

Comparison of Phatas versions and the Wind Turbine module

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Preface

The program Phatas is developed at ECN wind energy for the design and analysis of horizontal axis wind turbines. Phatas is part of the wind turbine design package Focus which is developed at WMC. Recently Phatas is re-structured such that it can be called as a module by existing computer programs for the (hydro-) dynamics of a floating support.

The use of Phatas for commercial application requires that the code is validated. The underlying document reports on a validation by comparison of the dynamic response calculated with the former Phatas release and the current Phatas releases.

The development of the Wind Turbine module and the tests reported here were conducted within the project 'Floating wind offshore structures' that is carried out within the 'Maritieme Innovatie Programma' with reference MAR1000015. The ECN work is part of the ECN project 5.1098.

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Summary

The program Phatas is developed at ECN wind energy for the design and analysis of horizontal axis wind turbines. Phatas is part of the wind turbine design package Focus which is developed by WMC. In addition Phatas is re-structured such that it can be called as a module by existing computer programs for the (hydro-) dynamics of a floating support.

A verification is performed by comparison of results calculated with the former Phatas release “APR-2005n”, with the current release “APR-2005o” and with the Wind Turbine module. These calculations are done for the 5MW ART5 wind turbine. In addition to the common practise for wind turbine design calculations, also the blade torsional deformation is included.

The comparisons start with a calculation of the aerodynamic rotor coefficients which show good agreement. Next the overspeed analysis is performed with the 3 Phatas versions which show the same rotor speed at which flutter occurs. Finally the fatigue load sets are calculated and a comparison is done on basis of the fatigue equivalent bending moments in the main parts of the wind turbine structure. The calculations with the Wind Turbine module were performed without tower bending deformation, because this was not yet fully developed in combination with (possible) motions of the support.

The aerodynamic coefficients and the overspeed analyses were also calculated with the current Phatas release for a 10x up-scaled and a 100x down-scaled model of the ART5 wind turbine.

The results of the comparisons show that the Phatas code is robust for a wind turbine dimension ranging from 1.3m diameter to 1300m diameter. If the calculated results for the up-scaled and down scaled wind turbine models are scaled back, then they show reasonable agreement with the results calculated for the un-scaled ART5 wind turbine. The comparisons of the results calculated with the different Phatas versions and with the Wind Turbine module show that they are close to each other. The minor differences in the calculated fatigue equivalent moment cycles between release “APR-2005n” and “APR-2005o” may be due to the improvements that are issued in release “APR-2005o”.

Finally it can be concluded that apart from the fact that tower dynamics can not yet be used in the Wind Turbine module the aerodynamic and structural dynamic response is the same as calculated with the conventional Phatas program.

1. Introduction

Phatas has been developed for the design and analysis of horizontal axis wind turbines. Since several years Phatas has been applied for the design of commercial wind turbines. Last years it is also part of the wind turbine design package Focus6. A manual for Phatas is given in [1]. Recently the structural dynamics code of Phatas is made modular to allow coupling with programs for the motions of floating bodies.

The use of Phatas by several institutes and manufacturers for the design and development of wind turbines make it necessary to perform some validations that can be published. This document reports on validations based on a non-existing design of a 128m diameter 5MW wind turbine that is also used for research purposes. The global characteristics of this design are reported in Appendix A.

The validations are performed by calculations with different Phatas releases. The results are compared and reported here. These releases are “APR-2005n” that is issued in April 2011, and “APR-2005o” that is issued in December 2011.

The calculations are also done with the Wind Turbine module ‘WTmodule.dll’ and a program ‘wtquake.exe’. The interface of the ‘WTmodule.dll’ is described in appendix A of [2]. The program ‘wtquake.exe’ is a program that calls the Wind Turbine module and applies a prescribed motion to the tower base. This can be used e.g. to calculate the response on earthquake motions.

For the comparisons reported in this document the applied motion is simply a constant position, so with zero velocities and zero accelerations. Tests of the Wind Turbine module with applied motions are reported separately, see [3].

In addition, calculations are also performed for:

- A 10 times up-scaled model of the ART5 rotor. Here all material properties (mass density, Young’s modulus of elasticity etcetera) are kept constant. The aerodynamics have the same characteristics by scaling all velocities down with factor 10, and likewise “stretching” the time scale with factor 10. The resulting structural dynamic response is only comparable (after scaling) if the gravity constant is divided with a factor 10. The latter is done in a specific Phatas release. Verification with a 10 times up-scaled model shows whether the numerical model will not run into e.g. overflow and whether the results for large (future) rotors are still consistent.
- A 100 times down-scaled model of the ART5 rotor. A down-scaling of 100 (instead of 10) was chosen such that the model has the dimensions that are representative for wind turbine models. As for the “up-scaled” calculations, a specific Phatas version has been compiled with gravity constant 981.0.

A global description and model comparison of the up- and down-scaled models is reported in Appendix B.

Several comparisons are performed. Chapter 2 reports on the comparison of the C_p -lambda-theta calculations, also called “rotor characteristics”.

Chapter 3 reports on the so-called ‘overspeed analysis’. This analysis is a calculation of an idling rotor with fixed pitch angle for an increased wind speed. By including blade torsional deformation (together with the conventional flap bending deformation) the response of this calculation may show the so-called ‘flutter speed’. For the comparisons reported here this ‘overspeed analysis’ is done for a rigid tower.

Chapter 4 reports on a comparison of the response for a stepwise increasing wind velocity. This response is used to verify the proper functioning of the controller. The controller used here is

the 'internal' model in Phatas of a simple P-D algorithm for pitch-to-vane controlled variable speed wind turbines.

Chapter 5 reports on the calculation of an IEC ed.2 [4] fatigue load set. Because the scaling of the turbulent wind loading requires some modifications of the program SWIFT and the load case preprocessor 'lcprep' the fatigue load sets are not calculated for the 10 times up-scaled and the 100 times down-scaled model of the ART5 rotor.

Finally Chapter 6 contains some concluding remarks.

2. Comparison of aerodynamic rotor characteristics

The aerodynamic rotor characteristics are calculated for the pitch angles of 0.0deg, 0.5deg, 1.0deg, 1.5deg, and 2.0deg because these are close to the pitch angles for optimum power coefficient. Likewise the tip-speed ratios are varied from 7.5 to 9.0 with increments of 0.1. The inclination of the wind and also the yaw misalignment are zero. The vertical shear is described with a power law with exponent 0.1429 ($= 1/7$) which is the value of the 'standard atmosphere'. The turbine-related aspects such as the aerodynamic flow stagnation of the blade-tower interaction (by aerodynamic stagnation) and the tilt angle of the rotor shaft are included.

Because the rotor characteristics are quasi-steady properties the tower is modelled rigid. The rotor blades however are modelled including the -2.5deg pre-cone, the pre-bend, and with bending and torsion deformation. In particular the torsion deformation may have an effect on the aerodynamic performance. Knowing that the rotor characteristics are used among others to select the operational pitch angle and tip-speed ratio in partial load, the blade deformation needs to be representative for the partial load state. Consequently the wind velocity was set to 8m/s. The rotor speed used for the rotor characteristics is then internally set in Phatas to the value that gives the respective tip speed ratio for the 8m/s wind speed.

Following table contains the maximum aerodynamic power coefficients for different pitch angles calculated with the different Phatas releases and models of the ART5 turbine:

Table 1 *Maximum aerodynamic power coefficients for different pitch angles.*

Pitch angle	0.0 deg	0.5 deg	1.0 deg	1.5 deg	2.0 deg
'APR-2005n'	0.47518	0.47689	0.47736	0.47624	0.47296
'APR-2005o'	0.47519	0.47689	0.47736	0.47624	0.47296
Idem 10x	0.47519	0.47689	0.47736	0.47624	0.47296
Idem 0.01x	0.47519	0.47689	0.47736	0.47623	0.47294
WTmodule	0.47496	0.47669	0.47719	0.47606	0.47277
T.s.r. at Cp_max	7.9	8.2	8.4 & 8.5	8.7	9.0

The maximum power coefficients that are found with the different Phatas releases are for the same tip-speed ratio, which is listed in the lower row of this table.

The aerodynamic power coefficient itself is slightly smaller for the Wind Turbine module 'wtmodule.dll'.

3. Comparison of overspeed analyses

Following the laws of proportional scaling –‘square cube law’- the mass of structures increases with the dimension to the power 3. For the same wind velocity the energy yield scales with the 2-nd power of the dimension which would make large wind turbine structures less material efficient. Rotor blade manufacturers try to ‘fight’ this 3-rd power increase of the blade mass by using a material efficient design, a more slender structure and sophisticated controllers. The more slender blade designs involve more flexibilities. Consequently more effort is spent on the aeroelastic analysis of wind turbine rotors with a diameter more than 100m. One of the phenomenas to be investigated is the rotor speed at which the rotor blade gets a growing vibration that is fed by instationary aerodynamic loading. For aircraft wings this is often a flap-torsion vibration, also called ‘flutter’.

