Guidelines for Aeroelastic Analyses of Wind Turbines Using Multi Body Simulations [D8, D2]

Holierhoek, J.G.

July 2015
ECN-E--15-036

Acknowledgement

The work described in this report was performed in several project that were funded by FLOW, “Far Large Offshore Wind”. These projects were: P201101-014-ECN, P201101-015-ECN, P201203-006-ECN and P201204-003-ECN. The author is very grateful for this support. As a deliverable, this specific report is D2 for P201203-006-ECN and D8 for P201204-003-ECN.
This is a public report.

Abstract

Wind turbine load simulations are currently mostly performed using tools that were specifically designed for that purpose. One of the draw backs of those tools is the inability to add more detail to the structural model when required. For example, there are very few degrees of freedom available in a drive train while one may need more for their simulation. For this reason general purpose multi body simulations could be a good way to resolve these issues. The aerodynamic forces can be added by coupling to the ECN Aero-Module. The calculation times for multi body codes will be larger in general than for the specific wind turbine tools. Especially when one increases the amount of detail, one can run into issues with the calculation time. Using a more detailed aerodynamic approach can also hamper the use. Therefore simulations were performed to get an indication the effect of some of the possible increases in model complexity. The focus was on the aerodynamic model, the structural model of the blades, the tower model and the drive train model. This report provides the main public results from the different projects.

It was found that the aerodynamic model does provide different results in cases such as blades individually pitching to reduce the variation in the loads. The structural blade model has significant effect on the variations of the loads on the turbine and its components. The effect of including more modes in a tower has less effect on the results, except for situations where the tower is suddenly excited.

‘Although the information contained in this report is derived from reliable sources and reasonable care has been taken in the compiling of this report, ECN cannot be held responsible by the user for any errors, inaccuracies and/or omissions contained therein, regardless of the cause, nor can ECN be held responsible for any damages that may result therefrom. Any use that is made of the information contained in this report and decisions made by the user on the basis of this information are for the account and risk of the user. In no event shall ECN, its managers, directors and/or employees have any liability for indirect, non-material or consequential damages, including loss of profit or revenue and loss of contracts or orders.’

Contents

1 Introduction

The accuracy of the currently used state-of-the-art tools for load analysis of drive train, yaw system and pitch system do not suffice and more detailed modelling is necessary. The usual practise at the moment is to determine some parameters based on the full load set calculation of the turbine design using a wind turbine load calculation tool such as Phatas-FOCUS or Bladed and the component designer creates a model of their component in detail and determines that it should withstand the loads provided in the (rather small and limited) table. One can imagine however that the actual designed component can possibly have an effect on the loads that have been calculated. On the other hand one can also understand that the small table with parameters might not be sufficient to design the optimal component.

It is theoretically possible to create models that include every detail of the turbine design, but this is at the moment not a realistic option. Not only due to the numerous iterations in the design that would be required to get to a reliable and close to optimal wind turbine design, but also due to unacceptable or even impossible calculation times. Actually it becomes realistic that the average life of the computer will less than the time it would require to complete one simulation if every little detail of the turbine is included combined with e.g. CFD for the most detailed possible aerodynamic loads. Therefore, since too detailed modelling could be prohibitive due to these unacceptable calculation times, knowledge and experience is necessary on achieving an optimal balance between the accuracy of the load predictions and the computational effort. This knowledge can then be used to improve the current standard design tools. Such improved design tools will increase the reliability of the load predictions for the main turbine components but also for the other components such as the drive train and-or the pitch system. This will then reduce the design uncertainty (safety factors), leading to material costs' savings or a reduction in unexpected maintenance and replacement costs.

It has become apparent that using general purpose multi body tools is not straightforward, because the blade flexibility does not compare to most other structures that are commonly analysed using multi body tools. The deformations in a wind turbine blade are large and especially the torsional deformations are very relevant due to the significant effect they have on the aerodynamic loads on the turbine. The coupling between motions in the rotor plane and the torsion have significant impact on the aeroelastic stability of the turbine and therefore on the fatigue loads experienced by a wind turbine. For this reason the tower and especially the blades of a wind turbine have to be modelled with care, i.e. using a simple linearised approach does not suffice. The mode shape linearization about the undeformed state does not resemble the blade modes well, due to the significant steady state deformations that will be present on an operating wind turbine. For this reason the blade model that should be used is expected to at least consist of different bodies, if one wants to resemble the blade accurately.

