Improved Aeroelastic Simulations using SIMPACK [D6]

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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 effect of IPC on the aerodynamic loads using different aerodynamic models (BEM and AWSM) has been investigated in this report. The effect of the aerodynamic model impacts the simulations, but the increase in the calculation time is perhaps more significant. A user should try to predict the most critical cases that show the largest deviations when comparing BEM to AWSM, and use AWSM for those cases.

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. One can imagine the life of a computer being 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 effect of IPC.

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 project 'Application of Advanced Design Tools to a 3-bladed offshore wind turbine', P201204-003-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 project, 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:

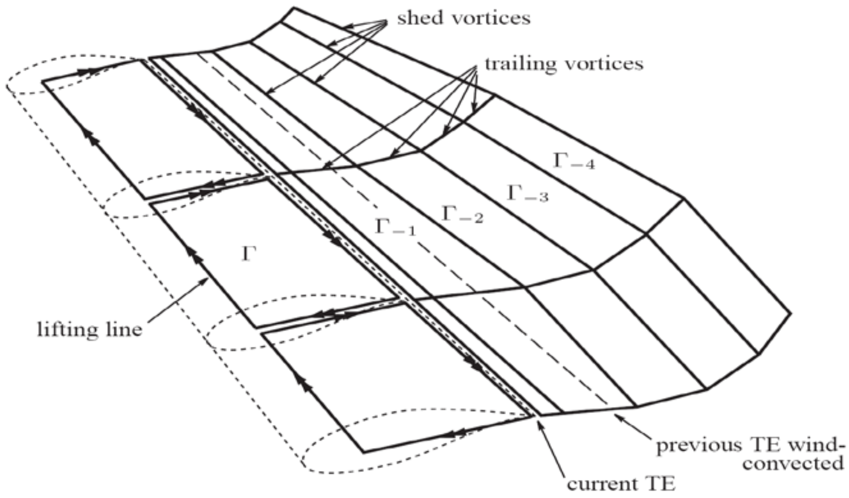
- yawed flow
- dynamic inflow
- dynamic stall
- turbulent wake state
- 3D aerofoil coefficient corrections
- ¾ chord point velocity evaluation with correction for moment coefficient
- tip and root correction
- tower shadow

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.

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



Please note that throughout the project, 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.

3

Aerodynamic Models and IPC

The aerodynamic model is very important in aeroelastic analysis. The standard for aeroelastic load calculations is the so-called BEM model, but the SIMPACK – ECN Aero-Module tool also provides another option called AWSM, which is based on free vortex simulation. Such an aerodynamic model contains more physics, but this comes at the cost of additional calculation time.
In the BEM method a lot of assumptions are used to derive at the theoretical equations, while it is clear that these assumptions are not valid for wind turbines. To name just two: one assumes that the different radial sections of the blade do not interact with each other and that there is no influence of one blade on another blade.

In case of IPC (Individual Pitch Control), the difference between the flow around the different blades increases. For this reason the effect focussing on aerodynamics has been looked at. The IPC effect is modulated using a small pitch angle that is a function of the azimuthal angle of each blade. So for each blade the same pitch angles will be attained at certain positions. This pitching is similar to the blades that are individually controlled to reduce the loads from e.g. sheared flow. By simulating a situation with a yaw error a clear cyclic excitation, similar to the excitation from sheared flow, but stronger, is included in the simulation. The pitch angle represents the difference in the inflow angle due to this yawed situation.
Due to the confidentiality of the turbine data and the results presented in this report, all illustrations are graphs without the numbers along the different axes. Still the results to give a good indication of the differences between the aerodynamic models.

3.1 IPC representation

To investigate the effect of IPC on the validity of the BEM approximation, a turbine has been modelled that moves with a fixed pitch variation at 1P for a wind speed at a significant yaw angle (in this case 45 degrees).