The load case preprocessor ‘lcprep’ that is provided with Phatas also generates an input file for the so-called ‘overspeed analysis’. This load case describes the speed of an idling rotor in response to an increasing wind velocity. The pitch angle is fixed to an angle that is 8deg more than the minimum pitch angle for normal operation.

With the Phatas releases mentioned in the introduction in Chapter 1 the overspeed analysis is performed for the ART5 rotor blades. Here the time increment was set to 0.004s. From the algorithm in Phatas it is known that for this time increment all vibrations with a frequency up to 10.8Hz have a numerical damping of maximum 1%.

The blade torsional frequency is 11.52Hz which means that a torsional vibration is modelled with a numerical damping of $(11.52/10.8)^3 \% = 1.2\%$.

The model for correction of the lift coefficient for the effects of rotation is set ‘ON’.

The model for dynamic stall effects is also selected.

Both these models have marginal effect as long as the blade sections operate in the ‘linear’ part of the lift curve (which is attached flow).

The ‘overspeed analysis’ is calculated with the blade pitch angles fixed at 8.0deg.

The wind velocity is 4.8m/s and increases from 40.0s to 520s ending at 44.8m/s.

Following pages show plots of the calculated results of the rotor speed and the torsional deformation at 60m blade span. For the scaled models the blade span for the torsional deformation is 600m and 0.6m. These plots clearly show at what rotor speed value the blades start a heavy vibration. This heavy vibration does not increase exponentially because the lift-curve has a limited range for “attached flow”.

Table 2 *The ‘flutter speed’ that was found from the different calculations*

	20 elements	23 elements
‘APR-2005n’	35.5rpm	35.5rpm
‘APR-2005o’	35.2rpm	35.2rpm
‘APR-2005o’ scaled 10x		3.53rpm
‘APR-2005o’ scaled 0.01x		3475rpm
Wind Turbine module	35.2rpm	35.25rpm

When the time-scale of the scaled models are taken into account, the flutter speed is the same for all Phatas versions and independent from size.

Following pages show the response of the ‘Overspeed analyses’ calculated with 23 elements.

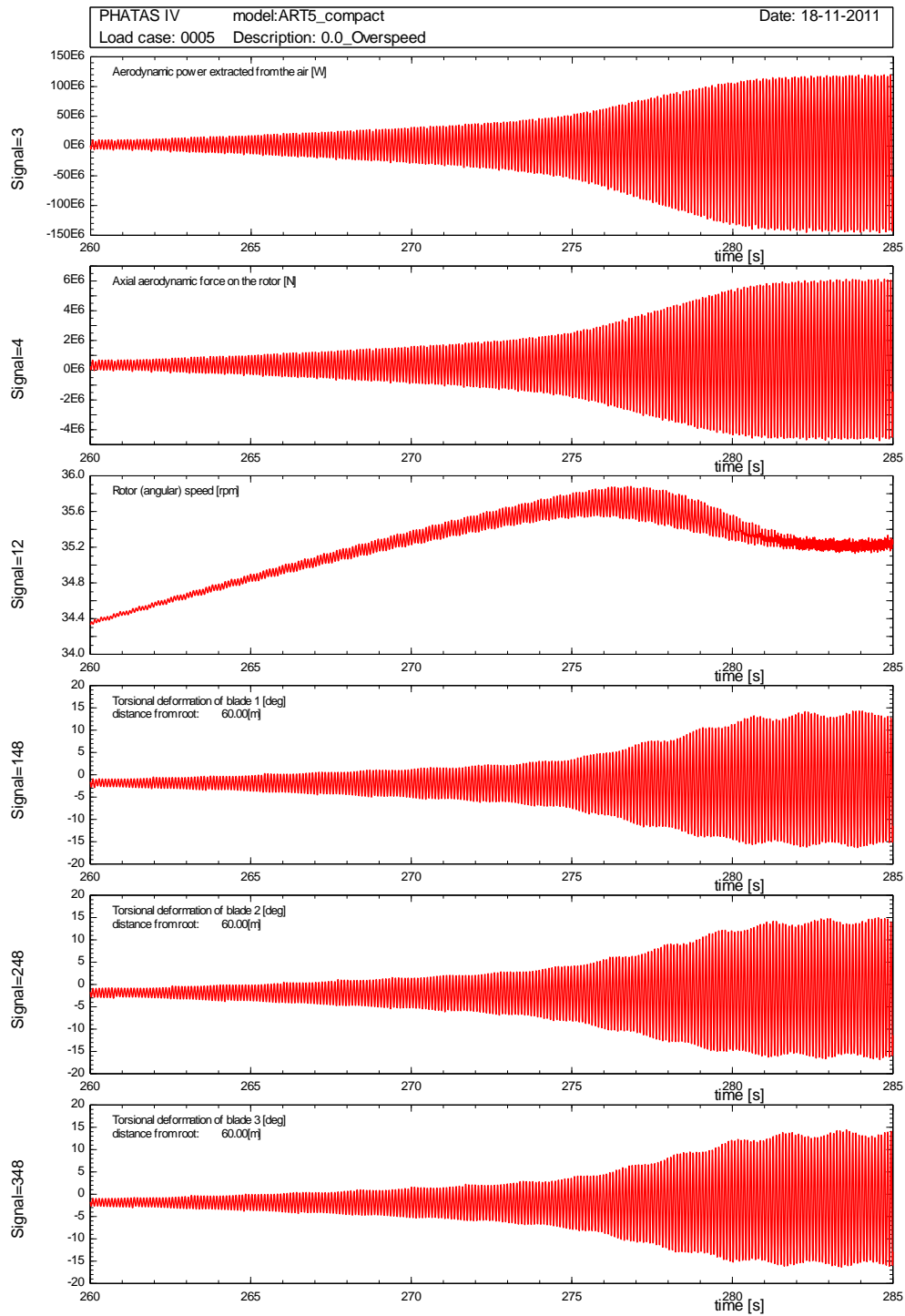


Figure 1 Overspeed analysis of 5MW ART5 turbine calculated with release "APR-2005n".

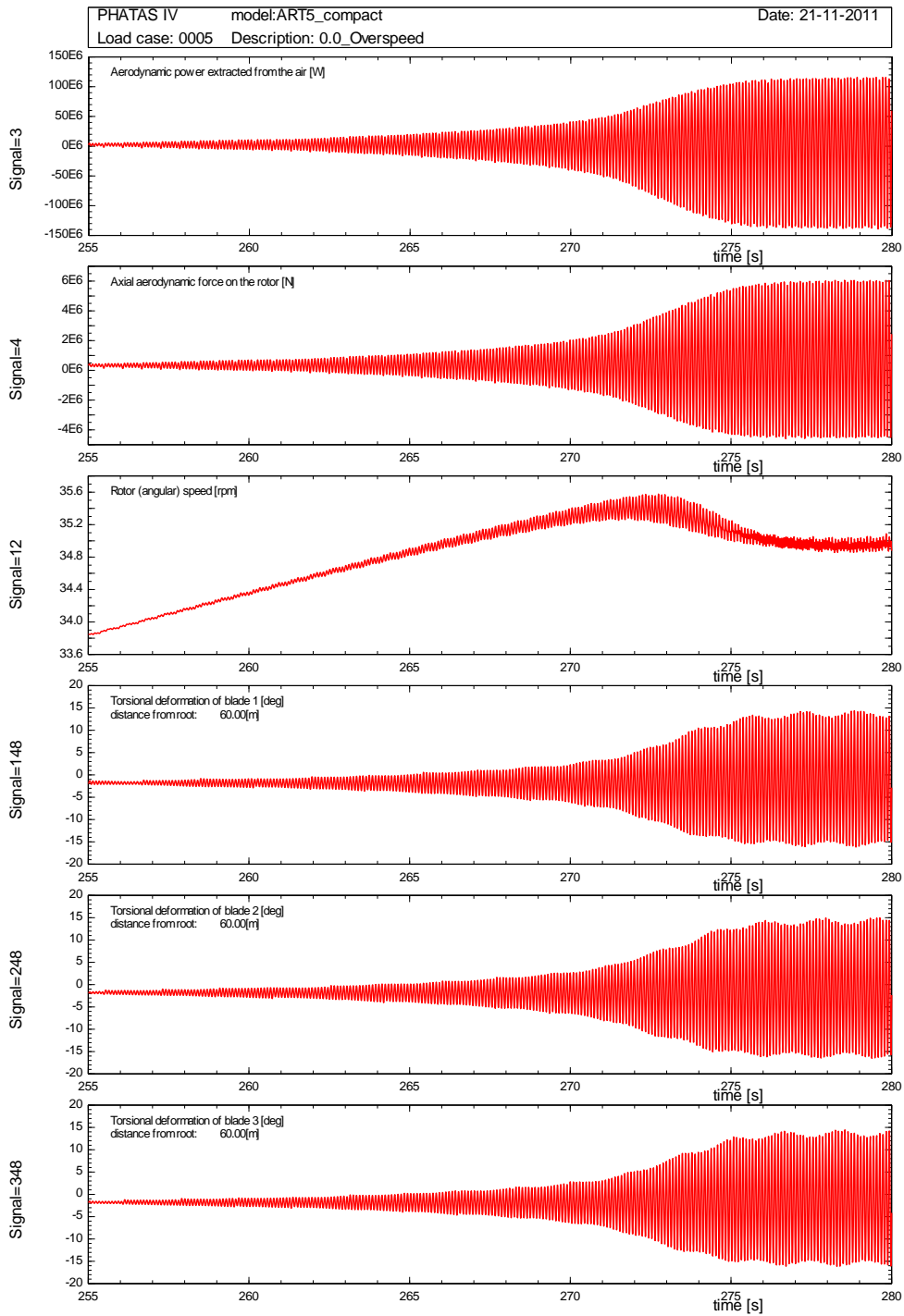


Figure 2 Overspeed analysis of 5MW ART5 turbine calculated with release “APR-2005o”.