The aerodynamic model that is used in general, the so-called Blade Element Momentum (BEM), is known to perform quite well, but for certain cases it can certainly be improved. This has been shown in different research project where BEM was compared to wind tunnel measurements, for large yaw angles for example, the validity of BEM is limited. Aerodynamic models that include more physics that the simple BEM method, can approximate these situations with more accuracy. For example the free vortex code AWSM uses a more advanced aerodynamic model that outperforms BEM, especially in cases where the engineering models in BEM are used in an attempt to capture effects that are not resembled by the BEM equations.

For several cases an indication is provided for the minimum requirements of the simulation: which details are significantly influencing the results and what is roughly the impact on the calculation time, as the calculation time becomes a limiting factor for the analyses. It is at this moment not realistic to perform the calculations of a complete load set using the most detailed models that have been used in this project (structural and aerodynamic), let alone the afore mentioned theoretical model that includes every detail of the turbine. The results discussed in this report provide an initial set of guidelines for improved and more accurate wind turbine analysis that are within the realistic possibilities for wind turbine and wind turbine component designers. The focus in this report is on the public results providing some guidelines for multi body simulations.

First a short description will be provided of the tools that have been used: SIMPACK and the ECN Aero-Module.

To perform the research for which the results are described in this report, several projects were undertaken within the Dutch FLOW research programme (Far Large Offshore Wind). Due to the confidential information required from the manufacturers, there were three projects that were closely related and are combined in the performed research concerning improvements in load analyses. These projects are: P201101-015-ECN, P201203-006-ECN and P201204-003-ECN. This current report was written as part of the projects ‘Application of Advanced Design Tools to a 3-bladed offshore wind turbine’, P201204-003-ECN and ‘Improvement of advanced design tools’, P201203-006-ECN within the FLOW research programme (http://flow-offshore.nl/).

2

SIMPACK and ECN Aero Module

In this chapter the tools that have been used for the calculations discussed in the report will be shortly explained and references for more information will be provided.

2.1 SIMPACK

SIMPACK is a general purpose multi body simulation tool [SIMPACK]. It has been used extensively by among other the car industry, the train industry and recently has become well used in the wind turbine industry.
SIMPACK can be used to run simulations and thereby predict the behaviour of any type of multi-body system by solving the equations of motion of the system. A wide range of systems can be simulated, such as machinery, vehicles, robotics and wind turbines.
A system consists of different bodies that are linked with joints or with kinematic constraints. SIMPACK can be used with rigid and with flexible bodies, forces can be included through many different models, including e.g. springs, dampers as well as wind turbine aerodynamics using an external module.
When using SIMPACK to model wind turbines, a utility is available to create the flexible body to model the wind turbine blade, the 'rotor blade generation' module, which requires a table of input consisting of mass and stiffness and aerodynamic properties at different cross-sections, rather similar to the input for wind turbine simulation tools such as Bladed or Phatas-FOCUS. The tower can be modelled using this same tool, or by using so-called sim beams, which actually is the modelling tool that is also used by the rotor blade generation tool.
For the aerodynamics a coupling can be made to the ECN Aero-Module. This enables the user to include different aerodynamic models to the multi body model, as described below in the next paragraph.
SIMPACK can be used to perform time simulations or to determine equilibrium situations or eigenmodes. However, the ECN Aero-Module can only be used in the time simulations. The determination of eigenmodes and frequencies cannot be performed

including the aerodynamic loads, unless one would first derive the steady state aerodynamic loads and explicitly include them as external constant forces in the model.

The details of the SIMPACK models used within this project will be discussed in other chapters of this report.

Please note that throughout the projects, there were regular updates of the SIMPACK code. For different simulations sometimes different versions of the code were used, though no large differences were observed due to the updates.

2.2 ECN Aero-Module

Many years of experience of ECN in the field of wind turbine aerodynamics have been captured in the ECN Aero-Module. The module can be coupled to structural solvers or be run stand alone for calculations assuming a rigid turbine. When coupled to a structural solver, this solver has to communicate velocities on different points of the blades and the ECN Aero-Module will provide the aerodynamic loads based on those velocities and the historical data.
The two models that are included in the ECN Aero-Module are BEM and AWSM. BEM, Blade Element Momentum theory is the standard approach for wind turbine aerodynamics, AWSM is a free vortex approach. AWSM is a more detailed (and therefore more time consuming) approach than BEM. Both approaches will be shortly discussed below.