The choice not to use the actual IPC controller is to get a better understanding of only the effect of the blades pitching at 1P and being at different pitch angles from each other. The settings are such that they do present the actual IPC values roughly.
To model a wind turbine without an external wind controller, the generator is modelled using an u-vector element with a pre-scribed function (equal to an excitation element which uses an expression element in SIMPACK).
To include a representation of IPC one has to create several elements. For each blade an **expression** element must be created that described the equation that is used to determine the pitch angle. Then an **excitation** element is created that uses this expression. A **u-vector** is created that uses the excitation and the joint on the blade connection is changed to a joint '**single axis u(t)**'.
The equation that is used to determine the pitch angle depends on the azimuth angle.

The pitch angle variation has been determined by looking at the results for a simulation without pitching at the specified yaw angle. To reduce the amplitude of the loads and moments, the blade will pitch roughly towards larger angles of attack for the lower loads and smaller angles of attack for the higher loads. When such a large yaw angle is used as 45 degrees, the variation of the loads is not mainly due to the difference in angle of attack at the blades depending on their azimuthal position, but mainly due to the difference in the total velocity of the blade element cross section.

The values of the pitch angles of the three blades combined with the azimuth angle of blade 1 are illustrated in **Figure 2**. The figure also illustrates that the maximum pitch angle is just after passing the tower and the minimum pitch angle just after passing the upwards vertical position.

The resulting angle of attack with and without this IPC model are illustrated for the BEM case in **Figure 3**. This graph shows that the angles of attack for the IPC cases are actually slightly larger than the angles of attack of the simulations without IPC model, but as will be illustrated in section 3.4, these pitching actions will decrease the amplitudes in the blade root flapwise moments.

Figure 2: The pitch angles for the three blades illustrated for a short section of the simulation combined with the azimuth angle of blade 1 illustrating the IPC model used in the calculations

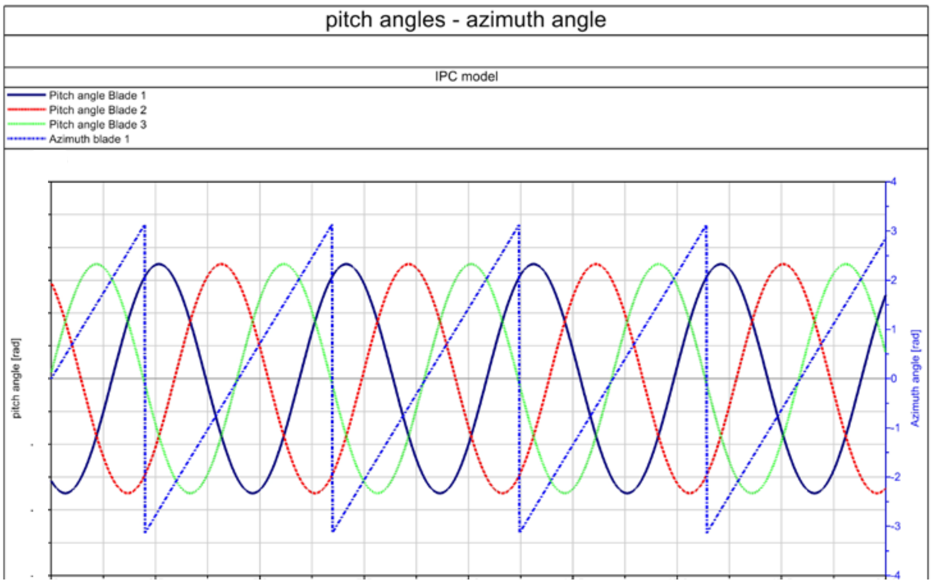
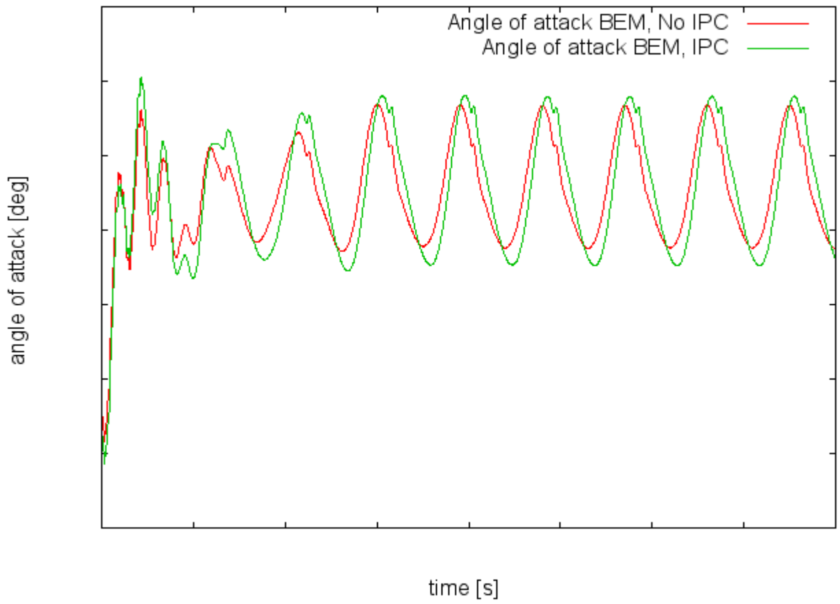


