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Soft foundation control design and its aero-servo-elastic stability

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Table of contents

Summary **5**

1. Introduction **6**

2. Support structure design **7**

2.1 Model parameters 7

2.2 Selection of cylindrical monopile diameter 8

2.3 Design process 9

2.4 Soft tower design 11

2.4.1 Soil model properties 14

3. Soft tower control design **16**

3.1 Introduction 16

3.2 D4REL soft tower model and control in ACT 16

3.3 Simulation results 17

3.3.1 Below rated winds 18

3.3.2 Around rated winds 20

3.3.3 Above rated winds 22

3.4 Conclusions 24

4. Aero-servo-elastic stability **25**

4.1 Stability analysis method 25

4.2 Results 26

4.2.1 Aero-elastic stability analysis 26

4.2.2 Aero-servo-elastic stability analysis 29

5. Conclusions **33**

Bibliography **34**

Summary

With the increasing size of wind turbines the height of the support structure increases both for onshore and for offshore wind turbines. This will reduce the natural frequencies of the support structure. These lower natural frequencies can be closer to and be excited by turbulence, waves and the rotor rotational frequency.

Within the ECN internal project “Soft tower control”, an ACT controller has been designed for a wind turbine with a very low first tower frequency. The purpose for this design is to investigate if there are specific challenges related to controller design for turbines with so-called soft-soft towers, towers with first frequency below the rotational frequency of the rotor (1p). To this end, the D4REL turbine model has been modified by only reducing the tower parameters to achieve a first tower frequency of 0.0855 Hz, according to a structural tower design performed using TURBU.
The support structure consists of a steel monopile together with a composite transition piece and tower.

A controller is designed for a turbine with a soft-soft tower. Besides baseline rotor speed and power control loops, tower fore-aft damping and tower sidewards damping control loops are designed. Based on the performed analysis in ACT, no issues were encountered in the controller design related to the very low tower frequency. It is concluded that a standard controller design achieved acceptable performance with respect to the rotor speed and power regulation. Tower top oscillations were significant with baseline control, but adding tower damping control achieved dramatic reduction the tower oscillations.

Finally an aero-servo elastic stability analysis is performed. The focus of the analysis was on the first tower bending modes. However the dynamics of the complete wind turbine system are considered. Modal analysis are performed with and without the controller included in the analysis. For 11m/s wind speed and the controller included the case without structural tower damping shows instable behaviour when a load simulation with TURBU is performed. It is therefore recommend always to check structural dynamic behaviour and control behaviour with an aeroelastic simulation.

The work of the current project is continued in the TKI innovation project IDL Tower.

1. Introduction

With the increasing size of wind turbines the height of the support structure increases both for onshore and for offshore wind turbines. This will reduce the natural frequencies of the support structure. These lower natural frequencies can be closer to and be excited by turbulence, waves and the rotor rotational frequency.

Aim of the current study is to design the controller with ACT and perform the load calculations and aero-servo-elastic stability analysis with TURBU for a soft foundation. For this a support structure in the soft-soft frequency range is designed for a modern 4MW offshore wind turbine.
First the design of the soft-soft support structure is described in Chapter 2. The support structure design is used as input in Chapter 3 for the controller design. Finally in Chapter 4 an aero-servo-elastic stability is performed for the complete wind turbine system using the ECN linear aero-elastic tool TURBU.

2. Support structure design

In this project, a soft support structure design is required for further analysis. This chapter described the design process towards a soft support structure design. The support structure is to be designed for a 4 MW turbine, as developed in the D4REL project. For the turbine, a reference design is available featuring a 7 m diameter monopile. However, this design has a first eigenfrequency in the soft-stiff frequency region.

2.1 Model parameters

Table 2-1 Basic model parameters

Parameter	Value
Water depth	30 m
Tower top above mudline	117 m
Rotor mass	101.6 tons
Nacelle mass	135.5 tons
Minimum generator speed	5.5 rpm

In order to design the tower in the soft-soft frequency range below the 1P region, a target frequency is set $\leq 0.9 * f_{1P,\min}$

$$f_{1P,\min} = \frac{5.5 \text{ rpm}}{60} = 0.0917\ Hz$$

→ target (first) tower frequency ≤ 0.9*min(1P) = 0.0825 Hz

2.2 Selection of cylindrical monopile diameter

In order to start the design process, a first estimate of the diameter is required. For this, the natural frequency is estimated for a straight support structure with a lumped mass at the tower top. The point on a stick model is used, as presented in the Phd thesis of Van der Tempel[9].

Figure 2.41. The bending flexibility of the tower represents the spring stiffness; the damping is given in the form of a damping coefficient.

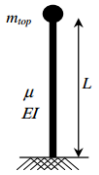

Figure 2.45 Structural model of a flexible wind turbine system

For this model consisting of a uniform beam with a top mass and a fixed base, the following approximation for the calculation of the first natural frequency is valid [33]:

$$f_{nat}^2 \cong \frac{3.04}{4\pi^2} \frac{EI}{(m_{top} + 0.227\mu L)L^3} \qquad (2.34)$$

with:

f_{nat}	first natural frequency	[Hz]
m_{top}	top mass	[kg]
μ	tower mass per meter	[kg/m]
L	tower height	[m]
EI	tower bending stiffness	[Nm^2]

Figure 2-1 Point on a stick model

Young's modulus E and mass density ρ are material properties and are given the following values:

- $E = 210\ GPa$
- $\rho = 8000\ kg/m^3$ (to account for flanges, internal ladders and secondary steel
- $m_{top} = m_{rotor} + m_{nacelle} = 237.1\ ton$
- $D_i = (D_o - 2t_w)$
- $I = \frac{\pi}{64}\left(D_o^4 - D_i^4\right)$
- $\mu = \rho\frac{\pi}{4}\left(D_o^2 - D_i^2\right)$

The inner diameter D_i is derived from the outer diameter and wall thickness. Area moment of inertia I and mass density μ (mass per meter length of the tower) are determined from D_o and D_i. A range of (outer) diameter and (outer) diameter over thickness ratios is tested, and the natural frequency is shown in Figure 2-2.

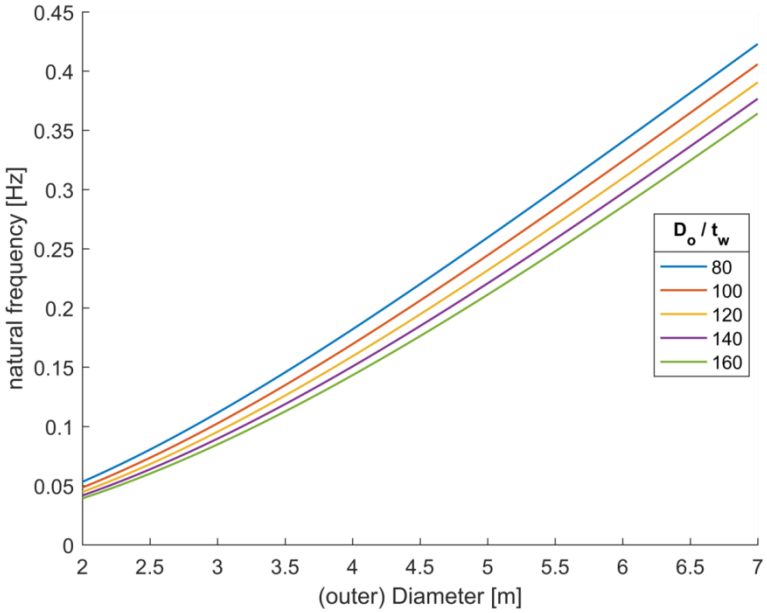

Figure 2-2 Natural frequency vs outer diameter 'point on a stick'

For each D_o/t_w ratio, a diameter and wall thickness combination is selected that meets the target frequency.

Table 2-2 Diameter and wall thickness combinations meeting the target frequency $\leq \mathbf{0.0825}\ \boldsymbol{Hz}$

D_o/t_w [-]	80	100	120	140	160
D_o [m]	2.6	2.7	2.8	2.9	3.0
t_w [mm]	32.5	27.0	23.3	20.7	18.7

2.3 Design process

In this section, the overall design process of the soft support structure is discussed. In Figure 2-3 the basic design steps are shown. The steps are further elaborated below the figure.

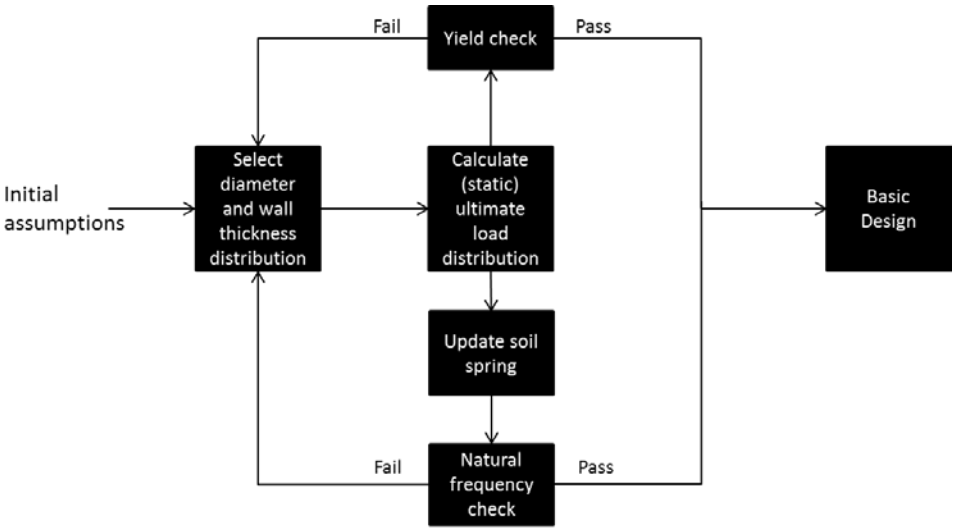

Figure 2-3 Design process diagram

Select diameter and wall thickness distribution
The diameter and wall thickness distribution throughout the support structure are the only geometrical parameters that affect the natural frequency of the structure. In last year's innovation project on XL monopiles [5] a Matlab tool was developed to design and evaluate the loads of a tapered support structure (monopile, transition piece and tower). This tool has been adjusted to prepare TURBU input files.

