Comparison of Aerodynamic Models for Calculation of Fatigue Loads in Turbulent Inflow
Deliverable 4.6

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1 Introduction

The present deliverable is part of AVATAR Task 4.2: Aeroelastic analysis of the reference wind turbine which constitutes a comparison platform of different aero-elastic models. The aim is to assess the prediction capabilities of the existing tools based on code to code comparisons. The main focus is on the aerodynamic aspect of the modeling. BEM, Hybrid and Vortex based aero-elastic tools are participating in this exercise. In the present document fatigue loads in turbulent inflow are considered.

First section 2 describes the load cases under consideration for this case. The codes used for the current exercise are highlighted in section 3. The results are discussed in section 4, followed by the conclusions in section 5.


2 Load case description

Both the AVATAR and INNWIND turbines have been modeled for a variety of wind speeds throughout the operational domain. The turbines (including structural flexibility of blades, tower etc.) were modeled in accordance with the specified descriptions. Both turbines are rated at 10MW, but the AVATAR rotor features a lower power density at a diameter of 205.76m where the INNWIND turbine features a diameter of 178.54m.

2.1 Controller

Both turbines are regulated using variable speed (collective) pitch to vane control. Care has been taken to ensure that all participants use the same controller. Therefore ECN has distributed source code as well as a compiled version of the controllers for the turbines under consideration amongst the participants. Nonetheless small differences in implementation can still occur. Even if the same controller is used, a different aerodynamic model will results in different pitch/rpm set-points making a time domain comparison rather difficult.

Although these differences are then processed by the aerodynamic model, it is hard to draw conclusions on whether the output differences are solely due to the aerodynamic models or there is a combined effect. Because of the stochastic nature of the wind, we would run into the problem of unrealistic simulations if we were to specify a constant rpm and pitch angle. Therefore ECN has also provided source code and DLLs of a controller that prescribes rpm and pitch angle as a function of time. The specific series have been produced by BEM simulations and provided by ECN for every test case. In order to ensure a similar initialization amongst the different codes, it was recommended to adjust the starting values of rotational speed and pitch angle in accordance to the time signal provided and start the simulation at zero azimuth angle.

2.2 Wind

The stochastic wind will largely be in agreement with IEC 61400-3, using the Kaimal turbulence model, class A, NTM, the default shear profile and 8° uptilt angle of the wind. Since the AVATAR and INNWIND turbine feature different hub heights and rated wind speeds, separate wind files have been provided for the two turbines. The length of the wind file is kept to 600 seconds. The time step of the wind files will be set to 0.01 s to allow for sufficient temporal resolution in the aero-elastic calculations. The averaged wind speed conditions are distributed between cut-in and cut-out conditions in steps of around 3 m/s, including the rated wind speed. One seed per wind speed condition has been provided. The wind files are generated using Turbsim in Full-Field Bladed-Style Binary format.

In addition to the stochastic wind simulations, a simulation with a constant hub height wind at 8 m/s (normal shear with power law exponent 0.2 and 8° uptilt) was performed for the AVATAR turbine to eradicate input/output errors and verify controller implementation. A summary of the load cases highlighting participant contributions is given in Table

3
Table 1: Load case summary

<table>
<thead>
<tr>
<th>Mean wind speed [m/s]</th>
<th>Normal controller BEM3</th>
<th>VRX3</th>
<th>BEM2</th>
<th>BEM1</th>
<th>VRX1</th>
<th>Prescribed rpm and pitch BEM3</th>
<th>VRX3</th>
<th>BEM2</th>
<th>BEM1</th>
<th>VRX1</th>
</tr>
</thead>
<tbody>
<tr>
<td>8†</td>
<td>x x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>x x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td>x</td>
<td>x</td>
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<td>-</td>
</tr>
<tr>
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<td>x x</td>
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<td>x</td>
<td>x</td>
<td>x x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
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<td>10.75</td>
<td>x x</td>
<td>x</td>
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<td>x</td>
<td>-</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
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<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>x</td>
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<td>x -</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
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<tr>
<td>20</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x -</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

† Constant wind test case featuring normal shear (power law exponent 0.2) and 8° uptilt

3 Code descriptions

3.1 ECN

The ECN Aero-Module is used as aerodynamic solver for the current investigation. The two aerodynamic models included are the Blade Element Momentum (BEM) method similar to the implementation in PHATAS and a free vortex wake code in the form of AWSM. Both models are lifting line codes, i.e. they make use of aerodynamic look-up tables to evaluate airfoil performance. Several dynamic stall models, 3D correction models, wind modeling options and a module for calculating tower effects are included. The set-up allows to easily switch between the two aerodynamic models whilst keeping the external input the same, which is a prerequisite for a good comparison between them. The package is coupled to the FOCUS-Phatas
simulation software\(^\text{a}\) that solves the structural dynamics of a wind turbine, thus enabling full aero-elastic interaction.

3.1.1 Wake modeling

The ECN dynamic inflow model\(^\text{b}\) has been implemented for usage with the BEM solver. This model adds another term to the axial momentum equation to account for the aerodynamic rotor ‘inertia’ in the case of pitch action, rotational speed variation or wind speed variation. The term is proportional to the time derivative of the annulus averaged axial rotor induction and has a dependency on the radial position.