2.2.1 BEM

Blade Element Momentum theory has been used for many years to determine the aerodynamic loads on rigid or flexible wind turbine structures. It is based on using blade elements for the aerodynamic loads and looking at the momentum in the flow due to the loads to determine the local induced velocity. This local induced velocity effects the local flow at the blade elements, so an iteration has to be performed to solve the steady state situation. Over the years many engineering models have been added to the theory to compensate for the many violations of the theory that occur on the flow across a wind turbine. Within the ECN Aero-Module engineering models are included to improve performance concerning:

- yawed flow
- dynamic inflow
- dynamic stall
- turbulent wake state
- 3D aerofoil coefficient corrections
- ¾ chord point velocity evaluation with correction for moment coefficient
- tip and root correction
- tower shadow

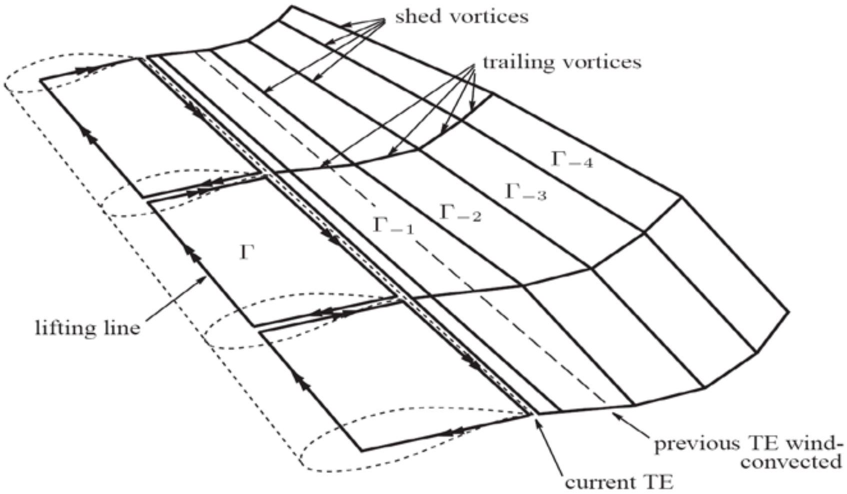
The BEM model is based on the BEM model that was part of the validated Phatas-FOCUS code.

2.2.2 AWSM

The Aerodynamic Wind turbine Simulation Module (AWSM) has been developed at ECN [van Garrel]. Its approach includes much more physics compared to BEM, and should therefore outperform BEM especially concerning wake and time dependent wake-related phenomena. The model is based on generalized lifting line theory in combination with a free vortex wake method.
It has been included in the ECN Aero-Module and therefore can also be used in combination with the dynamic stall model, tower shadow model and 3D aerofoil coefficient corrections.
The main assumption in the theory used in AWSM is that the extension of the geometry in span wise direction is predominant compared to the extension in chord wise and thickness direction. Because of this, the real geometry is represented by a line passing through the quarter chord point of each cross section and the total flow field in chord-wise direction is concentrated in this point.
In AWSM, the effects of viscosity are taken into account through the user-supplied lift-, drag- and moment coefficients as a function of the angle of attack. Along the lifting line, the generated elementary force can be determined by using the three-dimensional form of the Kutta-Jukowsky theorem. The two dimensional aerodynamic characteristics of the sections are known; this means that the elementary force can be calculated also from the sectional properties. By matching these two formulations, the lift along the blade is obtained.
As in the continuous flow field representation, the vorticity is shed from the trailing edge of the configuration surface and convected downstream in the AWSM flow model as time advances. The blade geometry consists of one or more strips that carry a vortex ring whose bound vortices are located at the quarter chord position and at the trailing edge. The vortex strengths of these vortex rings are to be determined. Each time step new vortex rings with these strengths are shed from the trailing edge and join the older vortex rings. These vortex rings together will form a vortex lattice. A sketch of the wake geometry for three strips at the fifth time step is shown in **Figure 1**. The position of the downstream part of the wake is determined each time step by convection of the wake vortex-lattice nodes.
Using the AWSM model, more detail is included in the aerodynamics. It also becomes possible to include the effect of winglets for example, without having to use engineering models to represent this.
The calculation time of the AWSM model is however much longer then when using BEM. There are many more complex iterations required when using AWSM. The complexity depends greatly on how many vortices are set as free wake (convection of these vortices depends on the iteration) and how many are included in total (wake points, those not free are convected at a constant velocity). The user will provide the number of free wake points and wake points and the choice made here greatly influences the accuracy as well as the calculation time.

More free wake points and more wake points provide more accuracy and increase calculation time

Figure 1: AWSM model: vortices are trailing in the wake and taken into account when calculating the induced flow



Please note that throughout the projects, there were regular updates of the ECN Aero-Module. For different simulations sometimes different versions of the code were used. Updates of the ECN Aero-Module sometimes concerned corrections also often new possibilities were added to the code, especially with the aim of increasing the speed of the calculation when using AWSM.