TURBU[10] is a fast and fully integrated wind turbine design and analysis tool, which deals with aerodynamics, hydrodynamics, structural dynamics and control of modern three bladed wind turbines. The linearized wind turbine model is derived from geometric and material properties and site conditions. The system is then transformed to the frequency domain, useful for load calculation, stability analysis and control design. The wind, gravity, wave and water current loading are
applied as input spectra to the wind turbine model. The results from load calculations can be
analysed both in the frequency domain (response spectra) and the time domain (simulations).

Calculate (static) ultimate load distribution
The ultimate load is approximated in Matlab by evaluating the internal loads for the maximum axial rotor force and solving the Morison equation to derive the wave loading.

The ultimate rotor force is 1.66 MN (from the Focus calculations listed in the ECN Trendwatcher database, controller rev03, SVN revision 966). The wave loads are determined for a wave height of 10 m. The combination of the ultimate rotor force for such a high wave is considered conservative. Safety factors are applied according to the IEC61400-1 standard. A safety factor of 1.35 is applied for the variable wind load (not the hydrodynamic load), a safety factor of 1.0 is used for the constant normal weight in the support structure and a material safety factor of 1.1 is used for the strength of the material.

Update soil spring
The ultimate loads at the mudline are entered in the Excel-VBA tool LatPilePY [1],[4] to calculate the deflection of the embedded pile under ultimate loads. From the deflection, and the slope of the deflection curve, an equivalent soil stiffness matrix is derived.

Natural frequency check
The soil spring matrix and support structure geometry is adjusted in the TURBU input files, and the modal analysis program of TURBU is run. The natural frequency check is only passed when the TURBU natural frequency is lower than the design target frequency (of 0.0825 Hz).

2.4 Soft tower design

The design process as described in section 2.3 was used to find a suitable design that passes both the yield check as the natural frequency check. The initial assumptions was one of the cylindrical monopile diameter/wall thickness options from Table 2-2. This option however did not pass the yield checks (since the diameter is so small, there is not enough structural strength to resist the ultimate loads). After many iterations, it became clear that it is very difficult to design a steel support structure that can satisfy both the low natural frequency and the yield check. Therefore, another approach was taken to replace the structural material of the transition piece and tower by monolithic fibre reinforced polymer (FRP), as applied in the Mega Wind project [3]. In the study the material properties are taken isotropic.

Table 2-3 Structural material properties

Material	Youngs Modulus E [N/m^2]	Shear modulus G [N/m^2]	Effective mass density ρ [kg/m^3]
Steel	2.1e11	8.08e10	8000
Monolithic fibre reinforced polymer [5]	1.7e10	2.55e9	1850

After multiple iterations, the basic design proposed is shown in Figure 2-4. The internal loads distribution for the ultimate static load is given in Figure 2-5, and the loads at mudline are tabulated in Table 2-4.

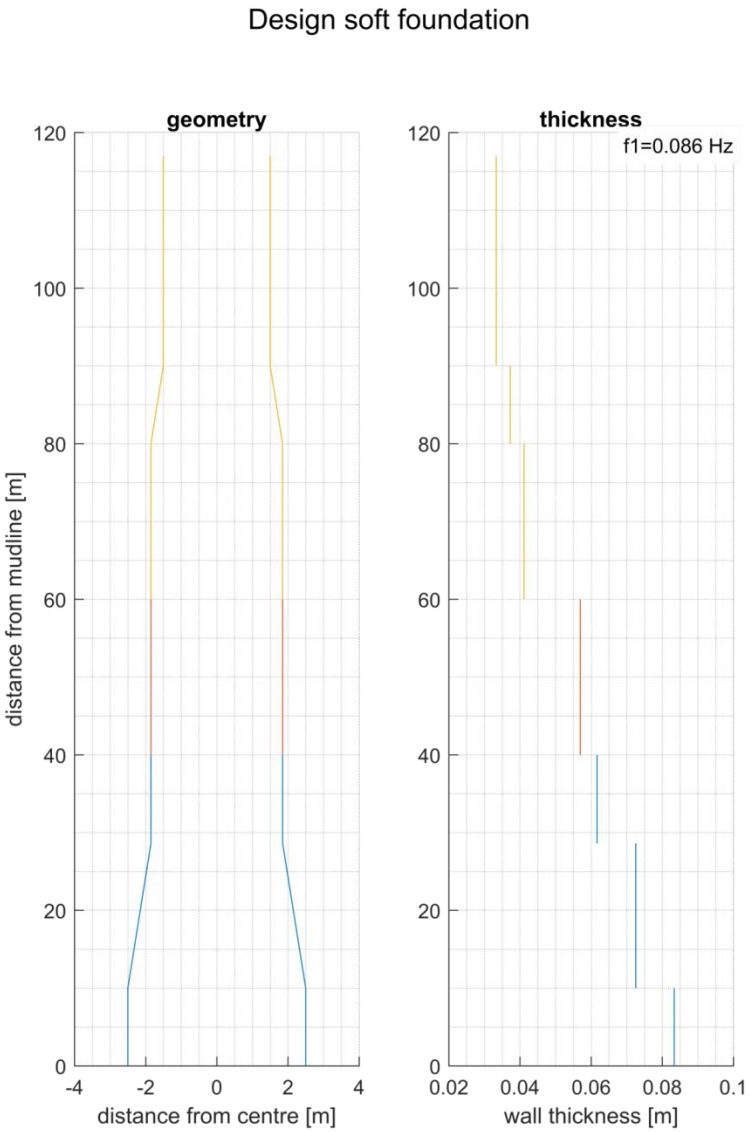

Figure 2-4 Diameter and wall thickness distribution of soft tower design
blue: monopile (steel), red: transition piece (FRP), yellow: tower (FRP)

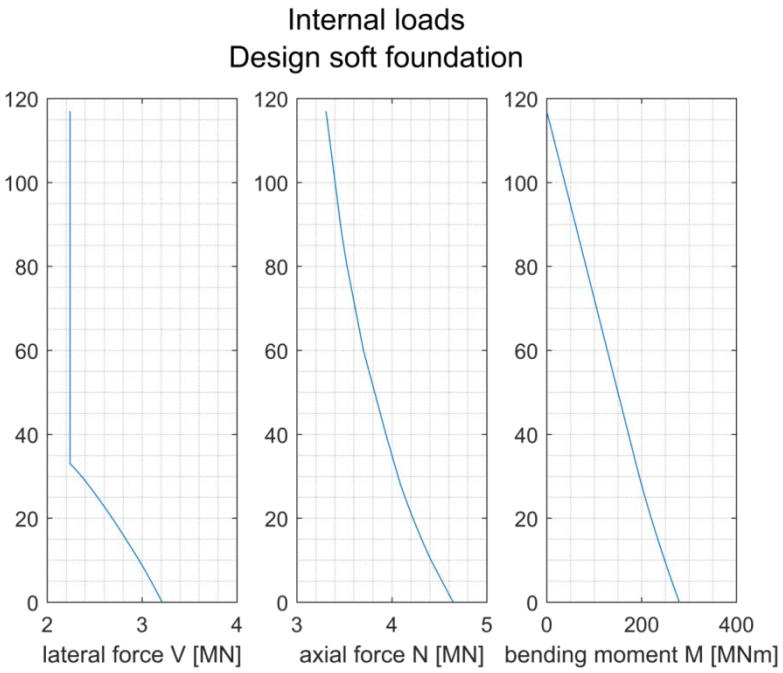

Figure 2-5 Internal load distribution for ultimate static load

Table 2-4 Load at mudline

Load component at mudline	Value
Bending moment at mudline	280 MNm
- - Contribution of rotor force	194 MNm
- - Contribution hydrodynamic load	85 MNm
Lateral force at mudline	3.2 MN
- - Contribution rotor force	2.2 MN
- - Contribution hydrodynamic load	1.0 MN
Axial force at mudline	4.6 MN

Since now the load distribution is known, the maximum stress in the cross section can be determined. This stress is shown in blue in Figure 2-6. As long as the stress is lower than the yield stress of 355 MPa (divided by the material safety factor, indicated by a dashed line), the yield check is passed.