AWSM models the wake geometry by convection of shed and trailing vorticity as depicted in Figure [1]. Here the trailing vorticity accounts for the effects of spanwise circulation variation, whilst the shed vorticity accounts for the effects of bound vortex variation with time. As a result, effects due to dynamic inflow (e.g. pitch step), shed vorticity (e.g. aero-elastic instabilities), skewed wake, non-uniformities in the rotor plane (e.g. shear, individual pitch, non-coherent gusts) and variation in spanwise circulation (e.g. tip and root effect), are modeled intrinsically, where they are covered by engineering models or not covered at all in BEM.

For a free wake, the wake convection speed at each wake point is determined by the aggregate of the induced velocities from all vortices using the law of Biot and Savart. However, to reduce CPU-time it is also possible to prescribe the convection (Figure [2]) for a specified number of wake points. The current prescription determines convection based on the induced velocity at the blade extrapolated using axial momentum theory. Alternatively it is possible to specify the near wake free and prescribe the far wake convection.

![Figure 1: AWSM wake geometry](image1.png)

![Figure 2: Wake modeling options (con-\text{vective velocity in blue): Top half illustrates fully prescribed wake, lower half partially free/prescribed wake)](image2.png)
Dynamic induction modeling in BEM  As noted above the implemented dynamic inflow model takes into account the effects of wake inertia in case of dynamic variations on a rotor scale (e.g. pitch steps). In order not to average out the effect of inflow variations (e.g. shear, turbulence) on local induction, an unsteady BEM implementation is employed. Here the momentum equation is evaluated locally for each blade instead of balancing the aggregate of all blade element forces within the annulus with the momentum of a full annulus.

3.1.2 Simulation settings

For most of these cases two different aerodynamic solver settings have been applied, namely BEM and AWSM with a hybrid free and prescribed wake. For the hybrid free and prescribed wake option the total wake length was kept to approximately two rotor diameters and the number of free wake points was set to cover approximately one rotor revolution. A full free wake simulation was not performed due to its excessive cpu-time requirements. With the same idea in mind, the time step was kept at the approximate equivalent of 4° azimuth for both the BEM and AWSM simulation (normally less than a degree is used for BEM simulations). The Snel dynamic stall model was applied to all simulations.

3.2 GE

The main characteristics of the model used by GE are as indicated below.

Rotor Aerodynamics

- Airfoil: Table lookup of interpolated polars (AoA). Beddoes-Leishman dynamic stall implementation identical to AeroDyn.
- Wake: Hansen-type BEM
- Prandtl tip loss model
- Hansen-type skewed inflow model
- Oye dynamic wake model
- Glauert high induction correction (Hansen)
- Discretization: 50 blade stations used (station 24 at 50.31m skipped). Linear distribution of pristine airfoil polar properties between blade stations (pristine airfoils positioned radially by t/c).
- Implementation of BEM equations synonymous to AeroDyn, where the aggregate of all blade element within the annulus are balanced with a full annular streamtube.
• Flexibility: Euler-Bernoulli beam; no torsional deformation

• Inertia: a constant term for the overall rotational inertia along pitch axis, independent of deformation

• Discretization: 50 blade stations used (station 24 at 50.31m skipped)

• Linear distribution of properties between blade stations

Solution

• Spatial: Matching at structural stations

• Temporal: Loose coupling, sequential aero-structures, no aero sub-cycling (aerodynamic states concealed from system solver)

3.3 NTUA

NTUA is using the hGAST simulation platform in its version for land based wind turbines. hGAST is a hydro-servo-aero-elastic time domain solver for the fully coupled wind turbine system. For the structural part, a multi-body formulation is applied combined with a sub-body Timoshenko beam model (Figure 3).

Then for the aerodynamic part two options are considered:

1. A BEM model, accounting for dynamic inflow conditions based on the ONERA model. It follows the usual guidelines of BEM modelling. It contains: tip and/or tip losses, 3D correction of the 2D polars (if not included already in the tables), yaw misalignment corrections. Dynamic induction modeling is employed solving the momentum equations separately for each blade.

2. A free-wake 3D model, GenUVP, using vortex particle dynamics (Figure 4). It combines a panel representation of the solid surfaces with a vortex particle approximation of the wake. Solid surfaces can take one of the following representations: non-lifting bodies represented by sources (the tower), open lifting surfaces carrying dipoles and shedding vorticity along their edges (blades), closed lifting surfaces carrying sources and dipoles (thick blades). The evolution of the wake is followed in the Lagrangian formulation of the vorticity including convection and deformation. In the present task the thin blade option is used, while the loads are corrected for viscous effects through the application of the ONERA model in which the so called attached part is directly taken from the flow model. Necessary input to the ONERA model is the effective angle of attack which is determined by the circulation distribution $G$ along the blade:

$$\rho \cdot V \cdot \Gamma = \partial C_L \cdot (\alpha - \alpha_0) \cdot \frac{1}{2} \rho \cdot V^2 \cdot c$$

(1)

Where $\rho$ is the density of air, $V$ is the flow velocity, $\partial C_L$ is the slope of the lift curve, $\alpha, \alpha_0$ are the actual angle of attack and the one of zero lift and $c$ the chord length.
3 CODE DESCRIPTIONS

Figure 3: In the sub-body partitioning of a true component (e.g. the blade), every sub-body is introduced within the context of multi-body dynamics. At the connection points between sub-bodies kinematic and dynamic continuity act as boundary conditions. Thus a specific sub-body by cumulatively receiving the deformations of the previous sub-bodies, will have in its dynamic equations the terms that correspond to large displacements and rotations.