3

Guidelines Aerodynamics

3.1 Introduction

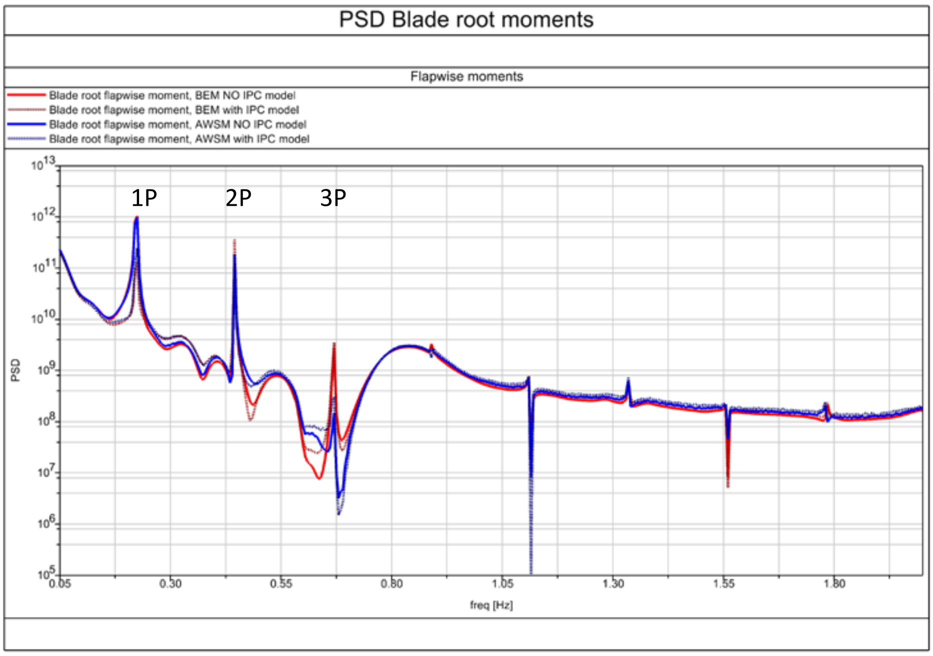
The more detailed aerodynamic model AWSM can in specific cases perform better than BEM as there is more physical background in the model. From aerodynamic research it is known that especially for yawed cases for example, BEM does not perform as well as AWSM. Adding more physics to the aerodynamic model does not come for free, calculation times using AWSM are significantly larger than those obtained using BEM. The calculation time using the combination of AWSM and SIMPACK is even so great that it is not realistic to perform a full load set calculation using such a model. To give an indication: using the settings for AWSM that is expected to provide the most reliable results (250 free wake points, 1000 wake point in total), a simulation of a 5MW turbine ran for 87 hours to complete only 39 seconds of simulation time. Therefore one needs to make a selection of specific cases that require the more detailed aerodynamic model and settle with the standard BEM model for the other cases, or in specific cases use the AWSM model with less free wake points.
For the future of quick and more reliable calculations, it would be most efficient if BEM models are further improved to better predict the situations where it currently is performing not as well as it should. A European project that is currently running, AVATAR will perform such analysis, to update the aerodynamic models to current state-of the art in turbines, for both size and for new developments such as add-ons to the blades [AVATAR].

AWSM using optimum settings for accuracy on a 5MW turbine: 87 hours to simulate 39 seconds

3.2 IPC representation

The latest generations of wind turbines are developed often with a very different approach of controls, the so-called IPC (Individual Pitch Control) algorithms, where each blade pitches separately from the other blade(s) and changes its pitch angle continuously during each cycle to compensate for load variations due to e.g. the difference in wind speed at the highest points and at the lowest points (wind shear). To investigate the differences in modelling IPC using BEM and AWSM, simulations were performed on a cyclic pitching turbine, similar to what would occur on an IPC controlled turbine. These results are presented in the public report by Holierhoek [Holierhoek]. To illustrate that there is a difference in the effect of IPC when using BEM or AWSM, **Figure 2** shows one of the results, clearly illustrating a difference in the effect of the IPC representation on the reduction in the PSD between AWSM and BEM. This does come at a significant cost of increased calculation time, so one should only perform simulations using AWSM when really necessary. There has since been a lot of progress in speeding up the AWSM part of the code, but there is still a long way to go there. A complete discussion of the results can be found in [Holierhoek].