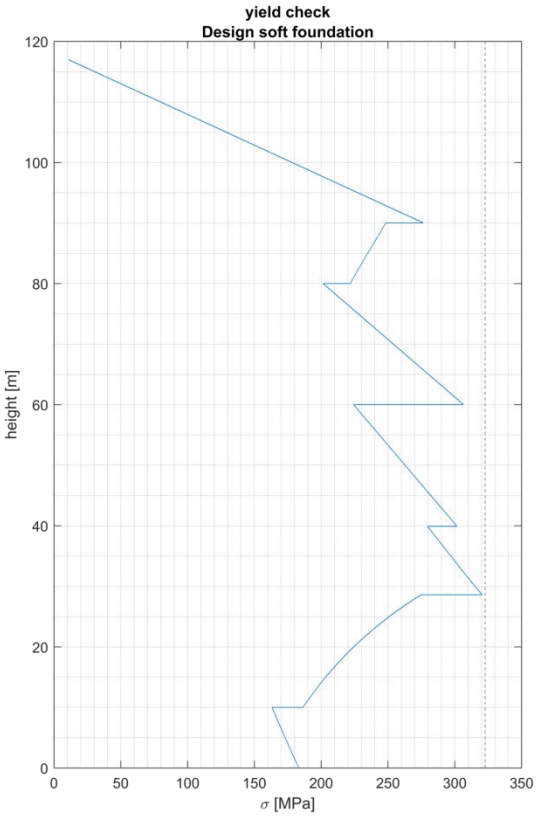

Figure 2-6 Stress under ultimate load

2.4.1 Soil model properties

The degrees of freedom considered in TURBU are shown in Equation 1.

$$\begin{bmatrix} M_x \\ F_x \\ M_y \\ F_y \\ M_z \\ F_z \end{bmatrix} = \begin{bmatrix} k_{roll} & -k_{crossSide} & 0 & 0 & 0 & 0 \\ -k_{crossSide} & k_{side} & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{tilt} & k_{crossLong} & 0 & 0 \\ 0 & 0 & k_{crossLong} & k_{long} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{tors} & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{axial} \end{bmatrix} \cdot \begin{bmatrix} \phi_x \\ u_x \\ \phi_y \\ u_y \\ \phi_z \\ u_z \end{bmatrix} \quad \text{Equation 1}$$

For the 7 m (D4REL) TURBU reference support structure, only the roll and tilt stiffness was defined. For the soft tower design, the deflection curve of the embedded pile for the ultimate loads is determined in LatpilePY [1]. In LatpilePY, non-linear P-Y springs are created for the given soil properties, following the API norm [2], including stiffening under repeated load cycles. The soil layer parameters are taken from the Ramboll report, shared in the WiFi project [8]. The embedded pile length is chosen to be 25 m, which is slightly longer than the embedded pile length to diameter ratio of the WiFi

monopile foundation (embedded length of 29 m for a 7.0 m diameter). However, the initial penetration depth of 20 m resulted in a mudline deflection of 2 m. The increase to 25 m penetration depth results in more acceptable values of deflection, internal shear force and bending moment, see Figure 2-7.

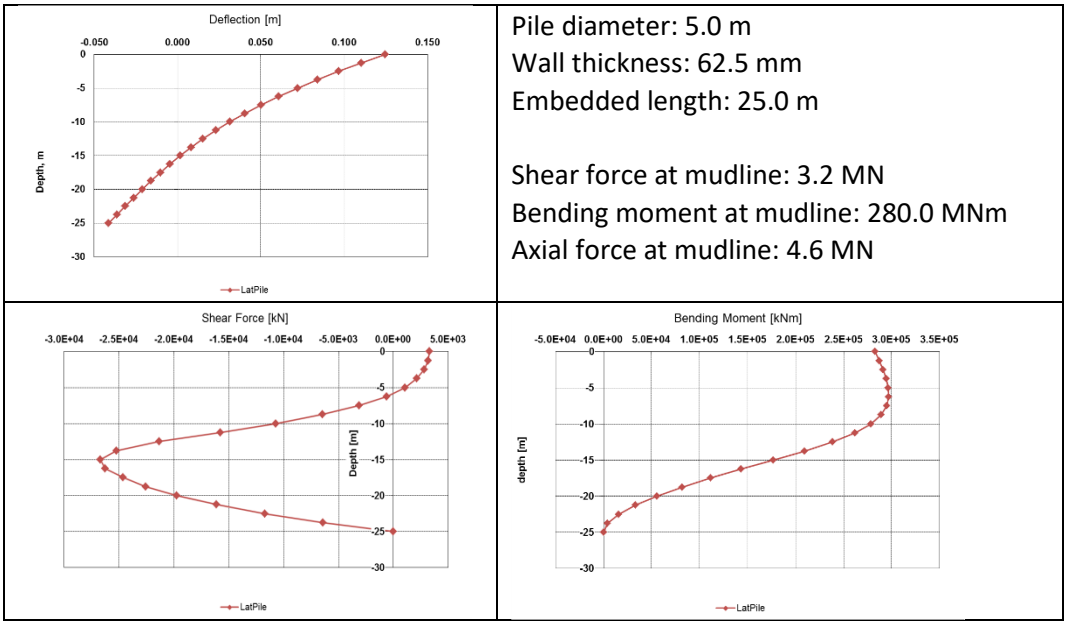

Figure 2-7 Deflection curve, internal shear force and bending moment of embedded pile

From the slope of the deflection curve, the rotation at the mudline can be 0.0114 rad. Together with the lateral deflection of 0.125 m at mudline the stiffness table can be found for the given combination of loads, as described in [4]. The resulting stiffness values are given in Table 2-5.

Table 2-5 Effective soil stiffness

	4MW stiff reference ($D = 7.0\ m$)	4MW soft foundation ($D = 5.0\ m$)
k_{roll} [Nm/rad]	6.603 e+10	1.13E+11
k_{side} [N/m]	∞	7.70E+08
$k_{crossSide}$ [N/rad]	∞	8.08E+09
k_{tilt} [Nm/rad]	6.603 e+10	1.13E+11
k_{long} [N/m]	∞	7.70E+08
$k_{crossLong}$ [N/rad]	∞	8.08E+09
k_{tors} [Nm/rad]	∞	∞
k_{axial} [N/m]	∞	∞

Using the soil stiffness table of Table 2-5, and the geometry of Table 2-4, a first natural frequency is found of **0.0855** Hz. This is very close to the target frequency, and is expected to show the sought-after structural behaviour in TURBU.

3. Soft tower control design

3.1 Introduction

The controller design for the soft-tower version includes active tower reduction loops, both in fore-aft and side-to-side direction. Besides these, no other loads-reduction loops have been considered. The performance analysis of the designed controller has been done by performing simulations with turbulent wind at one below rated, one around rated and one above rated wind speeds. The operational parameters (rotor speed, power, control signals) and tower dynamics are the primary focus of the study.

The results indicate that the rotor speed and power are well controlled both with and without tower damping control. The tower top motion is very significant with the baseline control only, but is reduced dramatically by the tower damping control loops, both in fore-aft and side-to-side direction. The overall performance of the controller is considered satisfactory and no control-related issues have been encountered.

3.2 D4REL soft tower model and control in ACT

The D4REL soft tower model in ACT is based on the existing D4REL model. The only difference is that the tower parameters have been modified to achieve a first tower frequency of 0.0855 HZ, in accordance with the soft tower design performed with TURBU. In the TURBU design, a composite tower has been chosen to realize the desired low frequency (below 1p). Compared with TURBU in ACT the support structure is modelled by single degree of freedom mass-spring system. Therefore, in ACT the tower weight was first selected about 4 times lower than the original one (which was originally 500 tons) to account for the weight reduction due to the composite design (tower height remains the same). However, this gave rise to unrealistically large tower top displacements (up to 30 m) in simulations in ACT. To get realistic tower top displacements, similar to those observed in TURBU (around 5 m at wind speed of 8 m/s), the tower weight was increased to 400 tons. In addition to that, the gravity constant was set to zero in ACT. With these changes the tower top displacements were comparable to those in TURBU. For future use a check of the underlying structural model in ACT is needed.

The modified parameters in the turbine model in ACT are summarized in Table 3-1.

Table 3-1 D4REL Soft Tower turbine model parameters, compared to the original D4REL model

parameters_turbine.txt	D4REL Soft Tower
TowerFassFreq [Hz]	0.0855
TowerMass [kg]	400e3
TowerTopDiameter [m]	3.082
TowerBaseDiameter [m]	5.511
envGravityConstant	0

The controller design parameters, related to the baseline control loops for rotor speed and power control have not been modified with respect to the original D4REL controller. The modified parameters are primarily related to the tower fore-aft and side-to-side control loops, that have different properties now due to the much lower tower frequency. These parameters are listed in Table 3-2 below. The tower top equivalent mass (including rotor and nacelle), TowerTopMass, is reduced to account for the lighter tower. The tower top equivalent stiffness, TowerTopStiffness, is chosen to achieve a tower frequency of 0.0855 Hz for the given tower top equivalent mass.

Table 3-2 D4REL Soft Tower control design parameters, compared to the original ones

parameters_controller.txt	D4REL Soft Tower
TowerTopStiffness [N/m]	6.5105e4
TowerTopMass [kg]	2.255907e5
TowerTopNayingLQRweight [m]	5
PitchActuatorConstraintTowerPos [deg]	2
PitchActuatorConstraintTowerSpd [deg/s]	2

The parameter TowerTopNayingLQRweight, a tuning parameter for the active tower side-to-side damping control, is chosen to achieve a good damping of the sidewards motion of the tower at reasonable generator torque (and power) variations. This loop was not designed for the original D4REL model, but was added here due to the larger motions of the softer tower.

Finally, the parameters PitchActuatorConstraintTowerPos and PitchActuatorConstraintTowerSpd, defining the maximum allowable pitch position and rate for the fore-aft tower damping loop, are increased, which proved necessary to get good tower fore-aft damping.

3.3 Simulation results

Simulation results are presented and discussed here, obtained by simulating in ACT the D4REL soft tower turbine and controller, described in Section 3.2.

Simulations are performed for three different mean wind speeds: below rated (WindGain=0.6), around rated (WindGain=1.0) and above rated (WindGain=1.5). All simulations are with turbulent wind (including n 3p-components, tower shadow and wind shear).

For each mean wind speed, three different controller options are simulated:
"**Baseline**": only baseline control (FlagEnableTowerNodding=FlagEnableTowerNaying=0)
"**Baseline + FA**": baseline and tower fore-aft damping control (FlagEnableTowerNodding=1)
"**Baseline + FA + SD**": baseline, tower fore-aft and sidewards damping control
(FlagEnableTowerNodding=FlagEnableTowerNaying=1)

The design of the different control options was performed in ACT only, i.e. no tuning is done based on results from aeroelastic simulations.
The results are presented for each different wind speed. The different control options are plotted on the same figure (Figure 3-1) for better comparison.