Figure 4: The surface singularity intensities are determined using the non-entry boundary conditions and the pressure Kutta along the emission lines. Upon convection, the surface vorticity of the recently released wake is transformed into vortex particles which are subsequently followed as fluid particles (as shown in the last plot).
A major issue of vortex methods is their cost which increases quadratically with the number of steps (or equivalently the number of vortex particles, i.e. \( N^2 \)). In order to reduce the cost, GenUVP has been parallelized under MPI. Further reduction has been achieved by using the Particle-Mesh (PM) technique rendering the cost proportional to \( N \log N \) (Figure 5).

**Figure 5:** The PM technique: In order to avoid the \( N^2 \) operations that are involved in the particle-to-particle interactions that are calculated by means of the Biot-Savart law, a smooth approximation of the vorticity is defined by projecting the intensity carried by the particles on a uniform rectangular grid (step 1). Then on the grid the Poisson equation for the vector stream function \( \psi \) is solved using a Fast Poisson Solver (step 2). Using finite differences the velocity and deformation are calculated at the grid nodes wherefrom they are back interpolated at the particle locations (step 3).

However, in case of long lasting simulations as those required in the IEC standard, the cost remains prohibitively high for systematic runs. When the interest is in the rotor region, a drastic reduction can be achieved by the "hybrid wake" approximation, Figure 6. The basic idea is to keep in fully active form only a limited part of the wake ("near part") covering a downstream length of 1-2D. Because vorticity must be conserved, it is necessary to also include the effect of the rest of wake in some approximate way. In steady state conditions it can be verified that the effect of the remaining of the wake on the "near" region can be approximated by an extra wake length of 2-3D provided that it contains the starting vortex or equivalently that vorticity is conserved. Clearly during the evolution of the wake, the starting vortex will be convected downstream rotor region and therefore its effect will decay. However as the starting vortex is convected additional vorticity will be added in the wake which will balance this decay and therefore on average the overall effect will remain constant and will correspond to the steady state to be attained. The same will also hold in periodic conditions while in turbulent conditions it is assumed that on average the effect is negligible.
Figure 6: Schematic description of the hybrid wake approximation: The "Hybrid Wake" model. The model has a preparatory phase in which the simulation runs until the wake covers the "near" and "medium" regions corresponding to 1-2D and 2-3D respectively. Over the last rotation of this phase, the effect of the medium region is calculated on the PM grid that covers the rotor and the near-wake regions. Out of the data recorded the mean and 1p variations are stored. Once the preparatory phase is completed, all subsequent time steps are restricted up to the near wake. The particles that exit the near wake region are discarded. In this way the cost of the wake evolution is kept to a reasonable level. In fact the application of the hybrid wake approximation allows performing long full aeroelastic simulation with turbulent wind inflow as defined in the IEC.
4 Results

To monitor differences between the codes, numerous comparison plots were generated. The signals used for this purpose vary from control variables to rotor and tower forces and moments, to sectional loads and induced velocities. For the definition of the signals the reader is referred to appendix A. Various post-processing techniques were applied to further quantify and understand the cause for the differences. A summary of the post-processing techniques applied is given in Table 2. The first 100 seconds of the simulation are disregarded to exclude initialization effects.

Table 2: Summary of applied post-processing

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Time span [s]</th>
<th>Applied settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Time variation (large scale)</td>
<td>100 - 580</td>
<td>-</td>
</tr>
<tr>
<td>Time</td>
<td>Time variation (small scale)</td>
<td>550 - 580</td>
<td>-</td>
</tr>
<tr>
<td>Bin</td>
<td>Bin average wrt azimuth angle</td>
<td>550 - 580</td>
<td>2° bin size</td>
</tr>
<tr>
<td>PSD</td>
<td>Power spectral density</td>
<td>100 - 580</td>
<td>10 blocks, no overlap, no window function</td>
</tr>
<tr>
<td>Stat</td>
<td>Statistics</td>
<td>100 - 580</td>
<td>avg, stdev, min, max†</td>
</tr>
<tr>
<td>EQL</td>
<td>Damage equivalent loads</td>
<td>100 - 580</td>
<td>1Hz equivalent using rainflow counting‡</td>
</tr>
<tr>
<td>EQL</td>
<td>Damage equivalent loads (relative)</td>
<td>100 - 580</td>
<td>relative difference [%] wrt mean of EQL values</td>
</tr>
<tr>
<td>Loop</td>
<td>Local Cl and Cd versus angle of attack</td>
<td>550 - 580</td>
<td>-</td>
</tr>
</tbody>
</table>

† ± standard deviation is indicated using black line on top of average, minimum and maximum are indicated using grey dotted line
‡ slope of SN curve has been taken as 11

Appendix C,D give the Time, Bin, Statistics, EQL and Loop plots for the various comparison cases (selected variables only). It is beyond the scope of this report to display all comparison plots, they can however be downloaded from the AVATAR teamsite at https://www.eera-avatar.eu/do/folder/?id=19921-766f66666f6c.

4.1 Constant wind test case

To eradicate input/output errors, verify controller implementation and detect model differences in constant conditions, simulations were performed using a deterministic wind at 8 m/s (partial load). It can be observed that if the normal controller is used, differences in rotational speed can be observed between the partners, possibly caused by differences in predicted torque (Figure 25). The so called ‘cascade’ effect between torque and rotorspeed will lead to a different equilibrium amongst the
different models. However the trend in torque differences is not in agreement with the trend in rotorspeed, implying other differences also playing a role here (possibly controller implementation). By using the prescribed controller this issue is resolved, as is demonstrated in Figure 53, allowing us to observe the relatively small differences in aerodynamic torque for the same rotorspeed. The time variation of azimuth angle in Figure 51 also shows a good overlay, although small differences remain because of some variance in the initialization settings. Figure 54 shows the wind excitation to be in good agreement between the codes, except for the green line showing a different vertical shear and consequently different load variation in Figures 52 and 53. This has a direct effect on the variation in angle of attack and loading which generates higher flapwise fatigue loads.

