.2095	13.0453	4.3949	0.4772	DU00-W2-401 (74,5%); Cylinder2 (25,5%)
29.4	9.2106	12.5111	4.1481	0.4504	DU00-W2-401 (83,5%); Cylinder2 (16,5%)
31.4	9.2047	11.8202	3.9195	0.4258	DU00-W2-401 (91,7%); Cylinder2 (8,3%)
33.4	9.1602	11.0133	3.6976	0.4037	DU00-W2-401 (99,1%); Cylinder2 (0,9%)
35.4	9.0080	10.1625	3.4588	0.3840	DU00-W2-401 (59%); DU00-W2-350 (41%)
39.4	8.4913	8.4588	2.9815	0.3511	DU00-W2-350 (97,8%); DU00-W2-401 (2,2%)
43.4	8.0221	7.1640	2.6036	0.3246	DU97-W-300 (50,9%); DU00-W2-350 (49,1%)
47.4	7.5986	6.2263	2.2936	0.3018	DU97-W-300 (96,3%); DU00-W2-350 (3,7%)
51.4	7.2219	5.6858	2.0397	0.2824	DU97-W-300 (64,9%); DU91-W2-250 (35,1%)
55.4	6.8685	5.3542	1.8256	0.2658	DU91-W2-250 (68,4%); DU97-W-300 (31,6%)
59.4	6.5294	5.0454	1.6427	0.2516	DU91-W2-250 (96,8%); DU97-W-300 (3,2%)
63.4	6.2145	4.7070	1.4885	0.2395	DU91-W2-250 (73,8%); DU93-W-210 (26,2%)
67.4	5.9362	4.3532	1.3598	0.2291	DU93-W-210 (52,3%); DU91-W2-250 (47,7%)
71.4	5.7003	4.0257	1.2525	0.2197	DU93-W-210 (75,7%); DU91-W2-250 (24,3%)
75.4	5.4966	3.7510	1.1605	0.2111	DU93-W-210 (97,2%); DU91-W2-250 (2,8%)
79.4	5.3501	3.4615	1.0867	0.2031	DU93-W-210 (77,1%); NACA64618 (22,9%)
83.4	5.1987	3.1203	1.0177	0.1958	DU93-W-210 (52,6%); NACA64618 (47,4%)
87.4	5.0374	2.7241	0.9538	0.1893	NACA64618 (68,9%); DU93-W-210 (31,1%)
91.4	4.8656	2.3328	0.8962	0.1842	NACA64618 (86%); DU93-W-210 (14%)
95.4	4.6846	1.9971	0.8466	0.1807	NACA64618 (97,6%); DU93-W-210 (2,4%)
99.4	4.4935	1.6970	0.8051	0.1800	NACA64618 (100%)
103.4	4.2938	1.4093	0.7704	0.1800	NACA64618 (100%)
107.4	4.0899	1.1403	0.7372	0.1800	NACA64618 (100%)
111.4	3.8824	0.8683	0.7019	0.1800	NACA64618 (100%)
113.4	3.7713	0.7286	0.6817	0.1800	NACA64618 (100%)
115.4	3.6442	0.5737	0.6556	0.1800	NACA64618 (100%)
117.4	3.4902	0.4050	0.6282	0.1800	NACA64618 (100%)
119.4	3.2943	0.2206	0.5918	0.1800	NACA64618 (100%)
121.4	3.0451	0.0653	0.5481	0.1800	NACA64618 (100%)
123.4	2.7541	0.0082	0.4896	0.1800	NACA64618 (100%)
125.4	1.8764	0.0001	0.3374	0.1800	NACA64618 (100%)
126.0	0.6725	-0.0001	0.1211	0.1800	NACA64618 (100%)

Appendix C Structural blade properties

C.1 Mass distribution

Span (m)	Blade mass(kg/m)	Y cg [m]	X cg [m]	Rdel xx [m2]	Rdel yy [m2]	Rdel xy [m2]
0.0000000E+00	0.1865523E+04	-0.7956E-05	0.9450910E-05	0.6109347E+01	0.6109344E+01	-0.6748E-06
0.4000000E+00	0.3744705E+04	-0.1186E-05	0.1240044E-06	0.6108606E+01	0.6108607E+01	-0.7214E-06
0.2400000E+01	0.3837793E+04	-0.9421E-06	0.6138008E-06	0.6102591E+01	0.6099564E+01	0.2081114E-02
0.4400000E+01	0.3889133E+04	-0.1183E-05	0.1925322E-06	0.6024246E+01	0.5905362E+01	0.8180840E-01