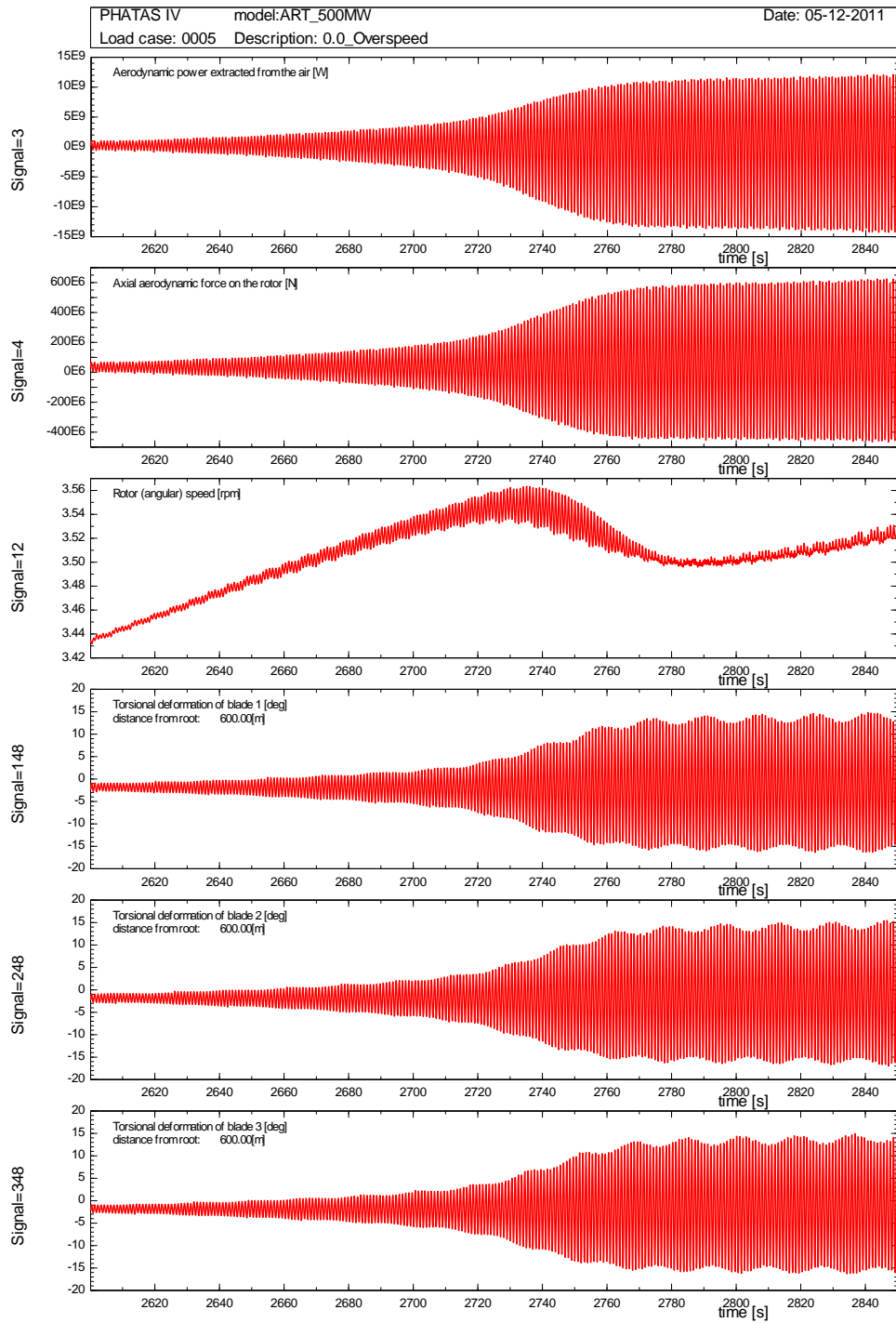


Figure 3 Overspeed analysis of 500MW ART5 turbine calculated with release "APR-2005o".

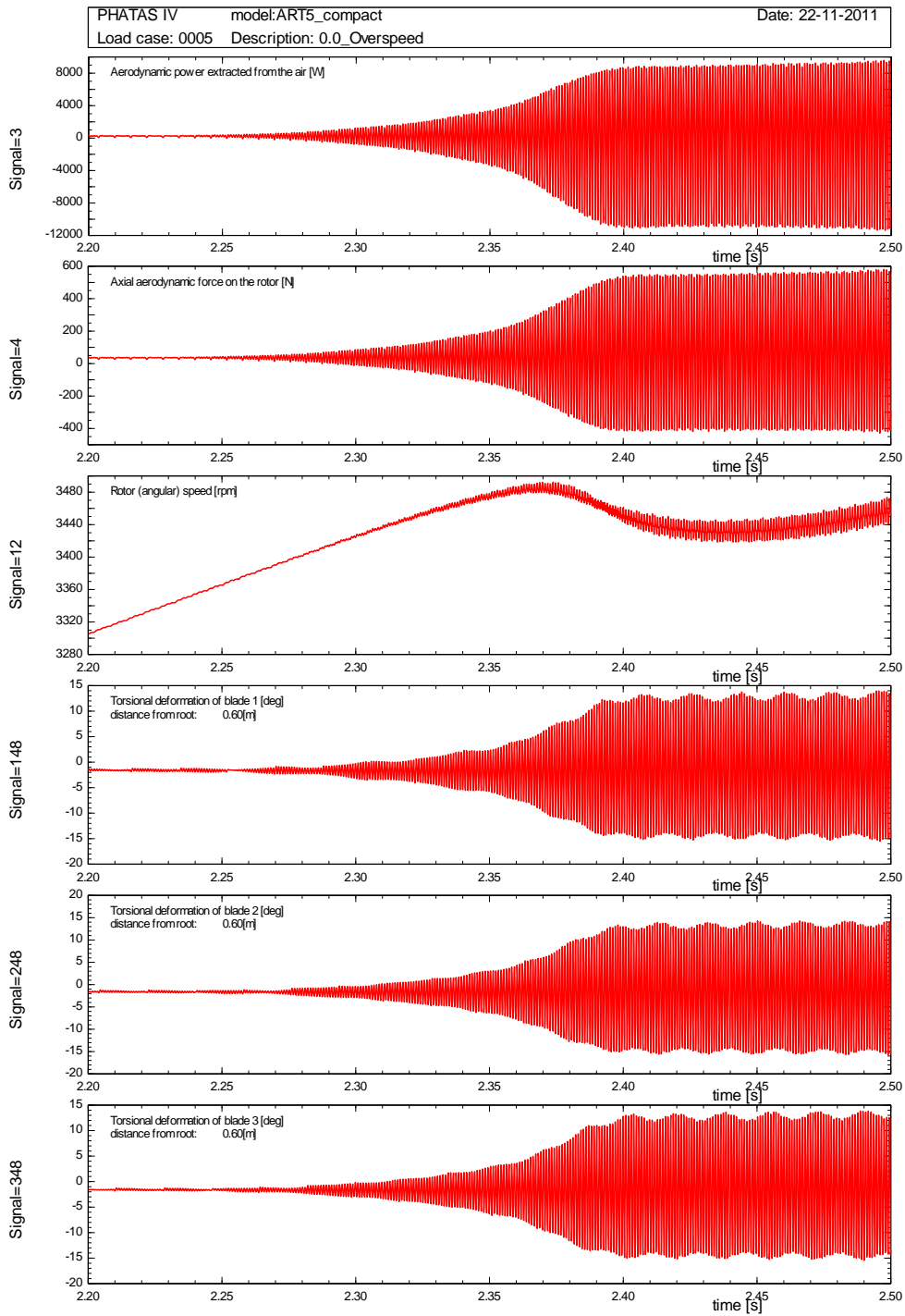


Figure 4 Overspeed analysis of 500W ART5 turbine calculated with release "APR-2005o".