In conclusion it is considered that the agreement is fair and that the constant wind test case has served its purpose to align the settings to a satisfactory agreement amongst the codes.

4.2 Stochastic wind

Also for the stochastic wind simulations using the normal controller, the differences in aerodynamics lead to different rotational speed, as shown in Figure 34 for the AVATAR 8 m/s case. Again the prescribed controller resolves this issue (Figure 64), and also the azimuth angle shows a reasonable overlay (Figure 66). Reading in of the turbulent wind file is the same between the codes, judging by the agreement in the hub height wind speed and wind speed as seen by blade 1 at 70%R. However, comparing the resulting flapwise blade fatigue loads show noticeable differences in absolute (Figure 76) as well as relative sense (Figure 77) that were found within a range of +/-10% at blade root. Similar observations can be made in the tower bottom moments and also in the other wind speeds and the INNWIND turbine cases. An overview of the resulting flapwise blade root moment fatigue loads from the several load cases is presented in appendix B.

Zooming in on the cause for the large fatigue load differences observed brings us to the core of the aerodynamic modeling, which is in the rotor induction. Significant differences in dynamic induction modeling can be observed, due to a different implementation of the BEM equations, either calculating momentum equilibrium along a local streamtube or along a full annulus. The latter option tends to average out the high frequency inflow variation between the blades. These modeling differences directly impact the dynamic induction variation both for the inboard (Figure 67) and outboard sections (Figure 68). It can also be observed in these Figures that if the induced velocities track the wind fluctuations better, angle of attack and hence load variations are smaller. Consequently the fatigue loads are reduced as well. The vortex results track the inflow velocity fluctuations even better. The explanation lies in the momentum assumptions inherent to BEM based modeling, which balances the induced velocity field of an entire streamtube with the local blade forces. For a vortex wake model the effect of a different inflow velocity at the blade is treated much more local and hence induced velocities vary more directly with wind speed variations. The loop plots in Figure 78 reveal significant differences in lift and drag modeling due to variation in modeling dynamic and rotational effects. The latter is shown to influences the absolute level of lift and drag for a given angle of attack in the inboard region (30%R). At 30%R the local angle of attack reaches values above stall resulting in dynamic stall loops for some results. For the 70%R section the angle of attack is in the attached flow region but some participants also model shed vorticity variation effects (so called "Theodorsen' effect) by altering the lift and/or drag coefficients from its static value. This effect is implicitly included in the vortex results, without having to alter airfoil coefficient data. The Theodorsen effect is known to introduce 'damping' of force fluctuations, consequently reducing fatigue loads.

Since the flapwise moment consists of aerodynamic, gravitational and inertial force contributions, it is interesting to see that
the aggregate of the fatigue equivalent aerodynamic normal force distribution (Figure 13) does not always agree with the observed trend of the flapwise fatigue moment. This could indicate that structural modeling differences are also significant contributors to the observed fatigue load differences. Large differences in the leadwise fatigue equivalent moment (dominated by gravitational forces) also point in this direction. Furthermore the results that feature a different aerodynamic model but the same structural solver do show consistency between normal force and flapwise moment and a similar leadwise fatigue equivalent moment. It is noted that numerical damping (e.g. due to a different time step or a different coupling between structural dynamics and aerodynamics) can also play a role here. An additional source for differences that influences fatigue loads was observed in the partial load cases of the INNWIND rotor featuring a high thrust coefficient. Here turbulent wake state modeling starts to play a role, which together with the dynamic wind speed variations poses another challenge for BEM type models.
5 Conclusion

Aeroelastic simulations have been performed using aeroelastic solvers of varying complexity. The simulations span the complete operation range of the INNWIND and the AVATAR reference wind turbines in accordance with the DoW. Results have been processed and a selective set of them has been presented in comparative format at different levels.

One of the main conclusions in previous deliverables of T4.2 was that to an important extent, differences in the results originate from the controller. In this connection, care has been taken to isolate the differences in aerodynamic modeling by prescribing rpm and pitch angle variation as a function of time and verifying that the wind speed excitations are identical. However, code differences remain due to differences in the numerical details (numerical damping, time step), structural dynamics and the interaction scheme between structural dynamics and aerodynamics (implicit, explicit etc.).

The simulation results produced in this task show differences up to 20% in the flapwise blade root fatigue loads, which can to a certain extent be attributed to differences in aerodynamic modeling. These differences were shown to translate in the rest of the turbine components. When the rotor speed and pitch were prescribed the difference dropped to 10%.

It is noted that differences exist both between different BEM implementations but also between BEM and vortex models. Vortex models were shown to yield the lowest fatigue loads due to better (more local) tracking of induced velocity variations with inflow variations together with intrinsic modeling of the effect of shed vorticity variation with time, resulting in more aerodynamic damping. It can be stated that the results that feature a different aerodynamic model but have the remainder of the aero-elastic code identical back up the conclusions drawn above.

Since the vortex wake simulations come at a radical increase of cpu-time (factor of 1000), further engineering improvements (wake prescription, reduction of far wake spatial and/or temporal resolution, hybrid BEM vortex methods) could open up the way for a more widely usage of vortex codes by industry for this purpose. Standards would have to be accommodated to take into account the increased accuracy of these methods though, e.g. by reducing corresponding safety factors.