Figure 3: The angle of attack of a representative section of blade 1 with and without IPC model, based on BEM simulations



3.2 Input

Simulations were performed for a situation of yaw at 45 degrees. The wind speed was defined as: u= 8.485 m/s and v= 8.485m/s, but to get the simulation to start smoothly, the wind speed started at 2.5455 m/s in both directions and increased to the afore mentioned velocity in 1.2 s.

3.3 Format used in output graphs

Throughout these discussions the following colour and line style choices have been followed, for as much as possible.

Table 1: Format of output variables

Aerodynamic model	Colour	Line type
BEM	Red (green, pink)	Depends on IPC Y/N
AWSM	Blue (cyan, grey)	Depends on IPC Y/N
IPC	Depends on AWSM/BEM	Dashed - - - -
No IPC	Depends on AWSM/BEM	Solid line ———

3.4 Effect IPC model on BEM results

The simulations were run using BEM and AWSM. To illustrate the difference between the simulations without any pitching action and with the additional pitching action, the axial aerodynamic forces on the three blades for both simulations are illustrated in **Figure 4**. For all blades. The graph does clearly show that the amplitude in the axial force is significantly reduced by adding the pitching motion to the blade. The axial force with the IPC emulation does however show more peaks than the axial force without IPC. In **Figure 5** the same output is shown, but for clarity for only one blade. From this graph it becomes clear that the reduction in amplitude (maximum – minimum in one rotor rotation) due to the IPC emulation is around 50%.

The blade root flap moments as calculated using BEM with and without the IPC model are illustrated in **Figure 6**. Especially in the figure showing a smaller time selection, **Figure 7**, the difference in the amplitude of the variations in the flap moment for one rotation becomes apparent. The amplitude (maximum – minimum in one rotor rotation) of the simulation with the IPC is only 55% of the amplitude in the simulation without IPC model. The PSD of the blade root flap moments illustrate the lower energy content in the 1P vibration and the slightly higher content for higher frequencies. This latter is mainly due to the 'double peak' that was clearly visible in the flap moments and the aerodynamic axial loads.

The edgewise moments are illustrated in **Figure 9** and **Figure 10**. Especially the latter illustrates that there is very little difference between the two simulations. The PSD of the edgewise moments also shows that there is very little difference between the simulation with the IPC model and without the IPC model.

Figure 4: A short sequence of the axial force on each blade as determined in simulations based on BEM.