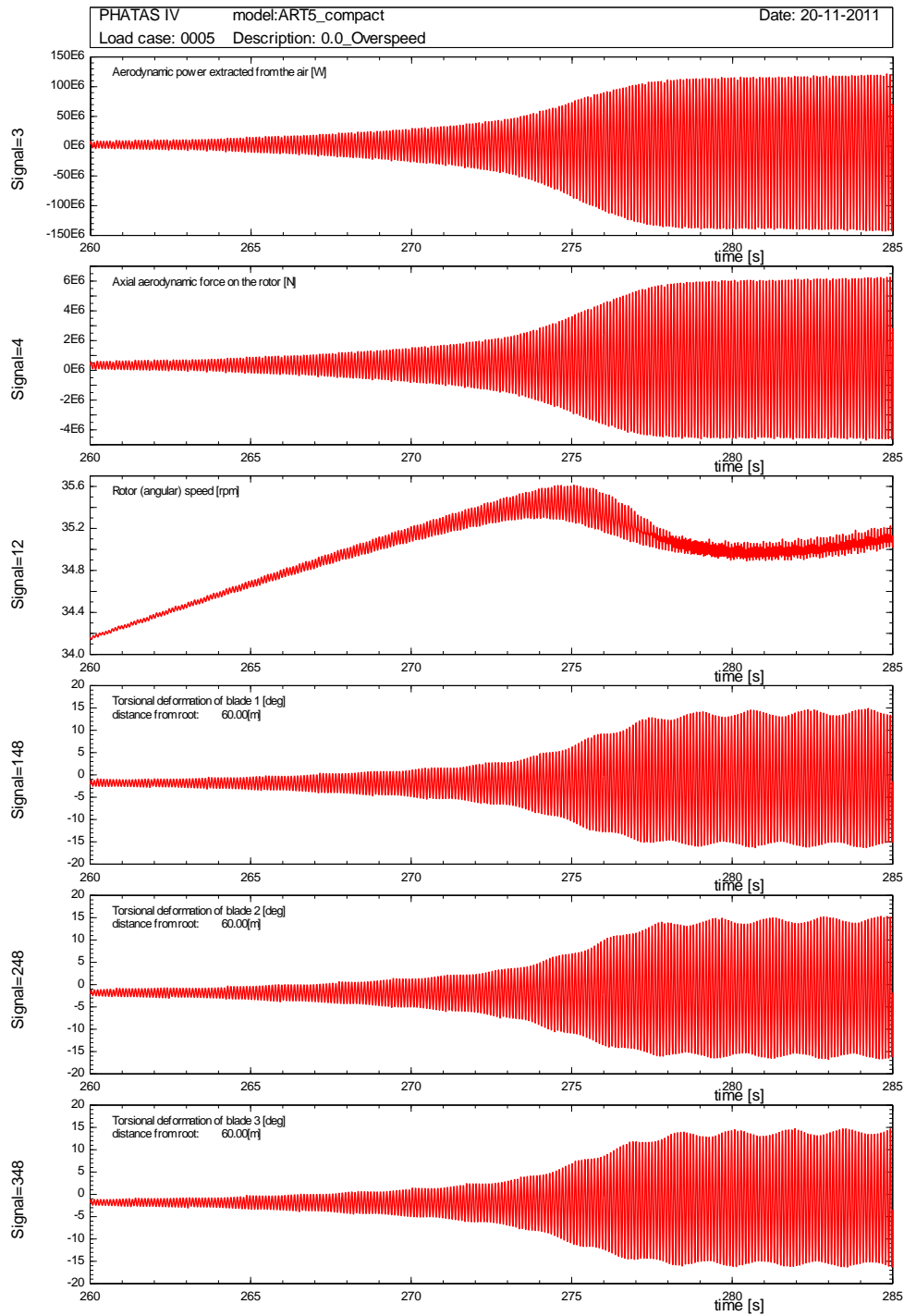


Figure 5 Overspeed analysis of 5MW ART5 turbine calculated with the Wind Turbine module.

4. Comparison of response on stepwise increasing wind

Phatas offers an option to apply a stepwise increasing wind velocity. This wind can be used to evaluate the (step-) response of the operational controller. This response is evaluated for the simple built-in P-D controller of Phatas. The controller settings are:

Average time 0.8s (1/6 of a revolution)
Proportional_gain 0.3
Differential_gain 2.0
Gain scheduling factor $1./(1. + 0.16*(Pitch - Pitch_min))$ 'Pitch' in [deg]
Threshold value 0.5deg/s.
Time delay of pitch actuator: 0.1s.
Maximum pitch_rate 5.0deg/s.
Maximum pitch acceleration 6.0deg/s²

These controller settings are also applied for the calculations with the Wind Turbine module.

The wind is increasing from 10m/s to 20m/s with steps of 1.0m/s.
Each wind velocity is maintained during 20s.

Plots of the calculated response are shown on the following pages. These responses are highly similar except for the response calculated with the Wind Turbine module which is calculated without tower dynamics, see Figure 10.

A scoping calculation of this step-response with release "APR-2005o" showed similar response as calculated with the Wind Turbine module in Figure 10. It was thus concluded that the different response in Figure 10 is due to the omission of tower dynamics.

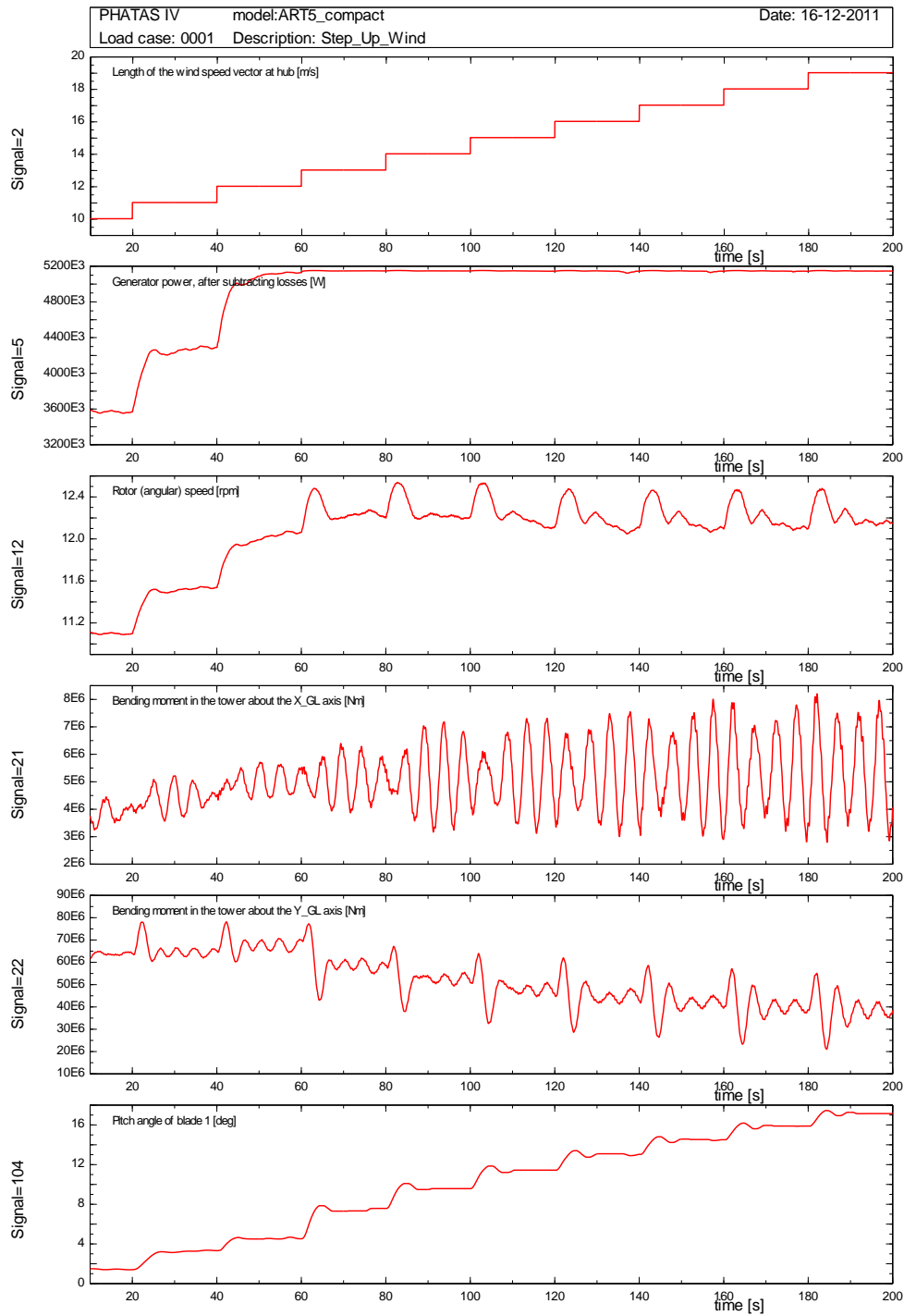


Figure 6 Response of ART5 wind turbine on stepwise wind calculated with “APR-2005n”.