0.6400000E+01	0.3922823E+04	-0.1040E-05	0.3328743E-06	0.5920178E+01	0.5645624E+01	0.1889315E+00
0.8400001E+01	0.2793360E+04	0.8109594E-02	0.8280597E-01	0.5914221E+01	0.5298237E+01	0.4421357E+00
0.1040000E+02	0.1478892E+04	0.1930401E-01	0.2139726E+00	0.5852573E+01	0.4891998E+01	0.7453635E+00
0.1140000E+02	0.1419278E+04	0.2125324E-01	0.2838680E+00	0.5942002E+01	0.4855587E+01	0.8480036E+00
0.1240000E+02	0.1360581E+04	0.2315759E-01	0.3495741E+00	0.6009156E+01	0.4816821E+01	0.9379206E+00
0.1440000E+02	0.1280889E+04	0.1778438E-01	0.5470072E+00	0.6190587E+01	0.4824149E+01	0.1057005E+01
0.1640200E+02	0.1193819E+04	0.1115709E-01	0.6616309E+00	0.6032016E+01	0.4694615E+01	0.1030230E+01
0.1740100E+02	0.1222583E+04	0.1195696E-01	0.6475793E+00	0.5867343E+01	0.4539147E+01	0.1042027E+01
0.1840000E+02	0.1251905E+04	0.1227226E-01	0.6362566E+00	0.5719796E+01	0.4385125E+01	0.1062667E+01
0.2040000E+02	0.1300254E+04	0.1147084E-01	0.5528521E+00	0.5269318E+01	0.3884915E+01	0.1129662E+01
0.2240000E+02	0.1241835E+04	0.1247514E-01	0.5636160E+00	0.5351841E+01	0.3628214E+01	0.1331302E+01
0.2440000E+02	0.1183065E+04	0.1387310E-01	0.5793295E+00	0.5451237E+01	0.3356097E+01	0.1490460E+01
0.2640200E+02	0.1106306E+04	0.1478108E-01	0.5840879E+00	0.5376309E+01	0.3045930E+01	0.1497691E+01
0.2840000E+02	0.1154795E+04	0.1185095E-01	0.5338024E+00	0.4843149E+01	0.2735312E+01	0.1192546E+01
0.3040000E+02	0.1202178E+04	0.9575659E-02	0.4335724E+00	0.4305585E+01	0.2437739E+01	0.9027192E+00
0.3240000E+02	0.1268029E+04	0.8752157E-02	0.4040357E+00	0.4007228E+01	0.2130665E+01	0.7723106E+00
0.3300000E+02	0.1285885E+04	0.5758552E-02	0.3951502E+00	0.3893524E+01	0.2040478E+01	0.7307172E+00
0.3640200E+02	0.1384271E+04	-0.1224E-01	0.3493593E+00	0.3307283E+01	0.1564513E+01	0.5387609E+00
0.3860000E+02	0.1447423E+04	-0.2823371E-01	0.3209440E+00	0.2970527E+01	0.1331053E+01	0.4763561E+00
0.4040000E+02	0.1498112E+04	-0.4201927E-01	0.3004826E+00	0.2723506E+01	0.1153893E+01	0.4358231E+00
0.4440000E+02	0.1614304E+04	-0.3759011E-01	0.2604886E+00	0.2307047E+01	0.8706477E+00	0.3265110E+00
0.4640000E+02	0.1671942E+04	-0.3593971E-01	0.2438304E+00	0.2134566E+01	0.7678831E+00	0.2928290E+00
0.4840000E+02	0.1727906E+04	-0.3419555E-01	0.2286132E+00	0.1976439E+01	0.6711564E+00	0.2639853E+00
0.5240000E+02	0.1836999E+04	0.5084120E-01	0.1932471E+00	0.1710463E+01	0.5485505E+00	0.2229561E+00
0.5640200E+02	0.1940623E+04	0.4542980E-01	0.1708067E+00	0.1486783E+01	0.4273637E+00	0.1909107E+00
0.6040000E+02	0.1768570E+04	0.4152789E-01	0.1786110E+00	0.1451108E+01	0.3486258E+00	0.1898042E+00
0.6440000E+02	0.1604826E+04	0.1225368E+00	0.1799397E+00	0.1437136E+01	0.3064387E+00	0.1827945E+00