It is believed that the above conclusions are of great significance for the design of large rotors. Acknowledging fatigue loads as an important design driver, improved aerodynamic modeling can contribute significantly to reduced safety factors and lower equivalent loads, paving the way for further reductions in the cost of wind energy. Future work should be put in reaching further consensus and unifying the wind turbine community in which modeling options should be used for load case and aero-elastic stability analysis. An appropriate validation campaign (either in the wind tunnel or the field) is a requirement to reach this goal in the future.
References


A Description of work
AVATAR D4.6 Fatigue loads: Description of work

K. Boorsma (ECN), version 6, 5th August 2016

1 Introduction

The description of work aims at providing a frame of reference for deliverable D4.6. The aim of this task is to compare aerodynamic models for the purpose of fatigue load analysis of the INNWIND.EU and AVATAR RWTs. As such it is important to realize that this work aims at identifying differences between the codes, rather than determining the absolute level of the fatigue loads.

The final report has to contain the following:

1. Description of the DLC cases included for comparison, specification of the test matrix. The cases will be defined according to the IEC standard as regards fatigue. The cases will scan the power production range of wind speeds (from 5-25m/s) with a step of 2-3m/s. The simulations will be run for the same wind fields. The defining parameters for the turbulent wind field will follow the specifications of the IEC standard in which depending on the class turbulent intensity is specified as function of the wind speed.

2. Results from the simulated time series of loads at blade root, tower top and tower bottom. Other sensors could be also included depending on the results which would be readily retrieved from the simulations. Spectrums and equivalent loads will be provided.

3. Discussion on the comparison of results, and evaluation of the differences with respect to their modeling assumptions. An assessment is carried out using the measurable KPI’s from section 1.3.1. (amount of empiricism, calculation time, differences in model results, code robustness and time/knowledge to set-up a calculation).

The analysis will be done using BEM (GE, ECN, NTUA) and Vortex methods (ECN, NTUA) (ECN, GE, NTUA, LM). Please note that other participant than GE, ECN and NTUA are welcome to join in as well.

2 Reference wind turbines

Both INNWIND.EU and AVATAR reference turbine will be simulated in this task. The design specification of the INNWIND rotor is available from the INNWIND project and the relevant information is available on the AVATAR project website. The design specification of the AVATAR reference turbine is also available on the project website.

3 Wind

3.1 Format

The wind files are Turbsim Full-Field Bladed-Style Binary format files. Information on how to read in these files can be found in:
- The relevant NREL/TP-500-39797 documentation (http://www.nrel.gov/docs/fy06osti/39797.pdf, appendix B)
The files with the following extensions will be provided for each wind condition:
- .wnd: Binary file containing the wind that needs to be read in
- .sum: Summary file containing detailed input specifications of the wind file
- .dat: Hub height times series in ASCII format
- .u/.v/.w (shared only for 1 wind condition): Full field turbulence files of the u, v and w component in ASCII format. Please consult p12 of NREL/TP-500-39797 for a description of column orders.

3.2 Specification

The files will largely be in agreement with IEC 61400-3, using the Kaimal turbulence model, class A, NTM, using the default shear profile and 8deg up tilt angle of the wind. Since the AVATAR and INNWIND turbine feature different hub heights and rated wind speeds, separate wind files will be provided for both turbines.

The length of the wind file is kept to 600 seconds. The time step of the wind files will be set to 0.01 s to allow for sufficient temporal resolution in the aero-elastic calculations.

The averaged wind speed conditions will be between cut-in and cut-out conditions in steps of around 3 m/s, including the rated wind speed. One seed per wind speed condition will be provided.

The resulting wind files will be uploaded to the AVATAR EPOS site.

4 Simulation settings

4.1 Simulation length

As indicated in section 3.2, wind files with a length of 600s are provided. The same timespan holds for the required simulation length. Because vortex wake codes need time to initialize the wake, only the results after 100 seconds of the simulation will be used for the comparison. In addition to that the required CPU time for vortex wake codes might complicate running a full 600 second simulation. Therefore, a simulation length of 200s can suffice for these codes if this problem occurs. It is realized that this time span (in combination with number of seeds) is not sufficient to determine representative fatigue loads. However the emphasis lies on the comparison between models, both in the time domain as well as the resulting statistics.

4.2 Controller settings

It was decided to perform a first test case at 8 m/s average wind using the AVATAR rotor with the same controller. The yaw angle will be fixed to zero degree. A stochastic wind simulation is performed for 8 m/s and differences will be identified. Based on these results the controller settings for the remaining simulations are determined.

NTUA has shared their INNWIND controller source code for this purpose. ECN has updated and provided this source code for the AVATAR rotor. Also the compiled DLLs (Bladed style interface) have been provided for these two rotors.
In addition to that ECN has also provided source code and DLLs of a controller that prescribes rpm and pitch angle as a function of time. For this purpose a file called ‘rpm_pitch.dat’ needs to be included in the work directory which contains three columns: time [seconds], rotor rotational speed [rpm] and collective pitch angle [deg]. This file is provided by ECN for each test case, where values are based on a BEM simulation. To ensure a similar initialization between the different codes, it is recommended to adjust the starting values of rotational speed and pitch angle in accordance with the first row of the file ‘rpm_pitch.dat’.