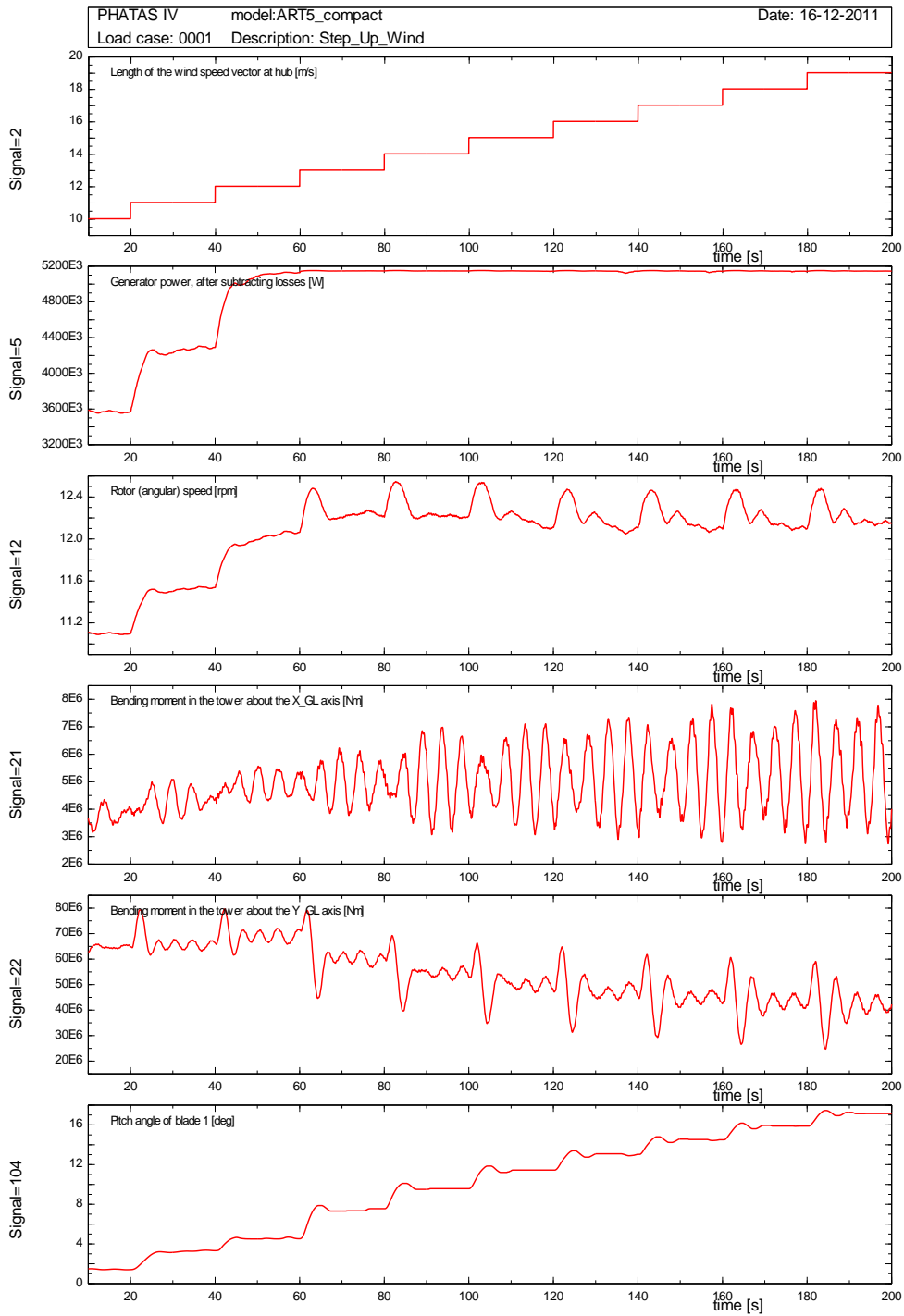


Figure 7 Response of ART5 wind turbine on stepwise wind calculated with “APR-2005o”.

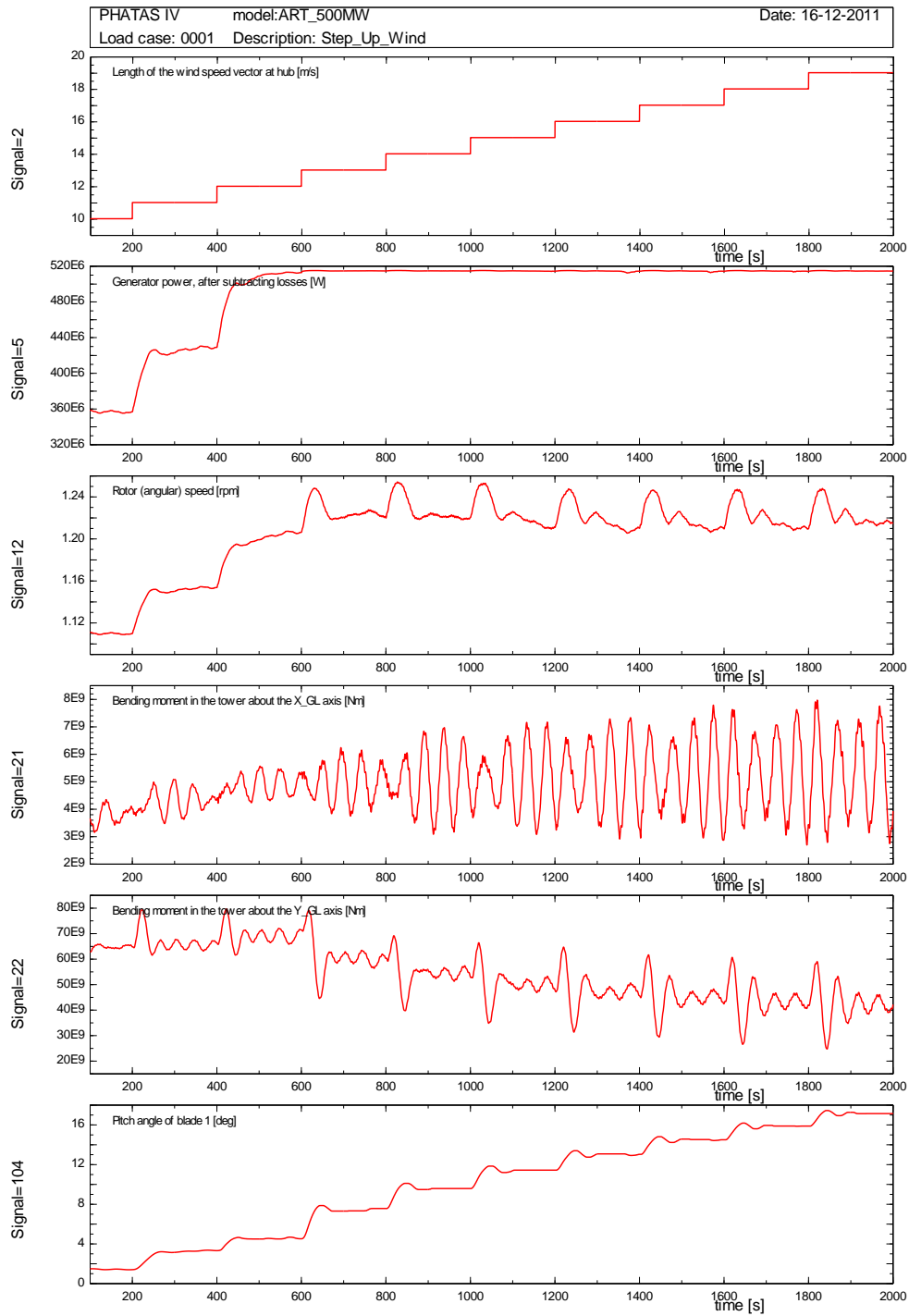


Figure 8 Response of 500MW ART5 turbine on stepwise wind calculated with “APR-2005o”.