0.6840000E+02	0.1447414E+04	0.1121100E+00	0.1942213E+00	0.1440447E+01	0.2584141E+00	0.1800171E+00
0.7240000E+02	0.1278098E+04	0.1032116E+00	0.1734330E+00	0.1344744E+01	0.2215551E+00	0.1575394E+00
0.7640200E+02	0.1132378E+04	0.9649029E-01	0.1804291E+00	0.1323555E+01	0.1942417E+00	0.1479024E+00
0.8040000E+02	0.9918203E+03	0.9049927E-01	0.1889585E+00	0.1308003E+01	0.1698851E+00	0.1363437E+00
0.8440000E+02	0.8525522E+03	0.1268839E+00	0.1817160E+00	0.1262702E+01	0.1584074E+00	0.1157022E+00
0.8840000E+02	0.7834777E+03	0.1193759E+00	0.1779489E+00	0.1183324E+01	0.1375429E+00	0.9507307E-01
0.9240000E+02	0.7164728E+03	0.1128326E+00	0.1735212E+00	0.1101243E+01	0.1209170E+00	0.7770807E-01
0.9640201E+02	0.6514688E+03	0.1073759E+00	0.1681527E+00	0.1016649E+01	0.1080375E+00	0.6271875E-01
0.1004000E+03	0.5886185E+03	0.1027944E+00	0.1619369E+00	0.9316668E+00	0.9789362E-01	0.4947347E-01
0.1044000E+03	0.5326332E+03	0.9793848E-01	0.1607308E+00	0.8726726E+00	0.8835875E-01	0.3985421E-01
0.1084000E+03	0.4783850E+03	0.9272098E-01	0.1595499E+00	0.8135977E+00	0.7875881E-01	0.3114819E-01
0.1104000E+03	0.4516512E+03	0.8978993E-01	0.1586314E+00	0.7817588E+00	0.7362761E-01	0.2702003E-01
0.1124000E+03	0.4246037E+03	0.8607565E-01	0.1567859E+00	0.7438355E+00	0.6734304E-01	0.2261743E-01
0.1144000E+03	0.3969748E+03	0.8212749E-01	0.1530474E+00	0.6962758E+00	0.6097122E-01	0.1800200E-01
0.1154000E+03	0.3819547E+03	0.7957529E-01	0.1492276E+00	0.6648106E+00	0.5706606E-01	0.1548669E-01
0.1164020E+03	0.3501265E+03	0.7655287E-01	0.1526787E+00	0.6532028E+00	0.5308414E-01	0.1399890E-01
0.1174000E+03	0.3179996E+03	0.7306530E-01	0.1553032E+00	0.6339250E+00	0.4856110E-01	0.1278030E-01
0.1184000E+03	0.2784233E+03	0.6912768E-01	0.1449245E+00	0.6065987E+00	0.4462359E-01	0.9819596E-02
0.1194000E+03	0.2479156E+03	0.6454581E-01	0.1492117E+00	0.5851878E+00	0.3906353E-01	0.9861780E-02
0.1204000E+03	0.2180240E+03	0.5985818E-01	0.1552400E+00	0.5655409E+00	0.3366299E-01	0.1001127E-01
0.1214000E+03	0.1864998E+03	0.4893775E-01	0.1307790E+00	0.4296135E+00	0.2214201E-01	0.9236732E-02
0.1224000E+03	0.1515047E+03	0.3742070E-01	0.1225630E+00	0.2781968E+00	0.1185113E-01	0.8170626E-02
0.1230000E+03	0.8546231E+02	0.1510135E-01	0.3053576E-01	0.2686097E-01	0.1139016E-02	0.8636098E-03

Xcg = x-coordinate (down wind) of mass centre line. (m)
Ycg = chordwise position of mass centre line (m)
Rdel xx= radius of inertia squared around the y-axis
Rdel yy = radius of inertia squared around the x-axis
Rdel xy = radius of inertia squared of the coupling between x and y axis.