Figure 2: PSD of the flapwise moments at the blade root of blade 1, for fixed pitch and pitching case, using BEM and AWSM

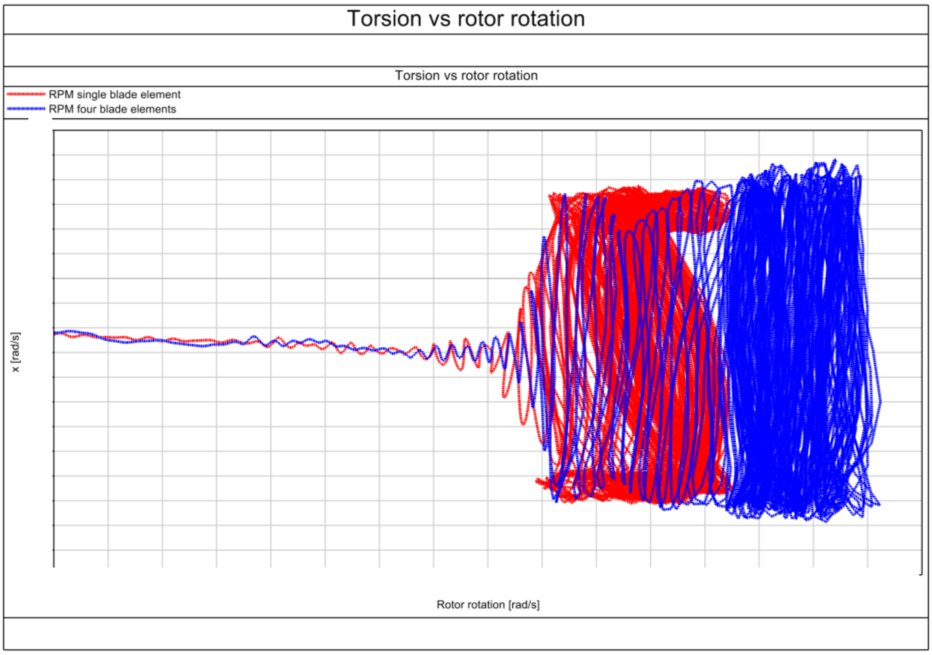


3.3 Classical Flutter Speed

For many different models (structural and aerodynamic) so-called classical flutter speed calculations were performed. These simulations are for a turbine that is allowed to speed up due to zero generator torque and an increasing wind speed. These type of simulations go through different operating conditions through the speed up and provide a nice case for comparisons of models.

From these simulations it was found that the classical flutter speed that is found using AWSM was somewhat higher than the speed found using BEM. The effect on the flutter speed of the blade model (see next chapter) was also more pronounced for the AWSM case then it was for BEM. For example, see the plots in **Figure 3** for BEM and **Figure 4** for AWSM. The numbers are not visible see to confidentiality of the data, but as the horizontal axes is the same for both figures, it is visible that the speed at which the torsional vibration starts when using BEM is lower than when using AWSM. Also the effect of the blade model is clearly visible in both results.

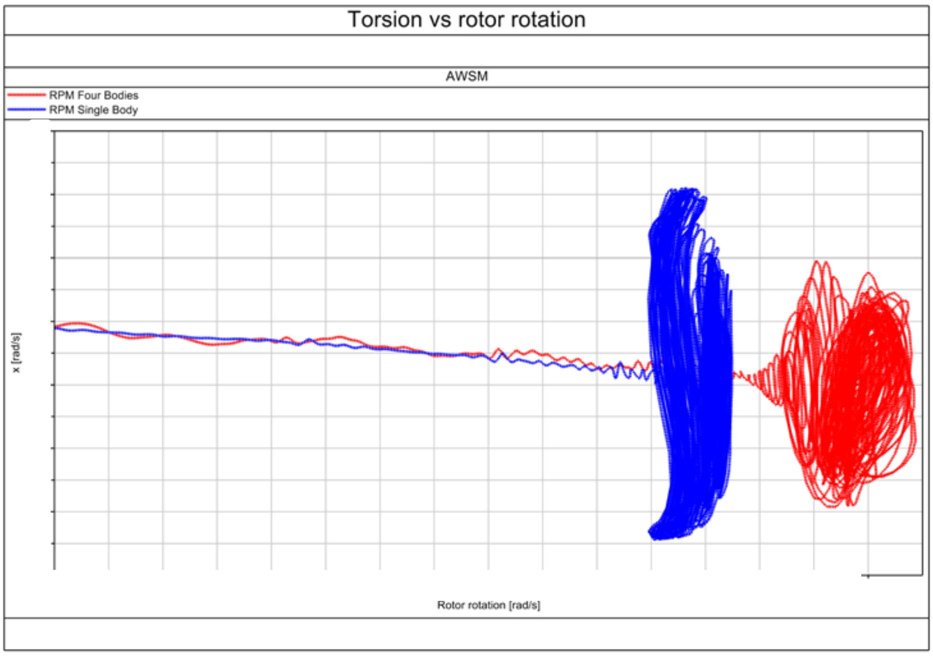
Figure 3: The torsion deformation of the blade tip plotted against the rotational speed of the shaft, using BEM and two different blade models, zoomed in on the critical rotational speed values