The fatigue loads at the tower are also computed with the different control options, see Table 3-3 and Table 3-4 for the loads in fore-aft and sidewards direction, respectively. Loads have been normalized with respect to those calculated with the Baseline control option to pinpoint the achieved reduction. Dramatic reductions are seen: loads are up to 14% lower in fore-aft direction, and up to 70% lower in side-to-side direction.

Table 3-3 Load on the tower in fore-aft direction, achieved by the considered control options (normalized to Baseline)

Control option	Below rated	Around rated	Above rated
Baseline	100%	100%	100%
Baseline+FA	86.0%	54.0%	50.2%
Baseline+FA+SD	86.1%	57.2%	56.1%

Table 3-4 Load on the tower in sidewards direction, achieved by the considered control options (normalized to Baseline)

Control option	Below rated	Around rated	Above rated
Baseline	100%	100%	100%
Baseline+FA	37.4%	36.5%	29.0%
Baseline+FA+SD	29.5%	15.8%	15.3%

3.3.1 Below rated winds

Figure 3-1 give the simulation results at below rated wind speeds with the three control options. Besides the large deviations of the tower top (plots at the bottom of Figure 3-1) under baseline control, no particularities are observed in the rotor speed and power control. Including tower fore-aft damping (Baseline+FA) drastically reduces the tower top oscillations not only in fore-aft direction, but also sidewards. Adding up the tower sidewards control (Baseline+FA+SD) reduces the sidewards oscillations even further at minimum effect on the fore-aft motion. Since sidewards damping requires significant amount of generator torque effort, it directly affects the power production adding up oscillations around the tower frequency. These are, however, less relevant below rated (power fluctuations due to wind speed changes are larger there).

The damping performance of the two tower control loops is well visible by inspecting the spectral plots in Figure 3-2, where clear reductions are seen around the tower frequency at 0.0855Hz.

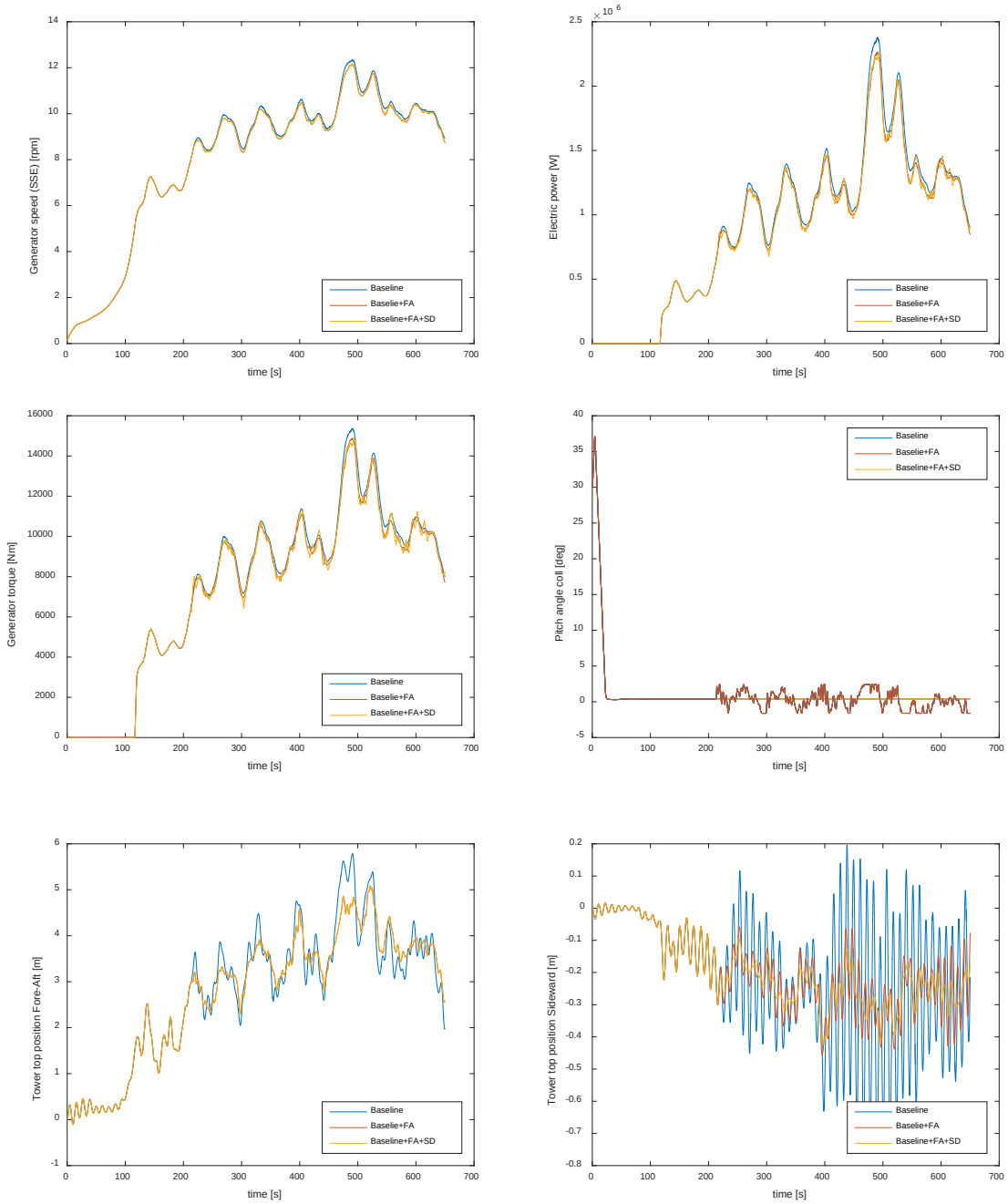

Figure 3-1 Simulation results at **below rated** wind speed

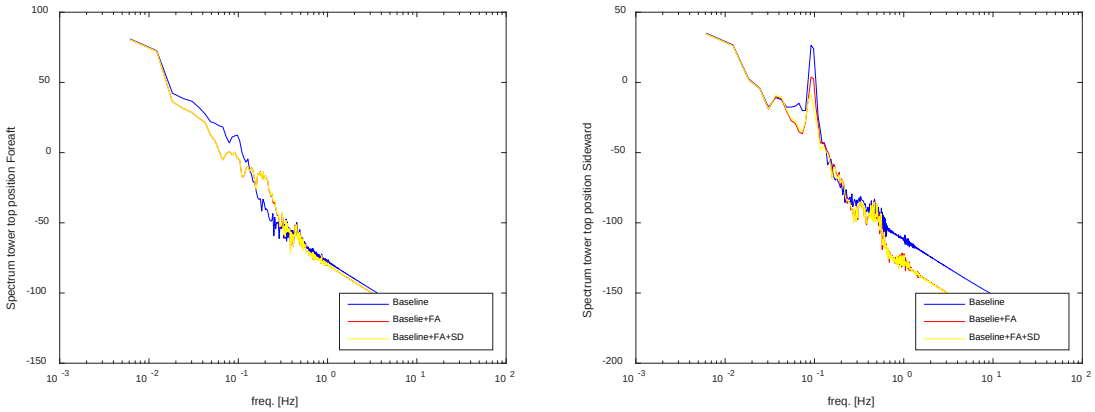

Figure 3-2 Spectra of the tower top position fore-aft (left) and sidewards (right) for **below rated** wind speeds

3.3.2 Around rated winds

Figure 3-3 gives the simulation results for around rated wind speeds. Rotor speed is regulated very well at rated, without large excursions (remain well below 10% above rated speed of 13.36 rpm). Clearly, adding tower fore-aft damping control has some effects on the rotor speed and power regulation, but they still remains good enough. Their effect on the tower top oscillations is even more pronounced than for below rated wind speed, achieving even higher fatigue load reductions (see third columns in Table 3-3 and Table 3-4). Adding the tower sidewards damping option to the controller results in fluctuations of the generator torque signal, of course, but these remain limited to an acceptable level. In fact, the tower top vibrations are already reduced significantly in both directions with the “Baseline+FA” option only, so that the inclusion of sidewards tower damping control seems unnecessary.

Figure 3-4 provides the spectra for the tower top fore-aft and sidewards positions. These confirm the statement that both tower damping loops operate properly, reducing tower oscillations around its frequency.