C.2 Bending properties

Span(m)	EI flat(Nm^2)	EI edge(Nm^2)	EI cross(Nm^2)	x elastic centre (m)	y elastic centre (m)
0.0000000E+00	0.1219154E+13	0.1219154E+13	-0.1949850E+05	-0.7327678E-06	0.2457762E-06
0.4000000E+00	0.3103761E+12	0.3103763E+12	-0.3299746E+05	-0.9261656E-06	0.2592811E-06
0.2400000E+01	0.3175731E+12	0.3178410E+12	-0.1937428E+05	-0.1110014E-05	0.3996627E-06
0.4400000E+01	0.3094363E+12	0.3201093E+12	-0.1161816E+06	-0.8141190E-06	0.3101874E-06
0.6400000E+01	0.2953920E+12	0.3202546E+12	-0.2590045E+06	-0.1010484E-05	0.4809725E-06
0.8400001E+01	0.2066391E+12	0.2534972E+12	0.2574681E+08	0.5183022E-03	0.9974229E-01
0.1040000E+02	0.1154523E+12	0.1612614E+12	0.2550215E+09	0.2587321E-02	0.2471060E+00
0.1140000E+02	0.1081738E+12	0.1560068E+12	0.3715797E+09	0.3316893E-02	0.3133218E+00
0.1240000E+02	0.1012757E+12	0.1494805E+12	0.4826485E+09	0.3921800E-02	0.3730480E+00
0.1440000E+02	0.9394689E+11	0.1368757E+12	0.7618099E+09	0.5164854E-02	0.5484244E+00
0.1640200E+02	0.8540183E+11	0.1154256E+12	0.1033956E+10	0.6145921E-02	0.6440645E+00
0.1740100E+02	0.8524371E+11	0.1161790E+12	0.1275214E+10	0.6050766E-02	0.6300558E+00
0.1840000E+02	0.8469380E+11	0.1171195E+12	0.1509142E+10	0.5418771E-02	0.6184798E+00
0.2040000E+02	0.7718895E+11	0.1164573E+12	0.2030252E+10	0.1944131E-02	0.5420724E+00
0.2240000E+02	0.6543097E+11	0.1141663E+12	0.1758682E+10	0.3123709E-02	0.5467985E+00
0.2440000E+02	0.5504964E+11	0.1109773E+12	0.1347387E+10	0.4859296E-02	0.5584384E+00
0.2640200E+02	0.4579738E+11	0.9968642E+11	0.8083264E+09	0.5850700E-02	0.5561159E+00
0.2840000E+02	0.4629368E+11	0.9019756E+11	0.1002138E+09	0.3144432E-02	0.4877810E+00
0.3040000E+02	0.4622167E+11	0.8076249E+11	-0.7095654E+09	0.1344437E-02	0.3619611E+00
0.3240000E+02	0.4421824E+11	0.7955788E+11	-0.1325083E+10	0.1598339E-02	0.3324498E+00
0.3300000E+02	0.4341773E+11	0.7857914E+11	-0.1410498E+10	-0.1275399E-02	0.3239696E+00
0.3640200E+02	0.3768646E+11	0.7303146E+11	-0.1688376E+10	-0.1887531E-01	0.2824369E+00
0.3860000E+02	0.3384517E+11	0.6975285E+11	-0.1112646E+10	-0.3437526E-01	0.2590532E+00
0.4040000E+02	0.3046336E+11	0.6709073E+11	-0.5436580E+09	-0.4776163E-01	0.2429411E+00
0.4440000E+02	0.2549661E+11	0.6245800E+11	-0.7636706E+09	-0.4201813E-01	0.2110415E+00
0.4640000E+02	0.2346228E+11	0.6049245E+11	-0.7642369E+09	-0.3988821E-01	0.1979497E+00
0.4840000E+02	0.2131057E+11	0.5850638E+11	-0.7332170E+09	-0.3770969E-01	0.1861255E+00
0.5240000E+02	0.1861635E+11	0.5515728E+11	-0.1086089E+10	0.4885070E-01	0.1555758E+00
0.5640200E+02	0.1534087E+11	0.5161457E+11	-0.8834122E+09	0.4383625E-01	0.1386703E+00
0.6040000E+02	0.1123234E+11	0.4629137E+11	-0.5496779E+09	0.4006933E-01	0.1484276E+00
0.6440000E+02	0.8483771E+10	0.4184004E+11	-0.7602544E+09	0.1220607E+00	0.1490908E+00