3.4 Loads on components

The effect of the aerodynamic models when determining the loads on several turbine components was looked at during these projects.
It was found that the pitch mechanism loads show significant differences when determined during a classical flutter analysis using BEM in comparison to the loads calculated using AWSM, especially the torque that will be required to keep the pitch angle constant.
For the yaw system, the force in fore/aft direction showed differences for only one of the turbines, the other forces and moments were rather similar.
The effect of the aerodynamic model on an element in the jacket structure did not show significant differences.

Figure 4: The torsion deformation plotted against the RPM value for the two different blade models and using AWSM.



4

Blade Modelling

One of the main conclusions from the projects is that the blade model has significant influence on the loads of the different components of the turbine This seems a rather trivial conclusion, but the standard approach that is used in the multi body codes is not the most reliable approach, therefore it is not as obvious as it sounds. The possible approaches concerning the blade are discussed first, followed by some of the main results from the projects concerning the blade model.

4.1 The Blade Models

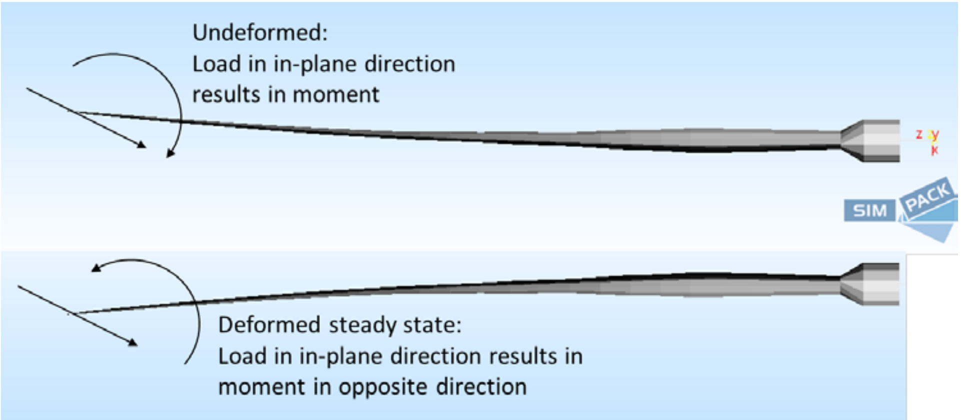
To create a wind turbine blade in SIMPACK, the quickest approach is to use the utility that is coupled to the code called rotorblade generation. This utility allows the used to input a table rather similar to most aeroelastic wind turbine simulation tools and translates this into a SIMBEAM with the prescribed properties. It will also generate the required markers that are used for the coupling to ECN Aero-Module. For a coupled simulation the ECN Aero-Module requires data on the position, direction and velocities of the chord-wise sections on the blade, therefore these markers are required for the coupling to work.
There are different options in the rotorblade generation utility that result in more or less detailed blade models. One can select:

- Basic format (bending flexible blade) or advanced format (bend-twist coupled blade)
- Euler-Bernoulli or Timoshenko beams
- Body Splitting

The basic format of blade input is for current size wind turbines, not representative. For example, it does not include torsion and therefore has not been considered in the calculations described in this report. The difference between Euler-Bernoulli beams and Timoshenko beams is relevant for current size turbines. According to SIMPACK the Timoshenko is the preferred theory as it also includes the effects of shear deformation and rotational inertia. This is particularly important when working with short beams.

Nevertheless, Euler-Bernoulli is the default method, as it is the standard methodology used in the industry.
The possibility of splitting the body is another detail that can be added to the model and possibly have effect on the accuracy of the calculations. The approach in SIMPACK of modelling blades as combinations of structural modal shapes, results in inaccuracies due to the linearisation about the undeformed state. Imagine a blade having prebend in one direction, whereby the edgewise mode in that undeformed state structurally couples to a torsional deformation, will have a coupling in the opposite direction for the deformed steady state around rated, where the flapwise bending situation will be in opposite direction compared to the prebend in unloaded condition. This is illustrated in **Figure 5**. For the turbine that was used in the analyses described in this report the effect might be smaller, as it is a down-wind turbine and the blade has no prebend. Still there will be a clear difference between the undeformed blade and the deformed blade, especially for high loaded situations such as around rated wind speed. For the unloaded situation there will be very little interaction in the edgewise mode with torsion, while in the deformed state this interaction will be much larger.