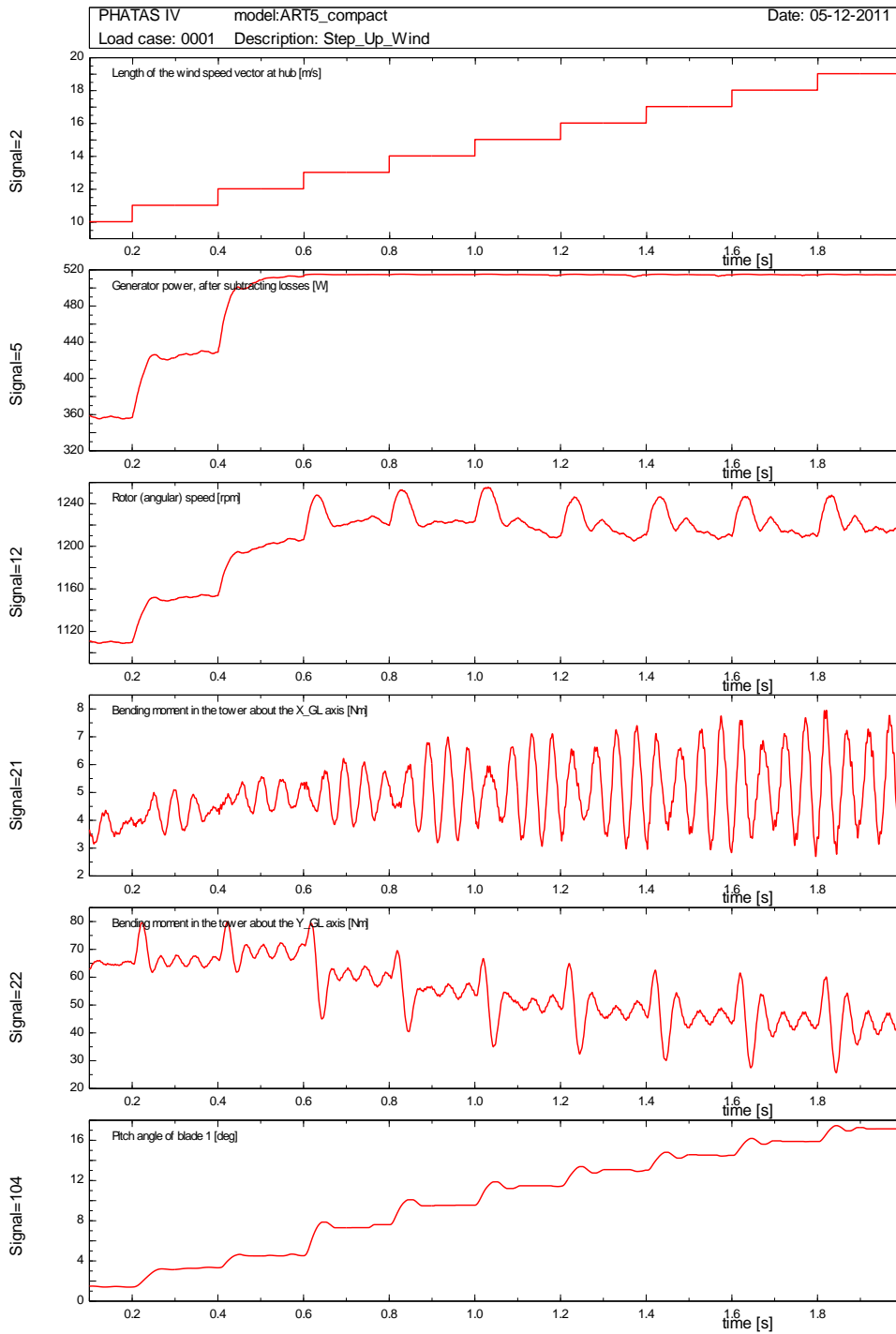


Figure 9 Response of 500W ART5 wind turbine on stepwise wind calculated with “APR-2005o”.

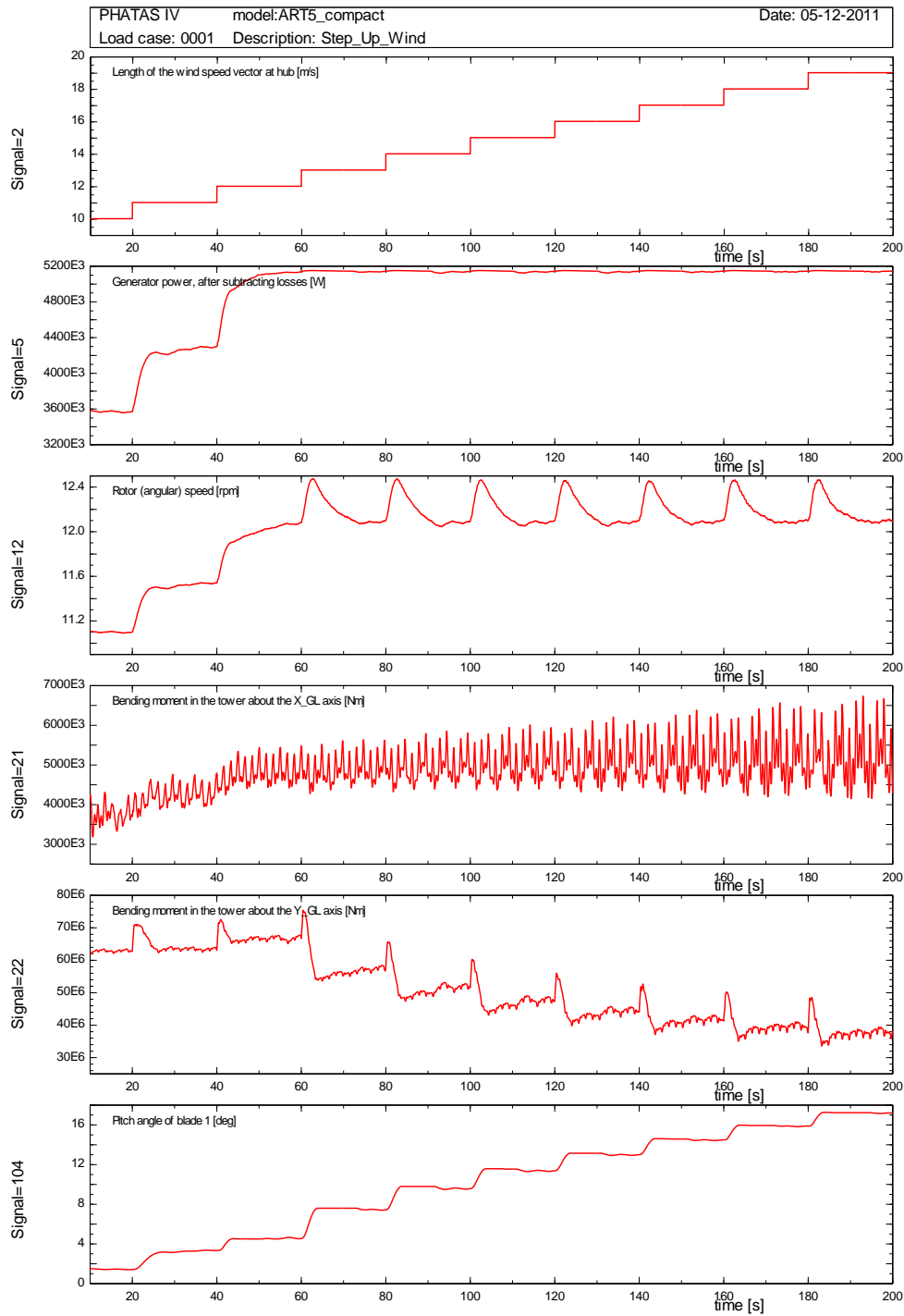


Figure 10 Response of ART5 wind turbine on stepwise wind calculated with 'WTmodule.dll'.

5. Comparison of fatigue load set properties

A Class IIA Fatigue load set following IEC ed.2 [4] is being calculated.

This load set is not calculated for the 10x up-scaled and the 100x down-scaled versions of the ART5 wind turbine model, because the load case input files that are generated with 'lcrep' do not scale in all properties with wind turbine dimension. This means for example that the time period of the gusts is independent from wind turbine dimension following IEC ed.2 [4].

Table 3 *Some of the statistical properties of the production load cases.*

	“APR-2005n”	“APR-2005o”	Wind Turbine module
Maximum rotor speed [rpm]	13.846 (0240)	13.850 (0240)	13.871 (0222)
Maximum axial force [kN]	878.5 (0132)	879.9 (0120)	911.4 (0152)
Maximum tip displacement [m]	6.665 (0150)	6.646 (0150)	6.624 (0150)
Smallest tip-tower clearance [m]	5.237 (0120)	5.245 (0120)	5.090 (0120)
Maximum pitch rate [deg/s]	2.848 (0240)	2.855 (0240)	2.582 (0240)
Maximum top acceleration [m/s ²]	1.7761 (0240)	1.7717 (0250)	Tower is rigid

The numbers between brackets are the load case numbers for which the value is traced.

Except for the maximum tower top acceleration, these largest/smallest properties from release “APR-2005n” and “APR-2005o” were found for the same load case. To some extent this is also the case for the largest production properties that are calculated with the Wind Turbine module.

The statistical properties of release “APR-2005n” and “APR-2005o” show differences. The largest blade deformation seems to be a bit stronger when calculated with release “APR-2005o”. This is due to the fact that release “APR-2005o” has a better solver for the dynamic equations for blade bending, and consequently gives better converged solutions. With these “better converged” solutions the controller input for rotor speed is slightly smoother and the controller actions generally tend to exceed the “threshold value” somewhat later.

The calculations with the Wind Turbine module are still done without modelling tower bending. The ‘rigid’ model for tower dynamics gives a larger axial force, and likewise a smaller minimum tower clearance. It is surprising that the maximum tip displacement for the rigid tower is somewhat smaller.