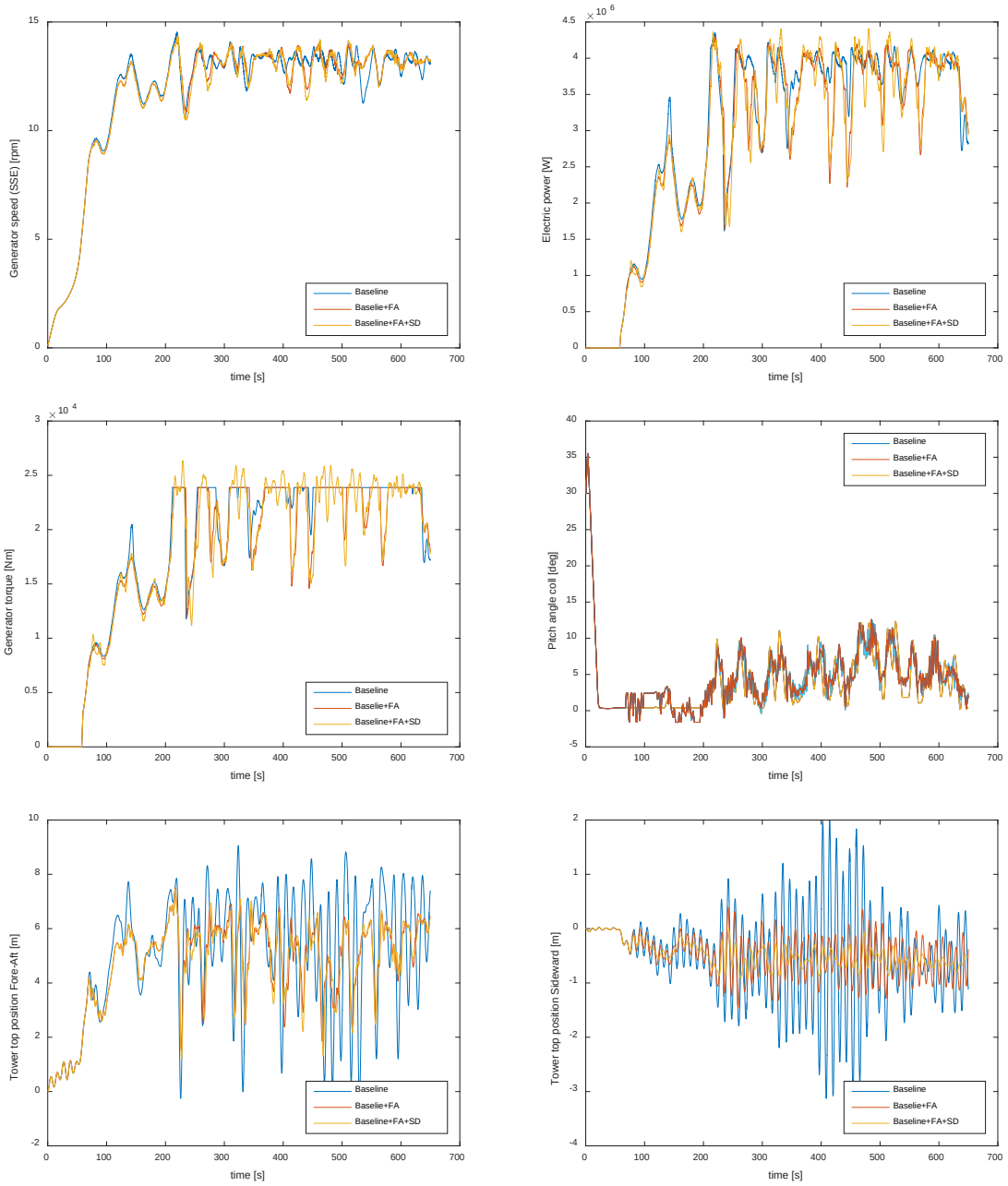

Figure 3-3 Simulation results at **around rated** wind speed

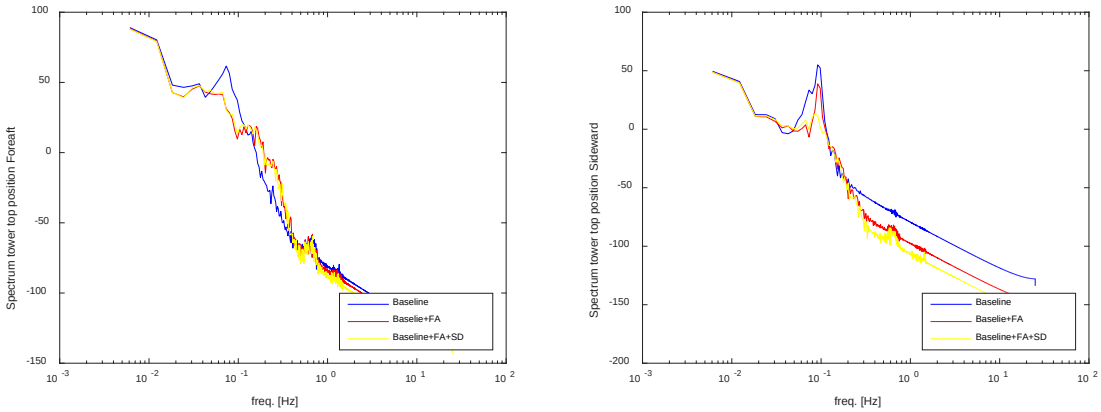

Figure 3-4 Spectra of the tower top position fore-aft (left) and sidewards (right) for **around rated** wind speeds

3.3.3 Above rated winds

Figure 3-5 gives the simulation results for above rated wind speeds. More or less the same conclusions can be drawn here as above in the case of around rated winds: rotor speed remains well controlled, and tower oscillations are very well reduced by the tower damping control loops. Probably a bit more pronounced here are the generator torque oscillations under tower sidewards damping control “Baseline+FA+SD” and the resulting fluctuations in the electric power. These are considered undesirable, and because the added value of the tower sidewards damping control loop on top of that from the fore-aft damping control is relatively small (see bottom plots in Figure 3-5, the spectra in Figure 3-6, and the loads reduction in the last columns in Table 3-3 and Table 3-4) it is recommended to stick to the “Baseline+FA” controller option. Altogether, no specific issues are observed related to the very low tower frequency.

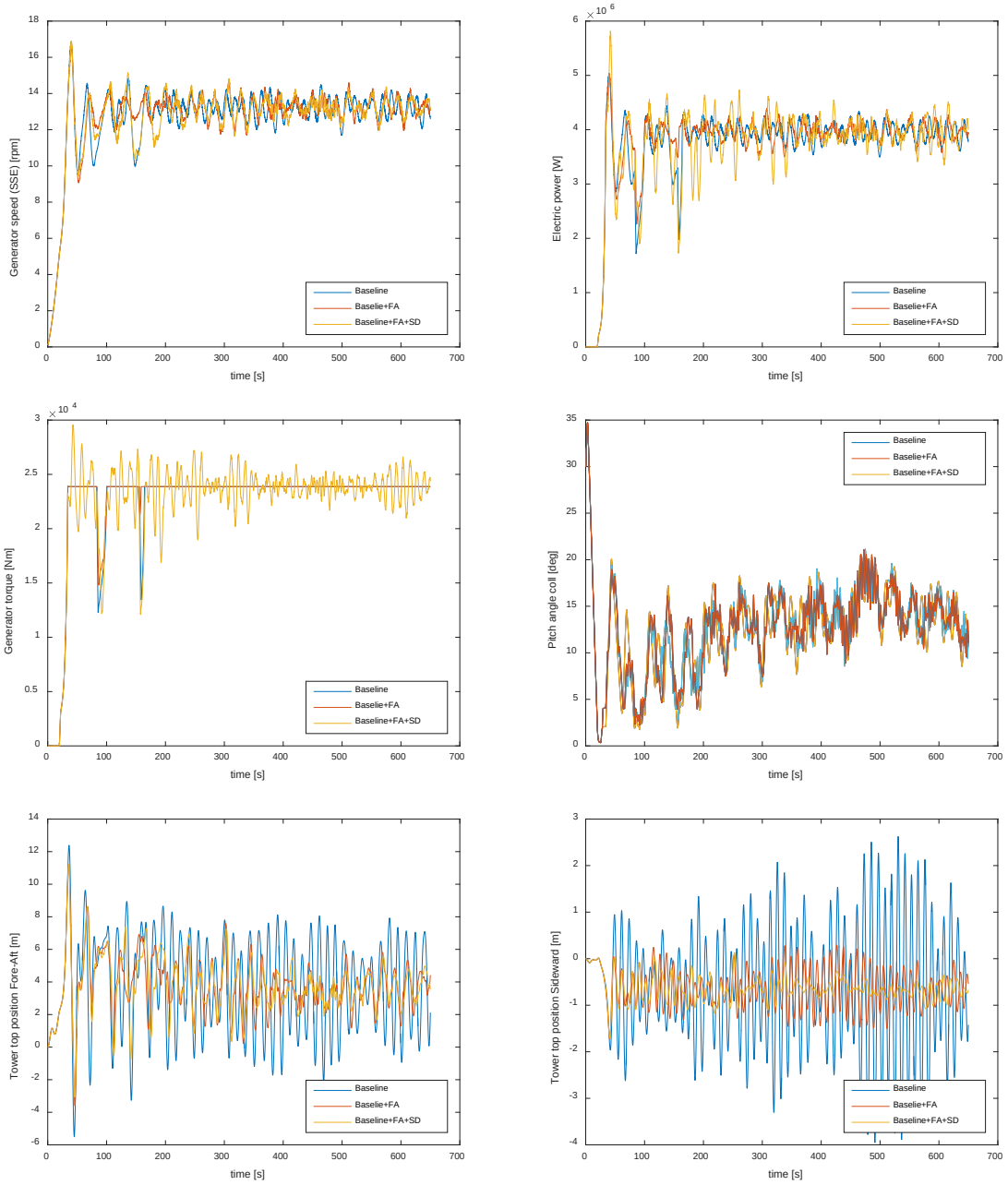

Figure 3-5 Simulation results at **above rated** wind speed

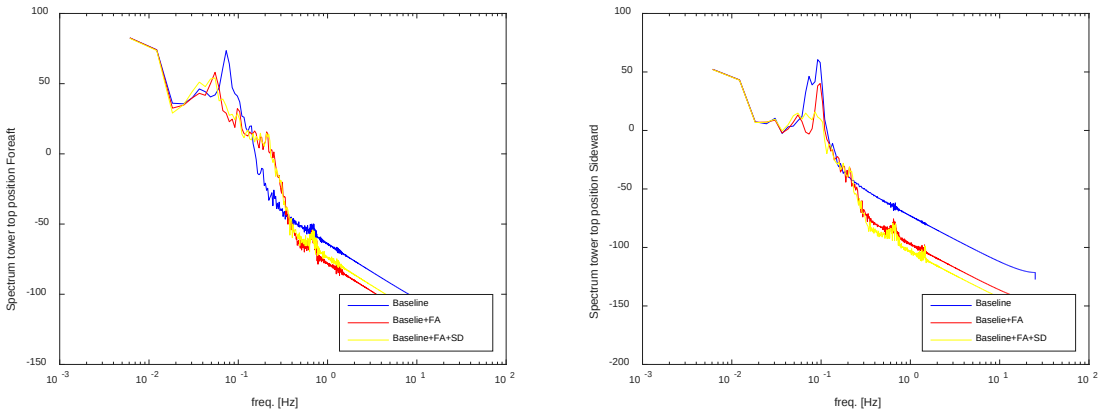

Figure 3-6 Spectra of the tower top position fore-aft (left) and sidewards (right) for **above rated** wind speeds

3.4 Conclusions on soft-tower control design

A controller is designed for a turbine with a soft-soft tower (first tower frequency of 0.085 Hz, below 1p). Besides baseline rotor speed and power control loops, tower fore-aft damping and tower sidewards damping control loops are designed. Simulations are performed in ACT for wind speeds below, around and above rated. It is concluded that a standard controller design achieved acceptable performance with respect to the rotor speed and power regulation. Tower top oscillations were significant with baseline control, but adding tower damping control achieved dramatic reduction the tower oscillations. Fatigue load reductions of up to 50% fore-aft and up to 85% sidewards.
A controller design recommendation is made to not include tower sidewards damping control because it only adds relatively small additional damping with respect to that achieved with foreaft damping, while leading to increased oscillations in the electric power.