4.3

5 Planning

17/05/2016 Distribution of updated description of work DoW (ECN)
01/06/2016 First iteration at 8 m/s wind, AVATAR rotor to eradicate input/output errors (All, ECN to compare results)
08/06/2016 Discussion of first iteration results at AVATAR meeting (Glasgow) and determination of further course of action
21/06/2016 Distribution of wind files for all speeds (INNWIND and AVATAR turbine) (ECN)
01/07/2016 Delivery of updated 8m/s results, sharing of comparison figures (All, ECN)
08/07/2016 Discussion of 8m/s results, possibly by telcon (All)
22/07/2016 Delivery of results for all wind speeds (Vortex results possibly added later) (All)
22/07/2016 Text input (code descriptions and settings) (All)
29/07/2016 Figures shared on teamsite (ECN)
05/08/2016 First version of report (ECN)
12/08/2016 Feedback and comments (All)
31/08/2016 Upload of report to EU server (ECN)
# Simulation scenario

<table>
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<th>AVG Wind speed [m/s]</th>
<th>Controller on</th>
<th>Prescribed rpm and pitch</th>
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<td></td>
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<tr>
<td>BEM</td>
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<td>BEM</td>
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<tr>
<td>8</td>
<td>X</td>
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<td>24</td>
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</table>

**Comment:** *constant wind with shear and uptilt*
7 Contents of the report

1. Description of the aerodynamic models that are used together with the structural model used in the aero-elastic tool of each partner
2. Description of the simulation cases and setup of each partner
3. Required simulation results by the report. Comparison of
   - Time series
   - Azimuth averages
   - Spectra
   - Statistics (avg, std, min, max)
   - Damage equivalent loads
4. Discussion regarding the code-to-code comparison of the aero-elastic results. An assessment is carried out using the taking into account the amount of empiricism, calculation time, differences in model results, code robustness and time/knowledge to set-up a calculation. Coordinate systems and output file structure
8 Output signal definition

Coordinate systems for the data output

8.1 Tower outputs coordinate system

Name of output variables in this frame:
Tower Mx   Tower Dx
Tower My   Tower Dy
Tower Mz
Tower Fx
Tower Fy
Tower Fz

Figure 1: Definition of the tower coordinate system

Tower coordinate system description: The vertical plane is defined by y-axis and z-axis in which the zero yaw and the wind direction are defined. For the tower, the “Flap” deflection and moment are also referenced as “Fore-Aft” is defined around x-axis. Fore-aft bending moment is named as “Mx”. The “Lag” deflection and moment as “Side-to-side” is defined around y-axis. The side-to-side bending moment is named as “My”. The torsional angle and moment is defined around z-axis and named as “Mz”. Fx, Fy and Fz are self-explained in Figure 1, which define the forces in x, y and z directions. “Dx” and “Dy” are the deflection in x and y direction.

Note: For a right-hand system the tower “Fore-aft” moment will be negative for a positive tower “Flap” deflection. In this simulation, “tower top” for AVATAR turbine is at 123.6 m.

8.2 Drive train output coordinate system

The output results on drive train are defined in the fixed reference frame as shown in Figure 2.
Drive Train coordinate system description: For the drive train torsion moment (Mz) is defined along the shaft axis. Positive torsion moment is around z-axis. The bending moment (My) is defined in the plane normal to the shaft axis. The positive bending moment (My) is around negative y-axis. $F_z$ is the force along the drive train in the direction of z-axis. Fx and Fy are in the plane perpendicular to z-axis. The original point of drive train coordinate (x-y-z) is at the intersection point between shaft and tower top.

Note: This definition of the original point of the drivetrain coordinate system (x-y-z) is consistent with the HAWC2 convention.

8.3 Blade output coordinate system

Blade coordinate system description: In BEM methods, the analysis can be either referred to the blade system (x-y-z) or the rotor disk system (α-β-γ) (See Error! Reference source not found.). In this report, the outputs of the blade structure loads and deflections should be in blade coordinate system (x-y-z). The original point of the blade coordinate system is at the blade root aligns with the pitch axis and coincides with the pitch centre. No pitch and twist are included.

Name of output variables in this frame:
- Blade Mx
- Blade My
- Blade Mz
- Blade Dx
- Blade Dy
- Blade theta_x
- Blade theta_y
- Blade theta_z
The blade flap-wise (out-of-plane) moment is around y-axis and named as “My”. The blade edgewise (in-plane) moment is around x-axis and named as “Mx”. The blade torsion moment is around z-axis and named as “Mz”. Fx, Fy and Fz are self-explained in Figure 3. “theta_x”, “theta_y” and “theta_z” are the three rotational angles around x,y,z-axis respectively. “Dx” and “Dy” are the deflection in x and y direction.

Note: Zero azimuth angle is defined when blade 1 points to the upward.

The aerodynamic information outputs are given in the blade cross section coordinate system shown in Figure 4.

Sensor list and format of the result text file

Each partner should deliver one text file which contains all the sensors in different columns. Each name of the record field/column is listed below. The data are in time domain with the useful simulation time 60 seconds with all the initial transients removed. The columns of the text file should be separated with the blanks (or TAB). The units of each sensor are also listed together with the name of each column. The post processing into azimuth averaged data, min-mean-max will be done when I make the final plots.