For some locations in the wind turbine model the $5 \cdot 10^6$ fatigue equivalent load cycles are calculated. For the steel parts the $5 \cdot 10^6$ equivalent cycles were calculated for a Goodman damage relation with slope parameter $m = 4$. For the composite blade root the $10 \cdot 10^6$ equivalent cycles were calculated with a slope parameter of $m = 9$.

Table 4 *Some of the fatigue equivalent bending moment cycles.*

	“APR-2005n”	“APR-2005o”	Wind Turbine module
Tower base bending Mx [kNm]	40483	40131	29400
Tower base bending My [kNm]	67549	67557	60168
Tower top bending Mx [kNm]	2610	2621	2560
Tower top bending My [kNm]	12231	12213	12273
Tower top bending Mz [kNm]	12928	12917	12186
Shaft bending My [kNm]	14443	14445	14779
Shaft bending Mz [kNm]	14397	14388	14782
Flatwise blade bending My [kNm]	10420	10405	10481
Edgewise blade bending Mx [kNm]	9843	9869	10009
Blade torsion Mz [kNm]	159.03	157.05	159.0

The fatigue equivalent bending moment cycles for the fatigue load sets calculated with the different versions appear to be similar. The fatigue equivalent tower base bending moment cycles calculated with the Wind Turbine module are smaller because tower dynamics are not included.

6. Concluding remarks

From the calculated results reported here the following conclusions can be drawn:

- The agreement of the aerodynamic rotor coefficients reported in Chapter 2 shows that the aerodynamic modelling of the Phatas versions and the Wind Turbine module is equivalent. The aerodynamic performance from the Wind Turbine module is slightly smaller (less than 0.1%) which is not resolved. The fact that the largest aerodynamic power coefficients were obtained for the same tip speed ratio indicates that the aerodynamic modelling of the Wind Turbine module is reliable enough for evaluation of different wind turbine concepts.
- From the similarity of the flutter speed reported in Chapter 3 it follows that the aeroelastic modelling of the rotor blades is to a high extent equivalent. The flutter speed calculated with release “APR-2005n” is somewhat different which is because this release contains some deficiencies in the description of the 3/4chord inflow velocity. These deficiencies are corrected in Phatas release “APR-2005o” and the Wind Turbine module.
- The response on a stepwise increasing wind as reported in Chapter 4 shows that the controller interaction of the different Phatas versions is equal. Differences are found for the Wind Turbine module (Figure 10) which is due to the omission of tower dynamics. This has been verified by calculations with release “APR-2005o” in which the tower dynamics were excluded, for which the response was similar to that of the Wind Turbine module.
- The similarity of the scaled performance and response for the 10X and 0.01X scaled wind turbine models shows that the results from Phatas are robust and insensitive for changes in wind turbine dimensions.
- The properties of the calculated fatigue load set (Chapter 5) are similar for the different Phatas versions. The fatigue equivalent bending moment cycles in the tower base calculated with the Wind Turbine module are different because this is without tower bending.

In general it is shown that Phatas release “APR-2005o” is to a high extent equivalent to the former release “APR-2005n”. The Wind Turbine module also gives equivalent results as long as tower dynamics are not included.

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Appendix A. The ART5 turbine model used for the verifications

The ART5 rotor model was developed by Koen Boorsma. The basis of this development was the former Dowec 6MW wind turbine model and the 5MW RWT model of the UpWind project. The development of the ART5 rotor model aimed at an aerodynamic rotor design that is more representative for well-designed modern wind turbine rotors.

The rated rotational speed is 12.1rpm and the rated generator power is 5MW.

A.1 Specific settings for the ‘compact’ ART5 model used here.

The tables with input properties are condensed such that the tables with blade properties and with the generator Q-n curve does not contain more than 12 records. This ‘compact’ model was edited such that the overall properties of the rotor such as mass, aerodynamic properties, and blade frequencies are conserved to a large extent.

For the purpose of verification and also for the purpose of demonstrations and courses this compact model is also sufficient and maybe more ‘handsome’.

The tower is a tubular tower of 107.6m long. With 20.0m water depth and 2.4m ‘hub_location’ the ‘hub_height’ of the ART5 model is 90.0m above the water level.

The foundation flexibility is modelled with a rotation-stiffness of $4.5E+10$ Nm/rad.

Tower dynamics are modelled with ‘bending_modes 3’. For conventional land-based wind turbine this input is set to 2. For calculations including wave loading on the tower more modes are used to give a realistic dynamic response.

The smallest rotor speed of the generator torque-speed curve is increased to 5.0rpm. This is necessary to avoid excitation of the tower bending by the 3P blade passing.

The controller is modelled with the ‘internal’ P-D algorithm of Phatas for pitch-to-vane controlled variable speed wind turbines. The pitch angle in partial load was set to 1.0deg, which is the value with the largest calculated C_p . The full-load controller settings are:

- No of pulses on the speed sensor: 8192.
- Eccentricity of the speed sensor: 0.0005.
- Average time on input of rotor speed: 0.8s.
- Proportional gain: 0.3.
- Differential gain: 2.0.
- Gain scheduling factor: 0.16.
- Threshold value: 0.5deg/s.
- Delay of the pitch actuator: 0.1s; modelled with first order differential equation.
- Maximum pitch control rate: 5.0deg/s.
- Maximum pitch control acceleration: 6.0deg/s².

Prior to entering the full-load operating state, the blades are pitched slightly to vane to reduce the axial aerodynamic forces near rated conditions. This ‘peak shaving’ pitch strategy starts at 11.0rpm and ends at 11.8rpm with a 4.5deg blade pitch angle.

Blade torsion is modelled. In the conventional design process blade torsion is not required so far, but for rotors with a diameter more than 100m analyses including blade torsion are generally done to investigate the aeroelastic stability.

The time increment is 0.02s, which is sufficient to describe dynamics up to the second blade flapping mode and the ‘collective edgewise’ mode. The latter mode is also known as ‘drive train’ mode.

The blade is modelled with 23 elements, which gives an 'AIRFOIL MATCHING' of 0.975. The value of the 'AIRFOIL MATCHING' is listed by Phatas in the *.mdl file. Blade models with 14, 17, and 20 elements also give a good 'AIRFOIL MATCHING'.

A.2 Specific ART5 model inputs for the Wind Turbine module

The wind turbine module 'WTmodule.dll' can not read the 'tubular-type of input format for the tower properties. Instead 'WTmodule.dll' expects a mass and stiffness matrix and a table with modal properties for the so-called Crag-Bampton modes.

For a rigid foundation an analysis of the ART5 turbine was done with Phatas release "APR-2005o". The resulting output file with tower properties 'towmod.out' contains also the Craig-Bampton type of modal properties of the tower dynamics. With these properties a tower input file was modelled. This input file was used for the calculations with the program 'wtquake.exe' and 'wtmodule.dll'.

Appendix B. Scaled input models of the ART5 turbine model

For verification of the wind turbine design tools it was decided to include analyses with an up-scaled and a down-scaled model of an existing wind turbine. These analyses show:

1. Whether the design tools such as Phatas do not run into overflow or underflow. This includes the post processor and to some extent the load case preprocessor.
2. Whether the calculated results remain the same after ‘scaling back’.

Initially one may think that a 10 times up-scaled version and a 10 times down-scaled version of an existing wind turbine gives sufficient proof of the robustness of an analysis program for variation of dimensions. Assuming that analysis programs such as Phatas are used to analyse results from wind tunnel measurements for turbine models of the scale of 1 m diameter it was chosen to scale the ART5 turbine model down with factor 100.

The resulting down-scaled rotor diameter is then 1.28m.

When scaling the dimensions of the ART5 rotor all material properties (mass density, Young’s modulus of elasticity etcetera) are kept constant. The aerodynamics have the same characteristics by scaling all velocities down with factor 10, and likewise “stretching” the time scale with factor 10. The resulting structural dynamic response is only comparable (after scaling) if the gravity constant is divided with a factor 10. The latter is done in a specific Phatas release. Verification with a 10 times up-scaled model shows whether the numerical model will not run into e.g. overflow and whether the results for large (future) rotors are still consistent.

A similar approach is used for scaling the ART5 rotor with a factor 0.01, for which a specific Phatas code has to be compiled with a gravity constant of 981.0m/s^2 .