However, based on the performed analysis in ACT, no issues were encountered in the controller design related to the very low tower frequency. Detailed aeroelastic simulations with Phatas have not been performed in this study, but higher order structural models are not expected to give rise to any significant issues – effects of higher order modes on the operation of the different control loops is typically easily removed by using proper notch filters.

4. Aero-servo-elastic stability

In modern wind turbine design knowledge of the dynamic loads and vibrations are important. Besides the loads on the turbine, possible instable conditions need to be avoided. Up to now aeroealistic stabililty analyses at ECN are mainly done by a combined use of Blademode [6] and PHATAS [7]. In Blademode, the instable blade modes are identified over a range of wind speeds. The vibration modes are determined for the blade only.

However, a wind turbine is a complicated dynamic system, in which the vibrations in support structure, drive train and rotor interact and are affected by the controller as well. This requires a aero-servo-elastic stability analysis of the complete wind turbine system. For this analysis the ECN in-house code TURBU [10] is used.

4.1 Stability analysis method

To perform a stability analysis for the complete wind turbine system the following steps are foreseen:

- Select the number of modes the analysis is done for;
- Perform the analysis between cut-in and cut-out wind speed for normal production conditions;
- Identify the critical modes by switching the structural damping off and on;
- Include the controller in the analysis;
- Check the modal analysis by performing a time domain analysis.

In this project the aeroelastic stability analysis is performed as follows. For mean wind speeds at hub height from 6m/s until 25m/s the rotor speed and corresponding blade pitch angle are determined first.

Next for each wind speed a modal analysis run is done with TURBU resulting in a plot of the mode shape and the associated damped natural frequency and logarithmic decrement.

In TURBU the modal analysis can be performed in two ways with and without the controller. Without controller the modal analysis is performed for a fixed rotor speed and blade pitch angle. With controller the torque (rotor speed) and the blade pitching are added as flexibility in the working point of the dynamic wind turbine model.

The number of modes to consider in the analysis TURBU 4MW model are set to 8 tower modes and 9 modes for each blades. This means that the maximum number of modes to be analysed in this case are 35.

4.2 Results

Although the aero-servo-elastic analysis comprises 35 vibration modes of the wind turbine focus is on the first tower bending moments in this report. For the selected normal production conditions two cases are considered:

1. An aero-elastic stability analysis, so without controller;
2. An aero-servo-elastic analysis, so with controller.

In both cases the analysis is done for the case without structural damping and the case with structural damping.
In TURBU the structural damping is modelled using the values in Table 4-1.

Table 4-1 Input of logarithmic decrement as structural damping in TURBU model.

Structure	Logarithmic decrement [%]
Blade	3.016
Tower	3.988
Foundation (soil)	0.000
Drive train	5.027

First results of the aero-elastic stability case are presented. Followed by the aero-servo-elastic case. Finally the aero-elastic and the aero-servo-elastic case are compared.

4.2.1 Aero-elastic stability analysis

In the aero-elastic stability analysis the controller is not included. In the analysis the focus is on the first for-aft and side-way tower mode as shown in Figure 4-1 and Figure 4-2 respectively. An example of an wind turbine mode at 6m/s wind speed is given in Figure 4-3.

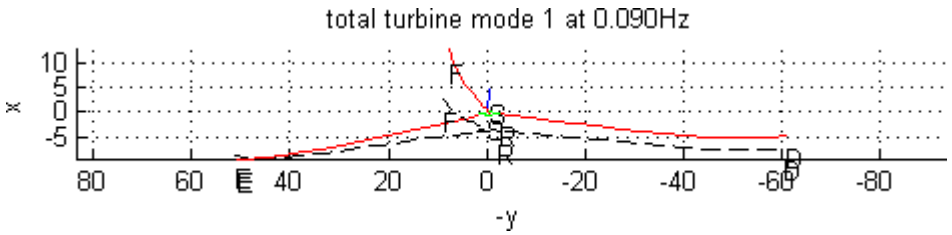

Figure 4-1 Top view of for-aft tower mode without controller, with x and y the longitudinal and lateral position in m.

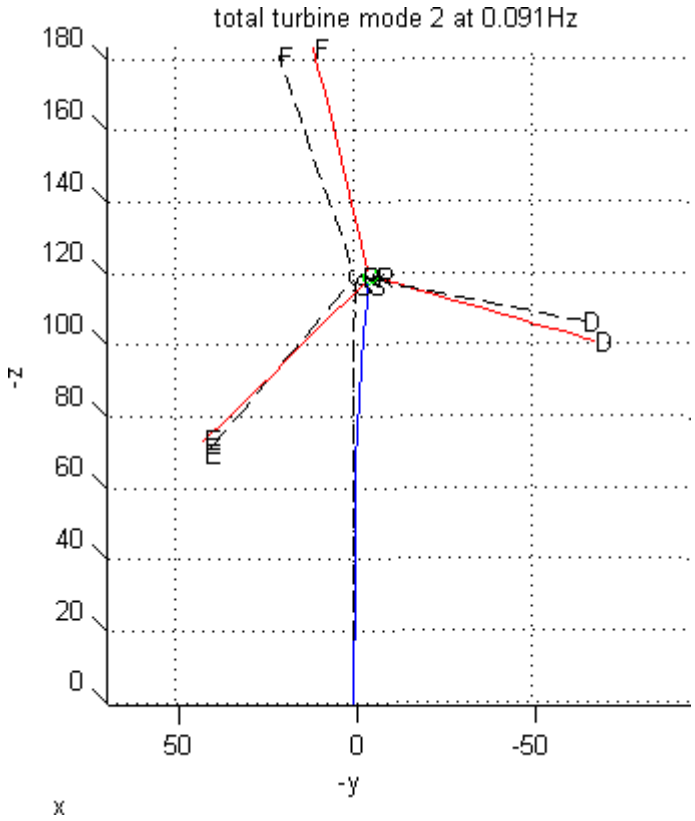

Figure 4-2 Front view of side-way tower mode without controller with y and z the lateral and vertical position in m.

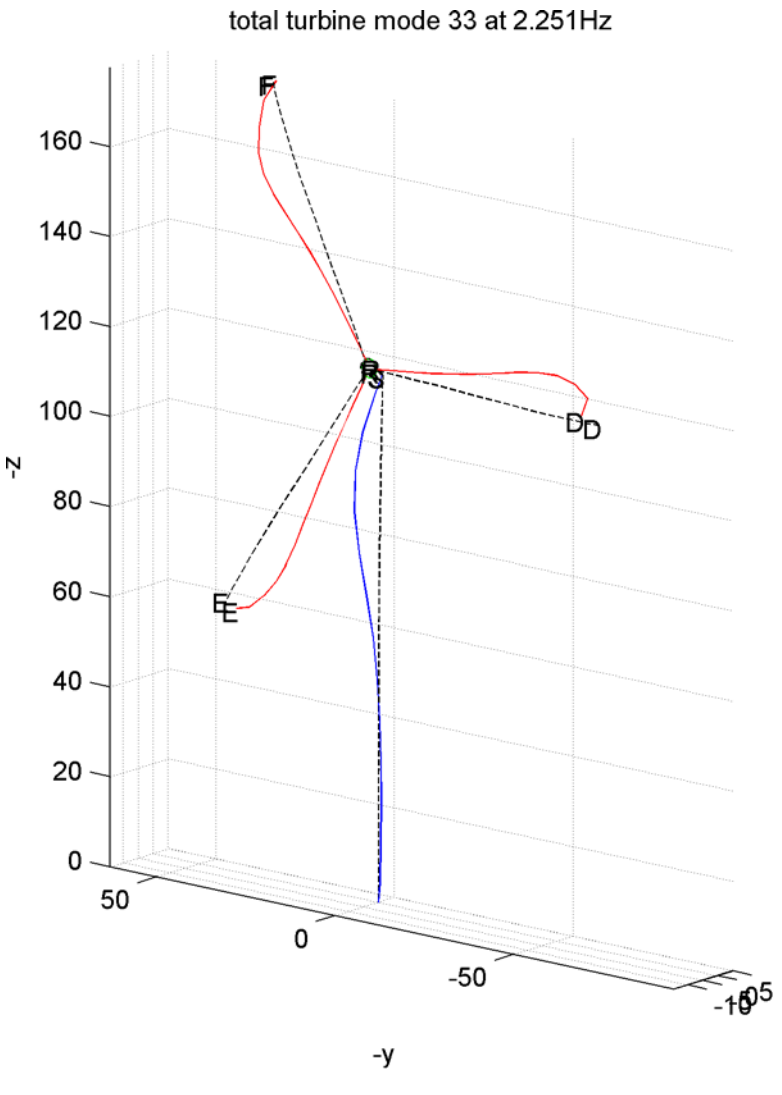

Figure 4-3 Example of wind turbine vibration mode at 6m/s with x, y and z the longitudinal, lateral and vertical position in m.