1 Time [s] (time should be in accordance with time setting of wind file, i.e. please donot apply shift due to initialization)
2 Azimuth of blade 1 [deg] (zero angle is with blade 1 pointing upwards and shaft x also pointing upwards)
3 Tower Mx, z=0m [kNm]
<p>| | |</p>
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<td>Tower My, $z=0$ m [kNm]</td>
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<td>5</td>
<td>Tower Mz, $z=0$ m [kNm]</td>
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<td>Tower Fz, $z=0$ m [kN]</td>
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63  Blade r=95%, Cn [-]
64  Blade r=95%, Ct [-]
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66  Aerodynamic Torque [kNm]
67  Aerodynamic Power [kW]
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Blade r=95%, My [kNm]
Blade r=95%, Mz [kNm]
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<td>lateral wind speed v @ 70%R blade 1 as read in from wind file (-x direction of Fig. 1) [m/s]</td>
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*Chord normal force means the force perpendicular to the local chord direction.
B  Flapwise equivalent moments

B.1  AVATAR turbine, normal control

Figure 7: Flapwise equivalent moments, AVATAR turbine, normal control (absolute levels)
Figure 8: Flapwise equivalent moments, AVATAR turbine, normal control (absolute levels)
Figure 9: Flapwise equivalent moments, AVATAR turbine, normal control (relative levels)
Figure 10: Flapwise equivalent moments, AVATAR turbine, normal control (relative levels)
B  FLAPWISE EQUIVALENT MOMENTS
B.2 AVATAR turbine, prescribed control

Figure 11: Flapwise equivalent moments, AVATAR turbine, prescribed control (absolute levels)
Figure 12: Flapwise equivalent moments, AVATAR turbine, prescribed control (absolute levels)
Figure 13: Flapwise equivalent moments, AVATAR turbine, prescribed control (relative levels)
Figure 14: Flapwise equivalent moments, AVATAR turbine, prescribed control (relative levels)
B FLAPWISE EQUIVALENT MOMENTS
B.3 INNWIND turbine, normal control

Figure 15: Flapwise equivalent moments, INNWIND turbine, normal control (absolute levels)
Figure 16: Flapwise equivalent moments, INNWIND turbine, normal control (absolute levels)
Figure 17: Flapwise equivalent moments, INNWIND turbine, normal control (relative levels)
Figure 18: Flapwise equivalent moments, INNWIND turbine, normal control (relative levels)
C Sample results for AVATAR rotor, normal controller

C.1 8 m/s constant wind

C.1.1 Time

Figure 19: Time plot, AVATAR turbine, normal control, 8 m/s constant wind (1)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

(a) Aerodynamic axial force

(b) Aerodynamic torque

(c) Flapwise blade root moment

Figure 20: Time plot, AVATAR turbine, normal control, 8 m/s constant wind (2)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

Figure 21: Time plot, AVATAR turbine, normal control, 8 m/s constant wind (3)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

(a) Axial induced velocity, 30%R

(b) Angle of attack, 30%R

(c) Normal force, 30%R

Figure 22: Time plot, AVATAR turbine, normal control, 8 m/s constant wind (4)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

(a) Axial induced velocity, 70%R

(b) Angle of attack, 70%R

(c) Normal force, 70%R

Figure 23: Time plot, AVATAR turbine, normal control, 8 m/s constant wind (5)
C.1.2 Bin

(a) Hub height wind speed
(b) Axial wind velocity @ 70%R
(c) Lateral wind velocity @ 70%R
(d) Vertical wind velocity @ 70%R

Figure 24: Bin plot, AVATAR turbine, normal control, 8 m/s constant wind
SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

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C.1.3 Statistics

Figure 25: Statistics, AVATAR turbine, normal control, 8 m/s constant wind (1)
Figure 26: Statistics, AVATAR turbine, normal control, 8 m/s constant wind (2)
Figure 27: Statistics, AVATAR turbine, normal control, 8 m/s constant wind (3)
Figure 28: Statistics, AVATAR turbine, normal control, 8 m/s constant wind (4)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER
C.1.4 Fatigue loads

Figure 29: Equivalent loads, AVATAR turbine, normal control, 8 m/s constant wind (1)
Figure 30: Relative difference between equivalent loads, AVATAR turbine, normal control, 8 m/s constant wind (1)
Figure 31: Equivalent loads, AVATAR turbine, normal control, 8 m/s constant wind (2)
Figure 32: Relative difference between equivalent loads, AVATAR turbine, normal control, 8 m/s constant wind (2)
C.1.5 Loops

Figure 33: Loops, AVATAR turbine, normal control, 8 m/s constant wind (1)
C.2 8 m/s

C.2.1 Time

(a) Hub height wind speed

(b) Rotorspeed

(c) Pitch angle

Figure 34: Time plot, AVATAR turbine, normal control, 8 m/s wind (1)
C  SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

Figure 35: Time plot, AVATAR turbine, normal control, 8 m/s wind (2)

(a) Aerodynamic axial force

(b) Aerodynamic torque

(c) Flapwise blade root moment
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

(a) Azimuth angle

(b) Axial wind velocity @ 70%R

(c) Lateral wind velocity @ 70%R

Figure 36: Time plot, AVATAR turbine, normal control, 8 m/s wind (3)
C  SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

Figure 37: Time plot, AVATAR turbine, normal control, 8 m/s wind (4)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

(a) Axial induced velocity, 70%R

(b) Angle of attack, 70%R

(c) Normal force, 70%R

Figure 38: Time plot, AVATAR turbine, normal control, 8 m/s wind (5)

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C.2.2 Bin

(a) Hub height wind speed

(b) Axial wind velocity @ 70%R

(c) Lateral wind velocity @ 70%R

(d) Vertical wind velocity @ 70%R

Figure 39: Bin plot, AVATAR turbine, normal control, 8 m/s wind
C.2.3 Statistics

![Figure 40: Statistics, AVATAR turbine, normal control, 8 m/s wind (1)](image)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