Figure 5: Visualising difference in coupling edgewise with torsion for the undeformed blade with prebend and the deformed blade



Classical flutter is an instability that will occur on most blade designs, above a certain rpm value. Above this high rpm value, one of the flapwise modes will couple to the torsional mode and an unstable vibration with increasing amplitude will occur. In most cases this will, in calculations, result in a limit cycle effect, due to nonlinearities in the aerodynamics, but on a real turbine it is possible that the torsion angle attained in the simulation is above the maximum possible deformation and the blade could be lost. Even if this torsion angle is within the elastic range of the blade, the blade will suffer from extreme fatigue loads and therefore it is an instability that needs to be avoided in every wind turbine design.
A load calculation to determine the rpm value above which flutter occurs and therefore the rpm the turbine should not reach, can be performed by allowing the turbine to over speed and see when the vibration starts. The over speed is achieved by using an increasing wind field and no generator torque on the turbine. A classical flutter load case provides significant large loads and is also a good test case for different

simulations, therefore this case was used to investigate the effect of using different blade models.
To solve the issue of using linearised structural models in the form of mode shapes and natural frequencies about the undeformed state, it is possible to use several elements within one blade. So, each element in the blade is modelled using the approach of determining the modes of that element, but for the complete turbine simulation, these different elements will be combined and a more accurate model is the result. For optimum accuracy, one requires to include higher order terms 0.
To simply illustrate some of the effects of using the inaccurate model and compare it to a more accurate model, simulations for classical flutter speed were performed using a single element blade and a blade consisting of four elements. These simulations were done using BEM and AWSM for the aerodynamic models.

4.2 Results and Guidelines

As was explained in the previous paragraph, using a modal approximation of a blade that is derived for a blade without any aerodynamic loads, is not reliable for large wind turbine blades. The differences between the underformed and the deformed shape are too large plus the very significant interaction that exists between bending and torsion can, for the current size large turbines, not be ignored. One should at least include several bodies in the blade, so use the blade splitting option in SIMPACK. How many bodies are required has not been determined in this study, in [Mabou] there were 15 bodies used, which showed very good results, but it is possible that less bodies would suffice. The calculation time increase when using more blade bodies is significant, but manageable. For some calculations the increase would be around 50%, but there were also cases where the increase in detail of the blade in the same way, resulted in an increase in calculation time by more than 250%. It would therefore in specific cases be wise to know where the detail in the blade is relevant.
This is similar to selecting your aerodynamic model, where the time of the calculation really becomes a limiting factor in which calculations you should perform using the more advanced model.

The choice of the blade model was found to influence the number of cycles of loads occurring on the yaw system, the pitch system, the drive train and the in the jacket members. Therefore the blade model can affect the fatigue loads that are determined from the analysis.

5

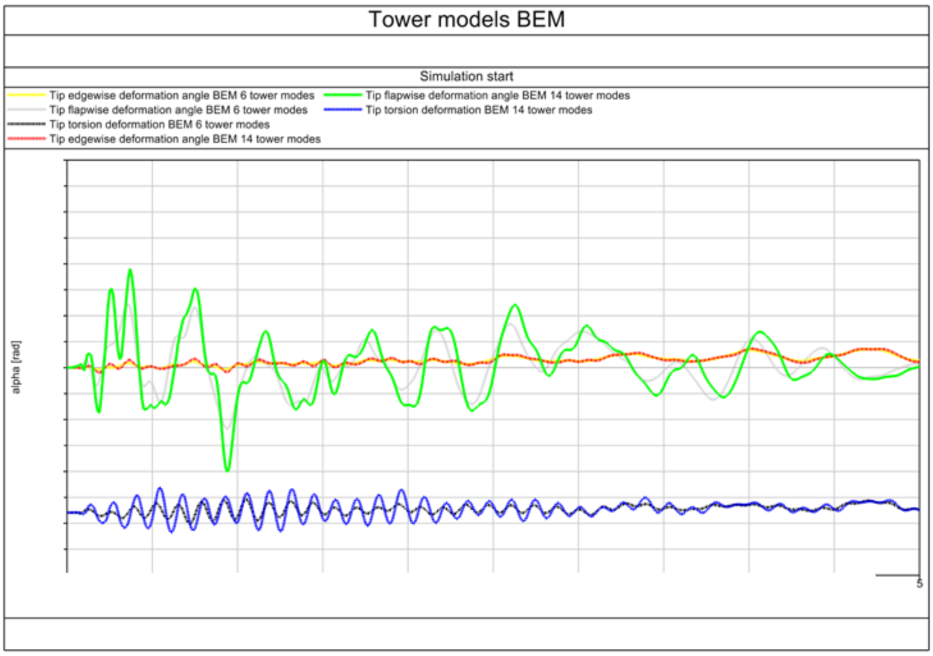
Tower Model

Two very different towers were analysed during the projects, one was a normal tower and one was a jacket tower up to the nacelle.