0.6840000E+02	0.6372026E+10	0.3791101E+11	-0.5506026E+09	0.1115967E+00	0.1646839E+00
0.7240000E+02	0.4848624E+10	0.3099273E+11	-0.4375796E+09	0.1026375E+00	0.1412591E+00
0.7640200E+02	0.3753773E+10	0.2674903E+11	-0.3339712E+09	0.9588262E-01	0.1467337E+00
0.8040000E+02	0.2874219E+10	0.2287669E+11	-0.2519860E+09	0.8985090E-01	0.1535686E+00
0.8440000E+02	0.2194661E+10	0.1868149E+11	-0.3062717E+09	0.1271472E+00	0.1411905E+00
0.8840000E+02	0.1772080E+10	0.1594643E+11	-0.2526958E+09	0.1196453E+00	0.1370967E+00
0.9240000E+02	0.1438965E+10	0.1345409E+11	-0.2072632E+09	0.1131045E+00	0.1325308E+00
0.9640201E+02	0.1179596E+10	0.1119630E+11	-0.1699416E+09	0.1076452E+00	0.1272300E+00
0.1004000E+03	0.9735901E+09	0.9186361E+10	-0.1392941E+09	0.1030585E+00	0.1211880E+00
0.1044000E+03	0.7994333E+09	0.7770378E+10	-0.1125221E+09	0.9812685E-01	0.1212974E+00
0.1084000E+03	0.6427259E+09	0.6496105E+10	-0.8798976E+08	0.9282629E-01	0.1215410E+00
0.1104000E+03	0.5683479E+09	0.5892452E+10	-0.7609101E+08	0.8985000E-01	0.1214665E+00
0.1124000E+03	0.4898122E+09	0.5278981E+10	-0.6325137E+08	0.8608685E-01	0.1207100E+00
0.1144000E+03	0.4159401E+09	0.4640043E+10	-0.5060922E+08	0.8208170E-01	0.1185555E+00
0.1154000E+03	0.3756168E+09	0.4290546E+10	-0.4342759E+08	0.7950428E-01	0.1164252E+00
0.1164020E+03	0.3204980E+09	0.3883734E+10	-0.3407955E+08	0.7641345E-01	0.1219144E+00
0.1174000E+03	0.2664724E+09	0.3445359E+10	-0.2463931E+08	0.7285124E-01	0.1269223E+00
0.1184000E+03	0.2158377E+09	0.2945413E+10	-0.1976897E+08	0.6891827E-01	0.1222534E+00
0.1194000E+03	0.1681163E+09	0.2543807E+10	-0.1134766E+08	0.6427912E-01	0.1290968E+00
0.1204000E+03	0.1271379E+09	0.2169165E+10	-0.4643211E+07	0.5953332E-01	0.1376273E+00
0.1214000E+03	0.7196500E+08	0.1448421E+10	0.6986118E+07	0.4868563E-01	0.1206457E+00
0.1224000E+03	0.3105963E+08	0.7751942E+09	0.1047360E+08	0.3728959E-01	0.1136674E+00
0.1230000E+03	0.1531466E+07	0.4410030E+08	0.7078229E+06	0.1511380E-01	0.2910883E-01

C.3 Geometric data

Span(m)	Chord(m)	Twist(degrees)	y of 25% (m)
0.0000000E+00	0.7084000E+01	0.1349982E+02	-0.1771000E+01
0.4000000E+00	0.7084000E+01	0.1349982E+02	-0.1771000E+01
0.2400000E+01	0.7084000E+01	0.1349982E+02	-0.1771000E+01
0.4400000E+01	0.7084000E+01	0.1349982E+02	-0.1771000E+01
0.6400000E+01	0.7085283E+01	0.1349982E+02	-0.1770697E+01
0.8400001E+01	0.7207054E+01	0.1349982E+02	-0.1741936E+01
0.1040000E+02	0.7546000E+01	0.1349982E+02	-0.1658762E+01
0.1140000E+02	0.7790000E+01	0.1349982E+02	-0.1598263E+01
0.1240000E+02	0.8033986E+01	0.1349982E+02	-0.1537766E+01
0.1440000E+02	0.8463969E+01	0.1349982E+02	-0.1421675E+01
0.1640200E+02	0.8769951E+01	0.1349982E+02	-0.1341640E+01
0.1740100E+02	0.8873000E+01	0.1349982E+02	-0.1317306E+01
0.1840000E+02	0.8976001E+01	0.1349982E+02	-0.1292988E+01