Figure 41: Statistics, AVATAR turbine, normal control, 8 m/s wind (2)
C SAMPLE RESULTS FOR AVATAR ROTOR, NORMAL CONTROLLER

Figure 42: Statistics, AVATAR turbine, normal control, 8 m/s wind (3)
Figure 43: Statistics, AVATAR turbine, normal control, 8 m/s wind (4)
C.2.4 Fatigue loads

![Diagram of fatigue loads](image)

(a) Normal force

![Diagram of tower forces](image)

(b) Tower forces

![Diagram of tower moments](image)

(c) Tower moments

Figure 44: Equivalent loads, AVATAR turbine, normal control, 8 m/s wind (1)
Figure 45: Relative difference between equivalent loads, AVATAR turbine, normal control, 8 m/s wind (1)
Figure 46: Equivalent loads, AVATAR turbine, normal control, 8 m/s wind (2)
Figure 47: Relative difference between equivalent loads, AVATAR turbine, normal control, 8 m/s wind (2)
C.2.5 Loops

Figure 48: Loops, AVATAR turbine, normal control, 8 m/s wind (1)
D Sample results for AVATAR rotor, prescribed rpm and pitch

D.1 8 m/s constant wind

D.1.1 Time

Figure 49: Time plot, AVATAR turbine, prescribed control, 8 m/s constant wind (1)
D  SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

(a) Aerodynamic axial force

(b) Aerodynamic torque

(c) Flapwise blade root moment

Figure 50: Time plot, AVATAR turbine, prescribed control, 8 m/s constant wind (2)

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D SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

(a) Azimuth angle

(b) Axial wind velocity @ 70%R

(c) Lateral wind velocity @ 70%R

Figure 51: Time plot, AVATAR turbine, prescribed control, 8 m/s constant wind (3)
Figure 52: Time plot, AVATAR turbine, prescribed control, 8 m/s constant wind (4)
Figure 53: Time plot, AVATAR turbine, prescribed control, 8 m/s constant wind (5)
D.1.2 Bin

Figure 54: Bin plot, AVATAR turbine, prescribed control, 8 m/s constant wind
D.1.3 Statistics

(a) Control parameters

(b) Global variables

(c) Tower forces

Figure 55: Statistics, AVATAR turbine, prescribed control, 8 m/s constant wind (1)
Figure 56: Statistics, AVATAR turbine, prescribed control, 8 m/s constant wind (2)
Figure 57: Statistics, AVATAR turbine, prescribed control, 8 m/s constant wind (3)
Figure 58: Statistics, AVATAR turbine, prescribed control, 8 m/s constant wind (4)
D.1.4 Fatigue loads

Figure 59: Equivalent loads, AVATAR turbine, prescribed control, 8 m/s constant wind (1)
Figure 60: Relative difference between equivalent loads, AVATAR turbine, prescribed control, 8 m/s constant wind (1)
Figure 61: Equivalent loads, AVATAR turbine, prescribed control, 8 m/s constant wind (2)
Figure 62: Relative difference between equivalent loads, AVATAR turbine, prescribed control, 8 m/s constant wind (2)
Figure 63: Loops, AVATAR turbine, prescribed control, 8 m/s constant wind (1)
D.2 8 m/s

D.2.1 Time

Figure 64: Time plot, AVATAR turbine, prescribed control, 8 m/s wind (1)
D SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

(a) Aerodynamic axial force

(b) Aerodynamic torque

(c) Flapwise blade root moment

Figure 65: Time plot, AVATAR turbine, prescribed control, 8 m/s wind (2)
D  SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

Figure 66: Time plot, AVATAR turbine, prescribed control, 8 m/s wind (3)
D  SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

(a) Axial induced velocity, 30%R

(b) Angle of attack, 30%R

(c) Normal force, 30%R

Figure 67: Time plot, AVATAR turbine, prescribed control, 8 m/s wind (4)
(a) Axial induced velocity, 70%R

(b) Angle of attack, 70%R

(c) Normal force, 70%R

Figure 68: Time plot, AVATAR turbine, prescribed control, 8 m/s wind (5)
D.2.2 Bin

Figure 69: Bin plot, AVATAR turbine, prescribed control, 8 m/s wind
D.2.3 Statistics

Figure 70: Statistics, AVATAR turbine, prescribed control, 8 m/s wind (1)
Figure 71: Statistics, AVATAR turbine, prescribed control, 8 m/s wind (2)
D SAMPLE RESULTS FOR AVATAR ROTOR, PRESCRIBED RPM AND PITCH

(a) Flapwise deformations

(b) Leadwise deformations

(c) Torsion angles

Figure 72: Statistics, AVATAR turbine, prescribed control, 8 m/s wind (3)
Figure 73: Statistics, AVATAR turbine, prescribed control, 8 m/s wind (4)
D.2.4 Fatigue loads

Figure 74: Equivalent loads, AVATAR turbine, prescribed control, 8 m/s wind (1)
Figure 75: Relative difference between equivalent loads, AVATAR turbine, prescribed control, 8 m/s wind (1)
Figure 76: Equivalent loads, AVATAR turbine, prescribed control, 8 m/s wind (2)
Figure 77: Relative difference between equivalent loads, AVATAR turbine, prescribed control, 8 m/s wind (2)
D.2.5 Loops

Figure 78: Loops, AVATAR turbine, prescribed control, 8 m/s wind (1)