In an aero-elastic model analysis the mode shape, the damped natural frequency and the damping of the mode is determined. In TURBU the damping is expressed by the logarithmic damping. In a stability analysis a conservative approach is not to include any structural damping. This is an conservative approach. If in this case the vibration mode has positive damping it will surely have it when the structural damping is included.
In Table 4-2 the frequencies and logarithmic decrement of the first two modes is given with and without structural damping. For the second mode the case without structural damping shows negative damping.. This indicates that the sidewards tower mode might be instable. However The case with structural damping shows positive damping.

Table 4-2 Frequency and logarithmic decrement (damping) of first two modes with and without structural damping at 6m/s wind speed.

6m/s	No control		No control no structural damping	
Mode	Freq [Hz]	Log. Decrement [%]	Freq [Hz]	Log. Decrement [%]
1	8.953e-02	1.528e+02	8.954e-02	1.463e+02
2	9.097e-02	7.143e+00	9.097e-02	-3.236e-01

For wind speeds above 14m/s the damping of the modes is always positive also in case of no structural damping. Table 4-3 shows the frequency and damping (logarithmic decrement) of mode 1 and mode 2 at 15m/s wind speed.

Table 4-3 Frequency and logarithmic decrement (damping) of first two modes with and without structural damping at 15m/s wind speed.

15m/s	No control		No control no structural damping	
Mode	Freq [Hz]	Log. Decrement [%]	Freq [Hz]	Log. Decrement [%]
1	8.562e-02	2.687e+02	8.571e-02	2.618e+02
2	9.086e-02	8.415e+00	9.087e-02	9.790e-01

4.2.2 Aero-servo-elastic stability analysis

In an aero-servo-elastic analysis the flexibility of the controller is included. Here a basic ECN controller for a 4MW generic wind turbine. Compared with the aero-elastic case instead of the first two modes the first three modes are considered. A low frequent mode 1 is added. See Figure 4-4. The for-aft and sidewards tower modes are presented in Figure 4-5 and Figure 4-6 respectively.

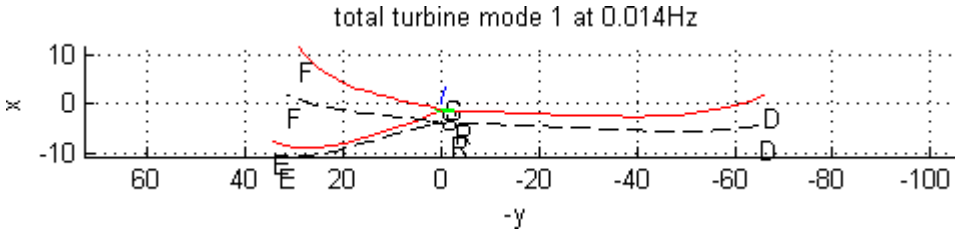

Figure 4-4 Top view of low frequent for-aft mode introduced by the controller, with x and y the longitudinal and lateral position in m.

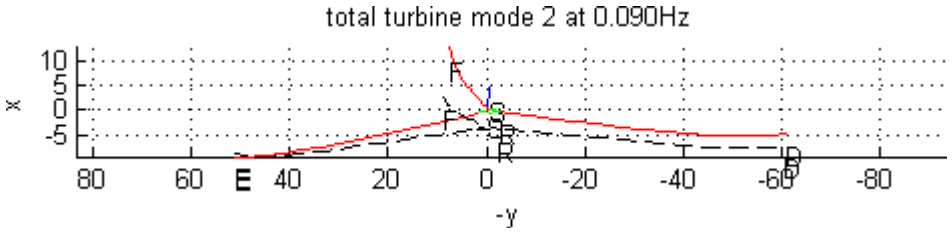

Figure 4-5 Top view of for-aft mode with controller, with x and y the longitudinal and lateral position in m.

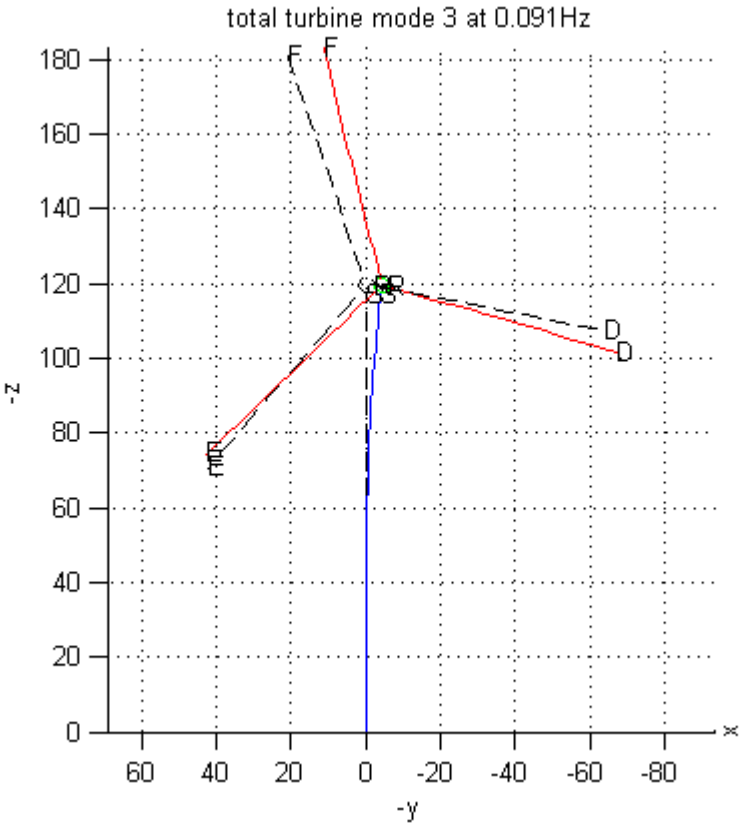

Figure 4-6 Front view of sidewards tower mode with controller with y and z the lateral and vertical position in m.

As was the case for the aero-elastic analysis again the modal analysis is performed with and without structural damping. Table 4-4 shows the frequencies and damping for 6m/s wind speed. As can be seen mode 1 and mode 2 are very well damped modes. As expected the sidewards tower mode 3 is less damped.

Table 4-4 Frequency and logarithmic decrement (damping) of first three modes with and without structural damping at 6m/s wind speed and the controller included.

6m/s	control		control no structural damping	
Mode	Freq [Hz]	Log. Decrement [%]	Freq [Hz]	Log. Decrement [%]
1	1.366e-02	5.946e+02	1.366e-02	5.946e+02
2	8.962e-02	1.540e+02	8.962e-02	1.475e+02
3	9.104e-02	9.744e+00	9.104e-02	2.270e+00

In TURBU the modes are determined by linearization in the working point. The mean deformation in the working point depends on the wind speed, the rotor speed and pitch angle. In Table 4-5 mode 1 is almost critical damped while both mode 2 and mode 3 are both low damped now. Beside that mode 2 is not close to 0.09Hz anymore.

Table 4-5 Frequency and logarithmic decrement (damping) of first three modes with and without structural damping at 11m/s wind speed and the controller included.

11m/s	control		control no structural damping	
Mode	Freq [Hz]	Log. Decrement [%]	Freq [Hz]	Log. Decrement [%]
1	2.338e-02	6.034e+02	2.338e-02	6.034e+02
2	6.484e-02	5.537e+00	6.492e-02	4.482e-01
3	9.404e-02	7.310e+00	9.402e-02	1.204e-02

The situation for 11m/s wind speed is most critical. Therefor the dynamics of the wind turbine are studied in more detail by performing a load simulation using TURBU. Both conditions with and without structural damping are simulated. Figure 4-7 shows the power spectral density of the sidewards mode at 11m/s with and without structural damping. The effect of the structural damping is clearly visible as a smaller area (less energy), below the blue spectral line.

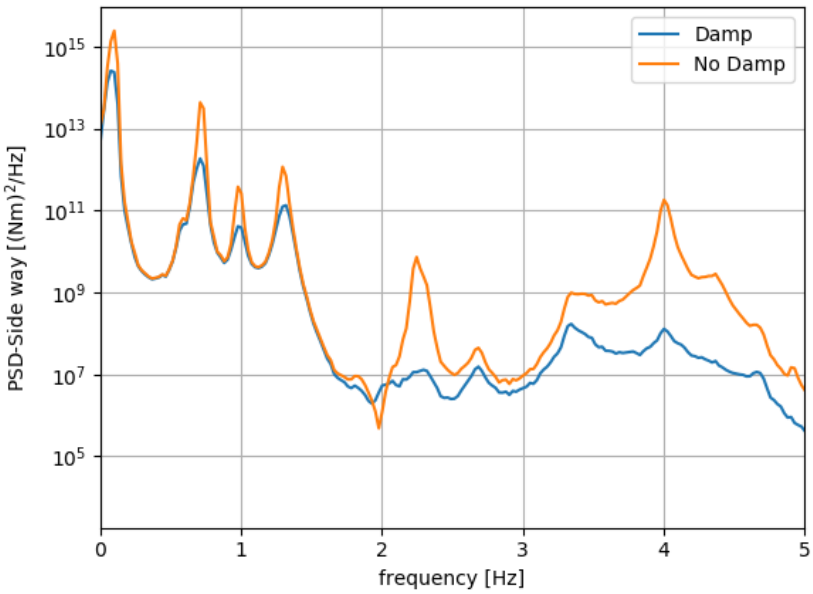

Figure 4-7 Power spectral density of sidewards tower mode at 11m/s wind speed for the case with and without structural damping.