The following pages show the Phatas output files ‘wtdat4control.txt’ from Phatas release “APR-2005o” that contain the global turbine properties that can be used for the design of the controller. These files are from the calculation of the response on stepwise increasing wind as reported in Chapter 4. These files are listed for the scaled versions of the ART5 turbine and for the un-scaled model as output from the different Phatas releases.

```

# PHATAS-4
# Release:      APR-2005n Stand.
# Model_identif: ART5_compact
# Turbine properties meant for controller design.
rated_rotorspeed      1.21000E+01 < [rpm]
rotor_radius          6.41389E+01 < [m]
rotor_inertia         3.79645E+07 < [kg*m^2]
drive_inertia         5.02441E+06 < [kg*m^2]
shaft_torsion_stiff  1.00000E+30 < [Nm/rad]
flap_frequency        6.99858E-01 < [Hz]
reaction_less_edge    1.04749E+00 < [Hz]
collective_edge       2.08967E+00 < [Hz]
tower_top_mass        4.37108E+05 < [kg]
tower_top_stiffness   9.39950E+05 < [N/m]
tower_height          8.76000E+01 < [m]
hub_height            9.00000E+01 < [m]
tower_top_diameter    3.87000E+00 < [m]
tower_diam_at_tip     5.56631E+00 < [m]
tilt_angle            5.00000E+00 < [deg]
rotor_distance        5.02000E+00 < [m]
cone_angle            -2.50000E+00 < [deg]
gear_ratio            9.70000E+01 < [.]
constant_loss         5.00000E+01 < [Nm]
proportional_loss     0.00000E+00 < [.]
pitch_time_lag        1.00000E-01 < [s]
generator_time_lag    0.00000E+00 < [s]
min_pitch_angle       1.00000E+00 < [deg]
max_pitch_angle       9.00000E+01 < [deg]
max_pitch_rate        5.00000E+00 < [deg/s]
max_pitch_acceler     6.00000E+00 < [deg/(s^2)]
air_density           1.22500E+00 < [kg/(m^3)]
shear_type            2
shear_parameter        1.42900E-01 < [.]
rated_power           5.00000E+06 < [W]

```

Figure 11 File 'wdata4control.txt' for the ART5 rotor, as output of release "APR-2005n".

```

# PHATAS-4
# Release:      APR-2005o Stand.
# Model_identif: ART5_compact
# Turbine properties meant for controller design.
rated_rotorspeed      1.21000E+01 < [rpm]
rotor_radius          6.41389E+01 < [m]
rotor_inertia         3.79646E+07 < [kg*m^2]
drive_inertia         5.02441E+06 < [kg*m^2]
shaft_torsion_stiff  1.00000E+30 < [Nm/rad]
flap_frequency        6.96531E-01 < [Hz]
reaction_less_edge    1.07560E+00 < [Hz]
collective_edge       2.14170E+00 < [Hz]
tower_top_mass        4.36746E+05 < [kg]
tower_top_stiffness   9.40477E+05 < [N/m]
tower_height          8.76000E+01 < [m]
hub_height            9.00000E+01 < [m]
tower_top_diameter    3.87000E+00 < [m]
tower_diam_at_tip     5.56631E+00 < [m]
tilt_angle            5.00000E+00 < [deg]
rotor_distance        5.02000E+00 < [m]
cone_angle            -2.50000E+00 < [deg]
gear_ratio            9.70000E+01 < [.]
constant_loss         5.00000E+01 < [Nm]
proportional_loss     0.00000E+00 < [.]
pitch_time_lag        1.00000E-01 < [s]
generator_time_lag    0.00000E+00 < [s]
min_pitch_angle       1.00000E+00 < [deg]
max_pitch_angle       9.00000E+01 < [deg]
max_pitch_rate        5.00000E+00 < [deg/s]
max_pitch_acceler    6.00000E+00 < [deg/(s^2)]
air_density           1.22500E+00 < [kg/(m^3)]
shear_type            2
shear_parameter       1.42900E-01 < [.]
rated_power           5.00000E+06 < [W]

```

Figure 12 File 'wldata4control.txt' for the ART5 rotor, as output of release "APR-2005o".

```

# PHATAS-4
# Model_identif: ART_500MW
# Turbine properties meant for controller design.
rated_rotorspeed      1.21000E+00 < [rpm]
rotor_radius          6.41389E+02 < [m]
rotor_inertia         3.79646E+12 < [kg*m^2]
drive_inertia         5.02441E+11 < [kg*m^2]
shaft_torsion_stiff  1.00000E+30 < [Nm/rad]
flap_frequency        6.96518E-02 < [Hz]
reaction_less_edge    1.07558E-01 < [Hz]
collective_edge       2.14165E-01 < [Hz]
tower_top_mass        4.37112E+08 < [kg]
tower_top_stiffness   9.39969E+06 < [N/m]
tower_height          8.76000E+02 < [m]
hub_height            9.00000E+02 < [m]
tower_top_diameter    3.87000E+01 < [m]
tower_diam_at_tip     5.56631E+01 < [m]
tilt_angle            5.00000E+00 < [deg]
rotor_distance        5.02000E+01 < [m]
cone_angle            -2.50000E+00 < [deg]
gear_ratio            9.70000E+01 < [.]
constant_loss         5.00000E+04 < [Nm]
proportional_loss     0.00000E+00 < [.]
pitch_time_lag        1.00000E+00 < [s]
generator_time_lag    0.00000E+00 < [s]
min_pitch_angle       1.00000E+00 < [deg]
max_pitch_angle       9.00000E+01 < [deg]
max_pitch_rate        5.00000E-01 < [deg/s]
max_pitch_acceler     6.00000E-02 < [deg/(s^2)]
air_density           1.22500E+00 < [kg/(m^3)]
shear_type            2
shear_parameter       1.42900E-01 < [.]
rated_power           5.00000E+08 < [W]

```

Figure 13 File 'wdata4control.txt' for the 10x scaled ART5 rotor, from release "APR-2005o".


```

# PHATAS-4
# Release:      APR-2005o Stand.
# Model_identif: ART5_compact
# Turbine properties meant for controller design.
rated_rotorspeed      1.21000E+03    < [rpm]
rotor_radius          6.41389E-01    < [m]
rotor_inertia         3.79646E-03    < [kg*m^2]
drive_inertia         5.02441E-04    < [kg*m^2]
shaft_torsion_stiff  1.00000E+30    < [Nm/rad]
flap_frequency        6.96533E+01    < [Hz]
reaction_less_edge    1.07556E+02    < [Hz]
collective_edge       2.14168E+02    < [Hz]
tower_top_mass        4.37107E-01    < [kg]
tower_top_stiffness   9.39950E+03    < [N/m]
tower_height          8.76000E-01    < [m]
hub_height            9.00000E-01    < [m]
tower_top_diameter    3.87000E-02    < [m]
tower_diam_at_tip     5.56631E-02    < [m]
tilt_angle            5.00000E+00    < [deg]
rotor_distance        5.02000E-02    < [m]
cone_angle            -2.50000E+00    < [deg]
gear_ratio            9.70000E+01    < [.]
constant_loss         0.00000E+00    < [Nm]
proportional_loss     0.00000E+00    < [.]
pitch_time_lag        1.00000E-03    < [s]
generator_time_lag    0.00000E+00    < [s]
min_pitch_angle       1.00000E+00    < [deg]
max_pitch_angle       9.00000E+01    < [deg]
max_pitch_rate        5.00000E+02    < [deg/s]
max_pitch_acceler    6.00000E+04    < [deg/(s^2)]
air_density           1.22500E+00    < [kg/(m^3)]
shear_type            2
shear_parameter       1.42900E-01    < [.]
rated_power           5.00000E+02    < [W]

```

Figure 14 File 'wtdata4control.txt' for the 0.01x scaled ART5 rotor, from release "APR-2005o".

```

# PHATAS-4
# Release:      APR-2005q Module
# Model_identif: ART5_compact
# Turbine properties meant for controller design.
rated_rotorspeed      1.21000E+01 < [rpm]
rotor_radius          6.41389E+01 < [m]
rotor_inertia         3.79646E+07 < [kg*m^2]
drive_inertia         5.02441E+06 < [kg*m^2]
shaft_torsion_stiff   1.00000E+30 < [Nm/rad]
flap_frequency        6.96531E-01 < [Hz]
reaction_less_edge    1.07560E+00 < [Hz]
collective_edge       2.14170E+00 < [Hz]
tower_top_mass        4.36532E+05 < [kg]
tower_top_stiffness   9.87886E+05 < [N/m]
tower_height          8.76000E+01 < [m]
hub_height            9.00000E+01 < [m]
tower_top_diameter    3.87000E+00 < [m]
tower_diam_at_tip     5.56633E+00 < [m]
tilt_angle            5.00000E+00 < [deg]
rotor_distance        5.02000E+00 < [m]
cone_angle            -2.50000E+00 < [deg]
gear_ratio            9.70000E+01 < [.]
constant_loss         8.29444E+04 < [Nm]
proportional_loss     0.00000E+00 < [.]
pitch_time_lag        1.00000E-01 < [s]
generator_time_lag    0.00000E+00 < [s]
min_pitch_angle       1.00000E+00 < [deg]
max_pitch_angle       9.00000E+01 < [deg]
max_pitch_rate        5.00000E+00 < [deg/s]
max_pitch_acceler     6.00000E+00 < [deg/(s^2)]
air_density           1.22500E+00 < [kg/(m^3)]
shear_type            2
shear_parameter        1.42900E-01 < [.]
rated_power           5.00000E+06 < [W]

```

Figure 15 File 'wdata4control.txt' for the ART5 rotor, as output of the Wind Turbine module.