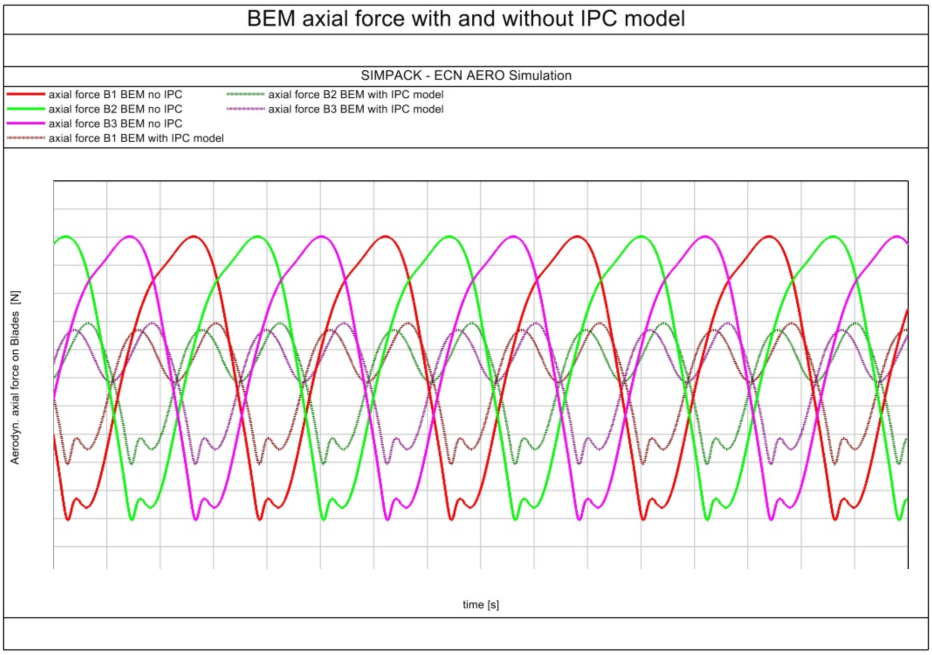


Figure 5: : Aerodynamic axial force on blade 1 for a BEM model with and without IPC model.

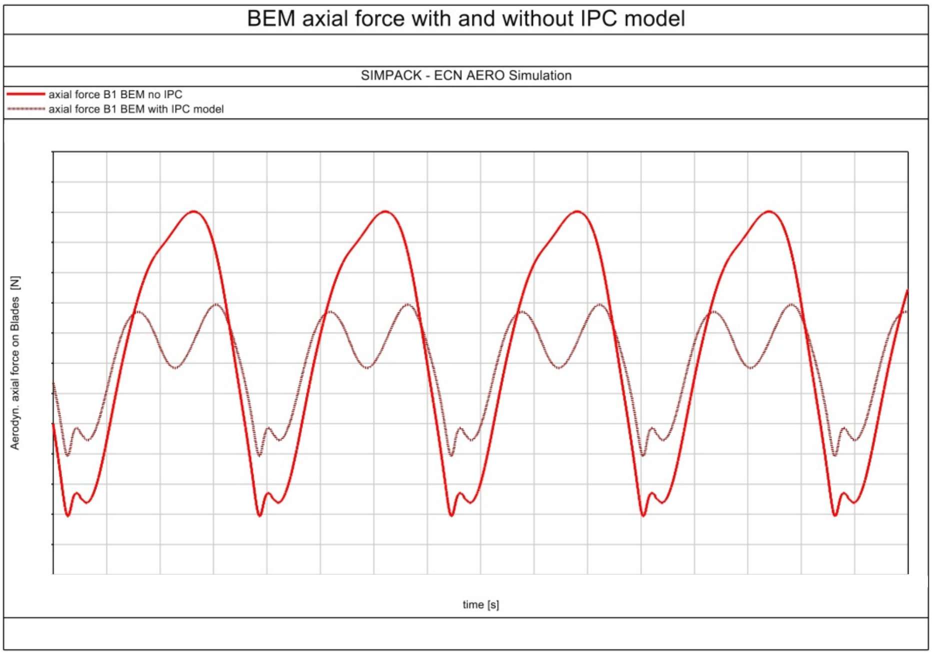


Figure 6: Flap moments as calculated using BEM for the model with and without IPC.