Figure 4-8 shows the time series of the sidewards bending moment for the case without structural damping. The simulation shows that bending moment increases and becomes unstable although the damping in the sidewards tower mode is positive.

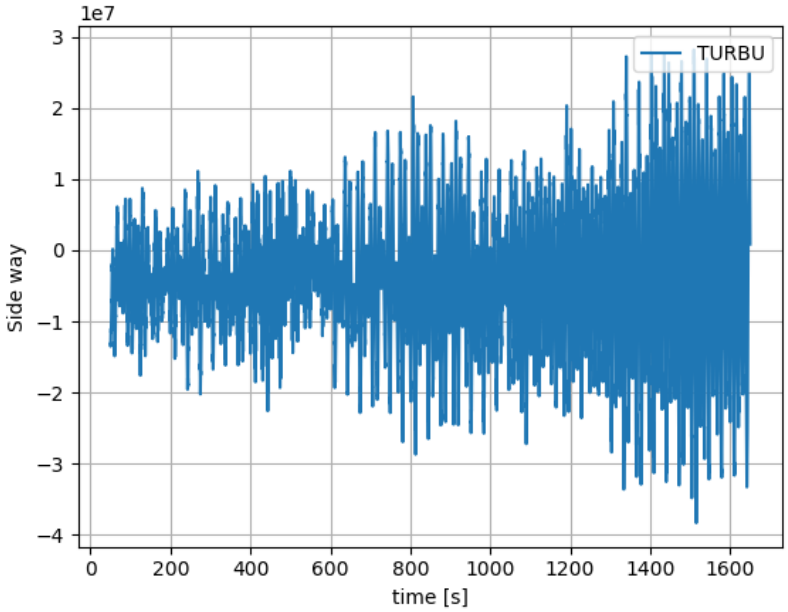

Figure 4-8 Time series of Sidewards bending moment [Nm] at 11m/s wind speed without structural damping.

Figure 4-9 shows again the sidewards bending moment now with structural damping included. This time the system remains stable due to the sufficient amount of structural damping.

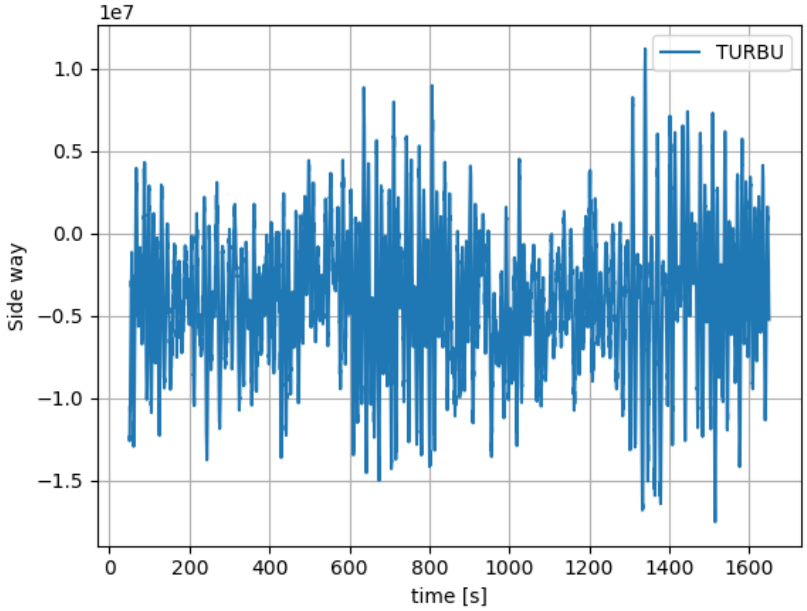

Figure 4-9 Time series of Sidewards bending [Nm] moment at 11m/s wind speed with structural damping.

The analysis at 11m/s wind speeds shows that concluding that there is no instability based on the positive damping observed in the modal analysis is not sufficient. An additional load simulation is necessary to verify whether the dynamic behaviour of the wind turbine system is “really” stable.

5. Conclusions

Within the ECN internal project “Soft tower control”, an ACT controller has been designed for a wind turbine with a very low first tower frequency. The purpose for this design is to investigate if there are specific challenges related to controller design for turbines with so-called soft-soft towers, towers with first frequency below the rotational frequency of the rotor (1p). To this end, the D4REL turbine model has been modified by only reducing the tower parameters to achieve a first tower frequency of 0.0855 Hz, according to a structural tower design performed using TURBU. The support structure consists of a steel monopile together with a composite transition piece and tower.

A controller is designed for a turbine with a soft-soft tower (first tower frequency of 0.085 Hz, below 1p). Besides baseline rotor speed and power control loops, tower fore-aft damping and tower sidewards damping control loops are designed. Simulations are performed in ACT for wind speeds below, around and above rated. It is concluded that a standard controller design achieved acceptable performance with respect to the rotor speed and power regulation. Tower top oscillations were significant with baseline control, but adding tower damping control achieved dramatic reduction the tower oscillations.

Based on the performed analysis in ACT, no issues were encountered in the controller design related to the very low tower frequency. Detailed aeroelastic simulations have not been performed in this study, but higher order structural models are not expected to give rise to any significant issues – effects of higher order modes on the operation of the different control loops is typically easily removed by using proper notch filters.

An aero-servo elastic stability analysis is performed. The focus of the analysis was on the first tower bending modes. However the dynamics of the complete wind turbine system are considered. Modal analysis are performed with and without the controller included in the analysis. The controller applied in the analysis is a basic ECN controller without tower damping. For 11m/s wind speed and the controller included the case without structural tower damping shows instable behaviour when a load simulation with TURBU is performed. It is therefore recommend always to check structural dynamic behaviour and control behaviour with an aeroelastic simulation.

The work of the current project is continued in the TKI innovation project IDL Tower.

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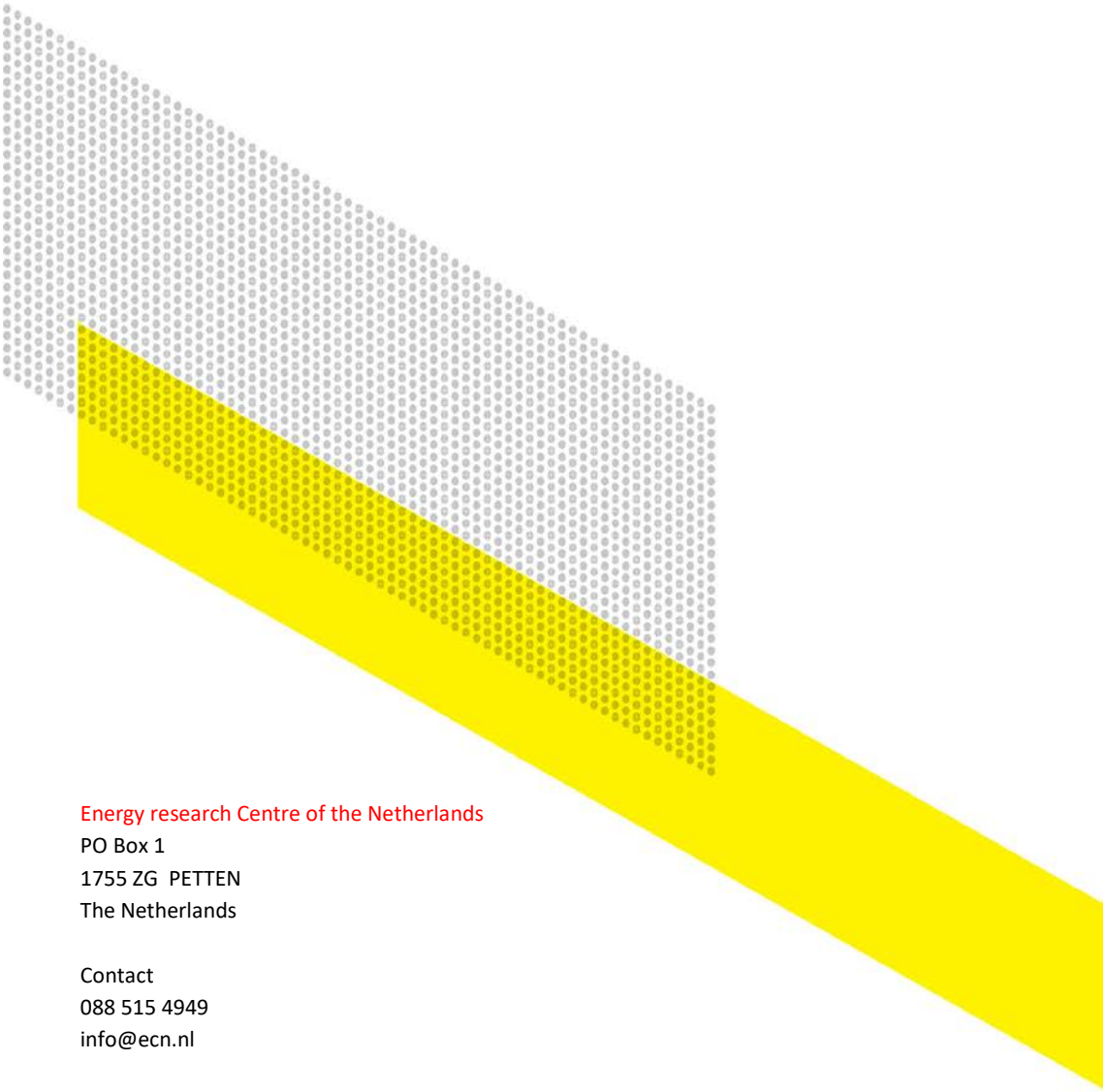

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