5.1 Modes in Tower

When including the tower as a flexible body, SIMPACK includes a number of modes or all modes up to a certain frequency, as inputted by the user. To investigate the sensitivity of the loads on the turbine to this setting, several simulations were performed using 6 modes in the tower and compared to using 14 modes in the tower. The differences that were found were very small, the increase in calculation time was not too significant, but it did not measure up to the differences that were found in the loads. Therefore the number of modes that should be included in a tower could for each turbine simply be checked by performing several simulations with increasing number of modes in the tower and if no clear differences are found, this number of modes should be included in the tower.
As there were visible differences at the start of the simulation, during the initialisation (see **Figure 6**), it is expected that only cases where there is significant excitation to be expected of the tower, such as an emergency stop, would be require inclusion of more modes in the tower. Such a strong sudden excitation will excite the different tower modes and higher modes will influence the actual loads on the turbine and its components. The difference at the start of the simulation using AWSM or BEM was very small. There was significant effect visible in the loads on the yaw system, on the blades and the pitch sytem.

Figure 6: Zoom on start of the simulation, illustrating differences due to different tower models for the tip deformation angles, using BEM



5.2 Jacket Tower

Including a jacket tower in a SIMPACK model is quite significant modelling work and once you have this in the model, the calculation times of your simulations become very high. Combining a jacket tower with the more advanced aerodynamic model results in simulations that can sometimes require more than a week for just 90 seconds. This approach is clearly not realistic for load calculations, except a small number of specific cases.

The jacket tower with BEM or with AWSM with less detail (so no free wake), is manageable. The loads in the members can be determined. The effect of the two different aerodynamic models on the loads in a member of the jacket was analysed and the difference was found to be very small.

6

Drive train

The drive train was simulated using a simple approach, similar to what is currently used in most wind turbine load analysis tools. To check if it would be relevant and practical to improve the drive train model in a SIMPACK ECN Aero-Module simulation, there were simulation performed with a stiff shaft and with a shaft with torsion and bending flexibility.

Adding these degrees of freedom in a model of a turbine with a jacket structure (which already holds many degrees of freedom), did not have any effect on the calculation time. As expected, it does influence the response of the turbine, therefore when using a tool such as SIMPACK, it makes good sense to include more details in the drive train and the connection to the nacelle and tower.

Note that this does not mean that one should (or could) include the complete gearbox. A gearbox will include very high frequencies, whereby the complete simulation of the turbine would demand a very small time step, which at this moment is not a realistic approach, unless used for only a small number of load cases.

7 Conclusions

Some details that can be included in a SIMPACK – ECN Aero-Module simulations result in calculation times that really inhibit the use of those models. Especially the aerodynamic model has to be selected with care, AWSM can outperform BEM in certain cases, but the calculation times of the combined simulation becomes a real issue. So one should really only use AWSM for the cases where there are doubts about the results from BEM.

A jacket tower also increases the calculation time significantly, while some other structural model improvements have little effect. For example including shaft bending does not really influence the calculation time. Including more tower modes has some influence on the calculation time and does not show significant differences, except when the tower is suddenly excited.

The blade model really has to be created with big care. After all, the blades they are modelling are the most important source of loads and for the current size wind turbines the torsional deformations can have significant impact on the loads on the turbine. The coupling between bending and torsion has to be represented well to ensure that the simulation does not show unrealistic aeroelastic blade instabilities or that actual instabilities do not show up due to the incorrect coupling in the mode shapes. The blade should be split in several bodies and higher order terms should be included.

Including flexibilities in other components as a number of (torsional) springs can quickly be done and has in general very little effect on the calculation time, but does influence the results. Therefore, if there is an idea of a representative flexibility of a system, it should always be included in the model.

References

SIMPACK: http://www.SIMPACK.com/

A. Van Garrel. *Development of a wind turbine aerodynamics simulation module*, Technical Report ECN-C–03-079, ECN, 2003

AVATAR: http://www.eera-avatar.eu/home/

H. Mabou, S. Hauptmann, L. Schön, *Advanced Multi-Body Modeling of Rotor Blades – Validation and Application*, SIMPACK News August 2014

J.G. Holierhoek, *Improved Aeroelastic Simulations using SIMPACK [D6]*, Technical Report ECN-E--15-037, ECN, 2015