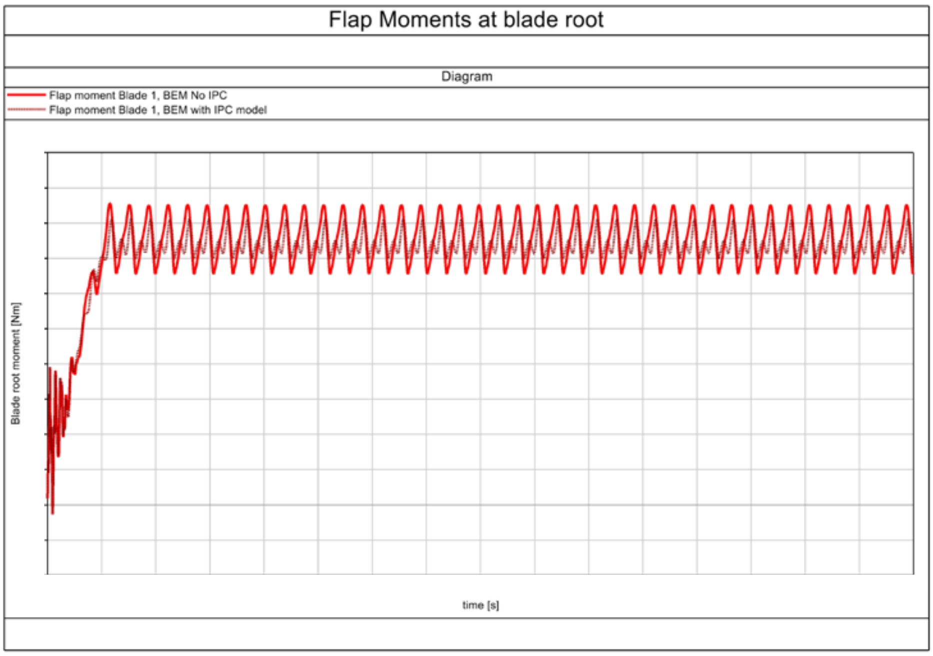


Figure 7: Flap moments as calculated using BEM for the model with and without IPC for a selection of time.

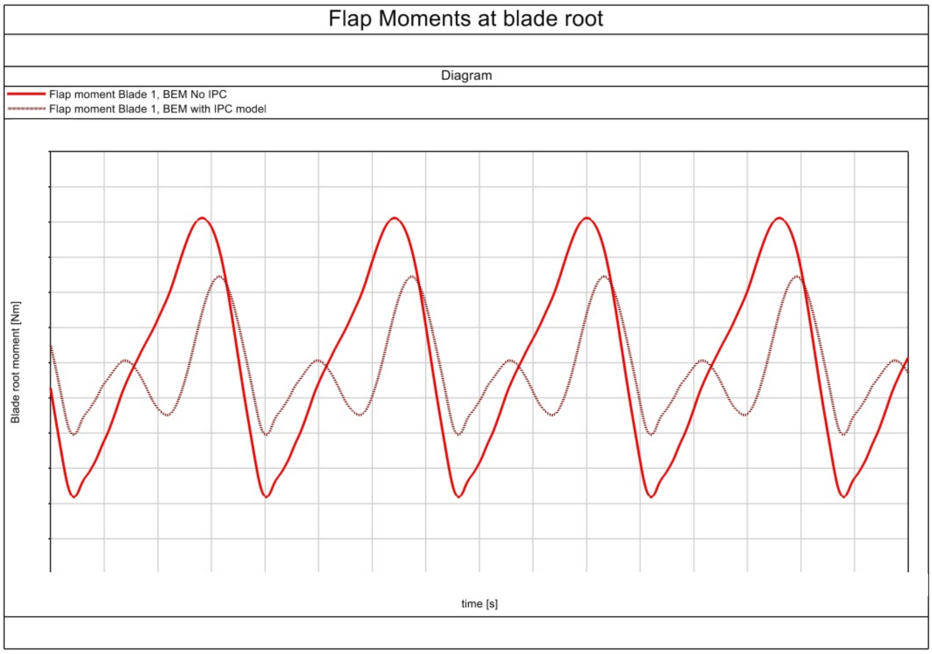


Figure 8: The PSD of the blade root flap moments of blade 1, using BEM with the IPC model and without the IPC model.