0.2040000E+02	0.9098987E+01	0.1349979E+02	-0.1263665E+01
0.2240000E+02	0.9169001E+01	0.1338408E+02	-0.1246936E+01
0.2440000E+02	0.9208991E+01	0.1304485E+02	-0.1237465E+01
0.2640200E+02	0.9210997E+01	0.1251082E+02	-0.1237164E+01
0.2840000E+02	0.9205001E+01	0.1181991E+02	-0.1238839E+01
0.3040000E+02	0.9159974E+01	0.1101317E+02	-0.1145019E+01
0.3240000E+02	0.9007948E+01	0.1016177E+02	-0.1125994E+01
0.3300000E+02	0.8930490E+01	0.9906479E+01	-0.1116311E+01
0.3640200E+02	0.8491013E+01	0.8459045E+01	-0.1061376E+01
0.3860000E+02	0.8233155E+01	0.7747046E+01	-0.1029145E+01
0.4040000E+02	0.8022000E+01	0.7164055E+01	-0.1002750E+01
0.4440000E+02	0.7599000E+01	0.6226127E+01	-0.9498751E+00
0.4640000E+02	0.7410501E+01	0.5955973E+01	-0.9263125E+00
0.4840000E+02	0.7222000E+01	0.5685825E+01	-0.9027500E+00
0.5240000E+02	0.6869004E+01	0.5354090E+01	-0.8586256E+00
0.5640200E+02	0.6529006E+01	0.5045242E+01	-0.8161258E+00
0.6040000E+02	0.6215000E+01	0.4707216E+01	-0.7768750E+00
0.6440000E+02	0.5936000E+01	0.4353125E+01	-0.7420000E+00
0.6840000E+02	0.5700004E+01	0.4025973E+01	-0.7125006E+00
0.7240000E+02	0.5497804E+01	0.3750737E+01	-0.6872254E+00
0.7640200E+02	0.5349955E+01	0.3460461E+01	-0.6687444E+00
0.8040000E+02	0.5198930E+01	0.3119771E+01	-0.6498663E+00
0.8440000E+02	0.5036999E+01	0.2724207E+01	-0.6296248E+00
0.8840000E+02	0.4866000E+01	0.2332878E+01	-0.6082500E+00
0.9240000E+02	0.4685000E+01	0.1997120E+01	-0.5856251E+00
0.9640201E+02	0.4492997E+01	0.1696899E+01	-0.5616245E+00
0.1004000E+03	0.4294000E+01	0.1409266E+01	-0.5367501E+00
0.1044000E+03	0.4089967E+01	0.1139952E+01	-0.5112458E+00
0.1084000E+03	0.3881809E+01	0.8677550E+00	-0.4852262E+00
0.1104000E+03	0.3770521E+01	0.7286719E+00	-0.4713152E+00
0.1124000E+03	0.3643163E+01	0.5734627E+00	-0.4553954E+00
0.1144000E+03	0.3488736E+01	0.4044223E+00	-0.4360920E+00
0.1154000E+03	0.3392000E+01	0.3129115E+00	-0.4240001E+00
0.1164020E+03	0.3292660E+01	0.2213801E+00	-0.4115824E+00
0.1174000E+03	0.3169500E+01	0.1430310E+00	-0.3961875E+00
0.1184000E+03	0.3043873E+01	0.6775548E-01	-0.3804842E+00
0.1194000E+03	0.2899500E+01	0.3646638E-01	-0.3624375E+00
0.1204000E+03	0.2753855E+01	0.7820566E-02	-0.3442318E+00
0.1214000E+03	0.2315000E+01	0.3804415E-02	-0.2893750E+00
0.1224000E+03	0.1782292E+01	0.3415094E-04	-0.2227865E+00
0.1230000E+03	0.6730000E+00	-0.2049057E-03	-0.8412500E-01

C.4 Torsion data

Span	GJT (Nm^2)	X shear centre [m]	Y shear centre [m]
0.0000000E+00	0.8993615E+12	-0.8498057E-01	-0.1539275E-05
0.4000000E+00	0.1792878E+12	-0.9458416E-01	-0.1868464E-05
0.2400000E+01	0.1834574E+12	-0.9705666E-01	-0.1953200E-05
0.4400000E+01	0.1816129E+12	-0.1004303E+00	-0.4863378E-08
0.6400000E+01	0.1772357E+12	-0.1043070E+00	0.2663367E-05
0.8400001E+01	0.9679367E+11	-0.6988714E-01	0.1351835E-03
0.1040000E+02	0.1687795E+11	-0.3260530E-01	0.4095771E-02
0.1140000E+02	0.1647729E+11	-0.8452439E-02	0.6987718E-02
0.1240000E+02	0.1602939E+11	0.9154934E-02	0.9774690E-02
0.1440000E+02	0.1592177E+11	0.1988868E+00	0.1227621E+01
0.1640200E+02	0.1519048E+11	0.3447863E+00	0.2226305E+01
0.1740100E+02	0.1426892E+11	0.2853777E+00	0.2040218E+01
0.1840000E+02	0.1335091E+11	0.2264833E+00	0.1853226E+01
0.2040000E+02	0.1079278E+11	0.3116481E-01	0.1314801E+01
0.2240000E+02	0.9914476E+10	0.5473708E-02	0.1282217E+01
0.2440000E+02	0.9032995E+10	-0.1670418E-01	0.1233670E+01
0.2640200E+02	0.8123858E+10	-0.2700785E-01	0.1171042E+01
0.2840000E+02	0.7499928E+10	-0.2818997E-01	0.1129278E+01
0.3040000E+02	0.6870680E+10	-0.1089896E+00	0.1126129E+01
0.3240000E+02	0.6130318E+10	-0.1330587E+00	0.1050211E+01
0.3300000E+02	0.5888527E+10	-0.1405358E+00	0.1022684E+01
0.3640200E+02	0.4592408E+10	-0.1831760E+00	0.8589967E+00
0.3860000E+02	0.3879326E+10	-0.2044036E+00	0.7600601E+00
0.4040000E+02	0.3334058E+10	-0.2182975E+00	0.6801633E+00
0.4440000E+02	0.2591889E+10	-0.2510838E+00	0.5597264E+00
0.4640000E+02	0.2306904E+10	-0.2664965E+00	0.5107147E+00
0.4840000E+02	0.2035769E+10	-0.2843652E+00	0.4618371E+00
0.5240000E+02	0.1670555E+10	-0.3260086E+00	0.4622637E+00
0.5640200E+02	0.1318883E+10	-0.3669946E+00	0.3822534E+00
0.6040000E+02	0.1069161E+10	-0.3749769E+00	0.3339391E+00
0.6440000E+02	0.9005183E+09	-0.3718990E+00	0.4556601E+00
0.6840000E+02	0.7505532E+09	-0.3688587E+00	0.4179542E+00
0.7240000E+02	0.5924984E+09	-0.4556235E+00	0.1319984E+00
0.7640200E+02	0.5080028E+09	-0.4307731E+00	0.1259803E+00
0.8040000E+02	0.4335145E+09	-0.4046879E+00	0.1209804E+00
0.8440000E+02	0.3733723E+09	-0.3688367E+00	0.1792547E+00
0.8840000E+02	0.3177238E+09	-0.3546356E+00	0.1679202E+00
0.9240000E+02	0.2718273E+09	-0.3388917E+00	0.1577995E+00
0.9640201E+02	0.2342200E+09	-0.3225738E+00	0.1490862E+00
0.1004000E+03	0.2029228E+09	-0.3056211E+00	0.1417058E+00
0.1044000E+03	0.1756285E+09	-0.2911267E+00	0.1356181E+00
0.1084000E+03	0.1492448E+09	-0.2761281E+00	0.1290731E+00
0.1104000E+03	0.1359960E+09	-0.2683193E+00	0.1252959E+00
0.1124000E+03	0.1210974E+09	-0.2608224E+00	0.1202764E+00
0.1144000E+03	0.1064024E+09	-0.2538039E+00	0.1146473E+00
0.1154000E+03	0.9799743E+08	-0.2506987E+00	0.1107019E+00
0.1164020E+03	0.8806920E+08	-0.2391114E+00	0.1078169E+00
0.1174000E+03	0.7728862E+08	-0.2270150E+00	0.1040170E+00
0.1184000E+03	0.6141144E+08	-0.2012669E+00	0.1000702E+00
0.1194000E+03	0.5145551E+08	-0.1943344E+00	0.9529272E-01
0.1204000E+03	0.4204947E+08	-0.1880580E+00	0.9078637E-01
0.1214000E+03	0.2551744E+08	-0.1901305E+00	0.6929474E-01
0.1224000E+03	0.1141506E+08	-0.1660233E+00	0.5242656E-01
0.1230000E+03	0.2683274E+06	-0.2655694E+00	0.2472148E-01