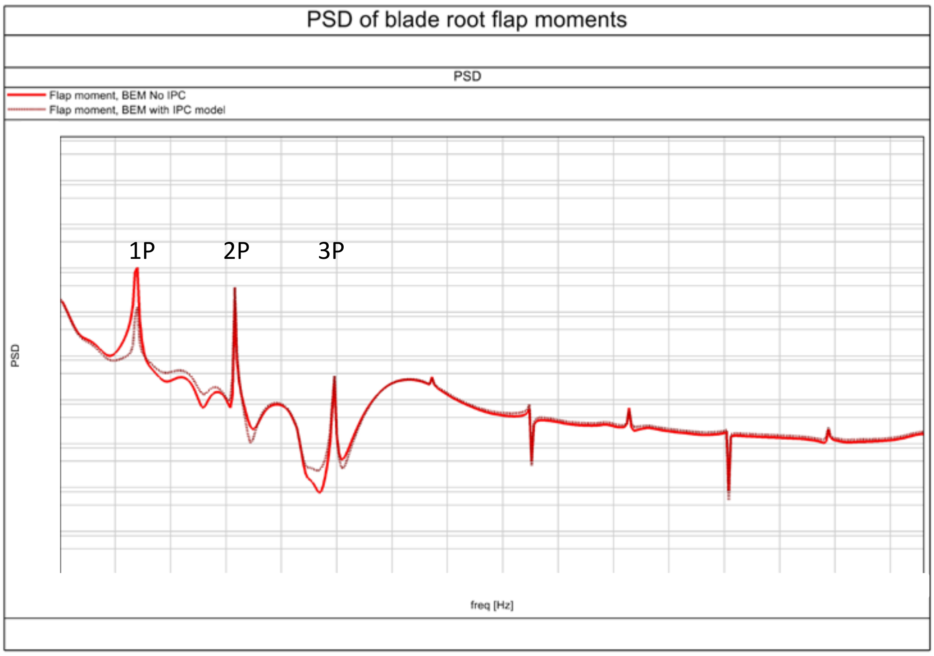


Figure 9: Edgewise moments as calculated using BEM for the model with and without IPC.

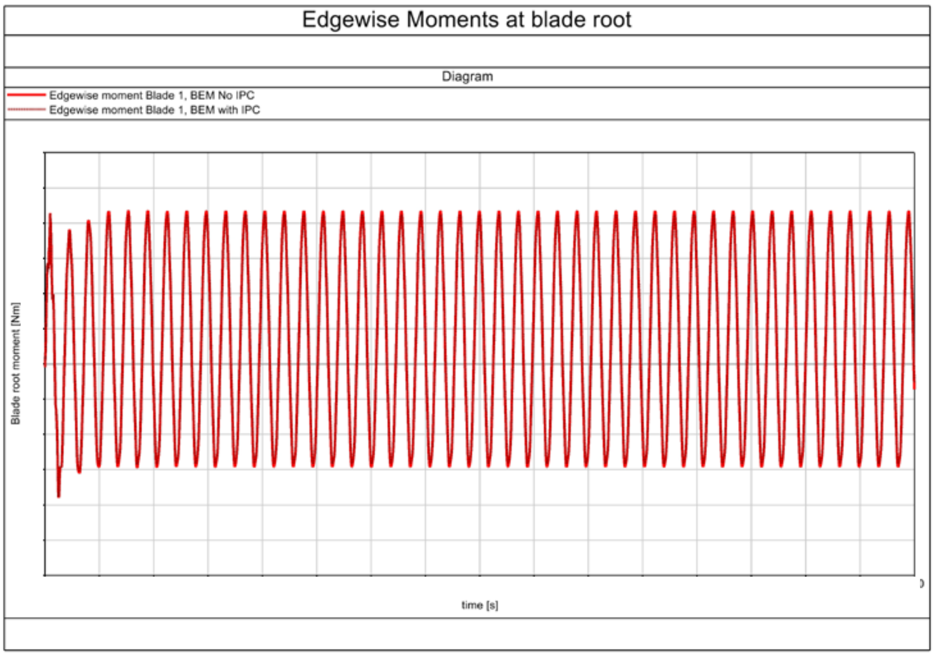


Figure 10: Edgewise moments as calculated using BEM for the model with and without IPC for a short selection of time.

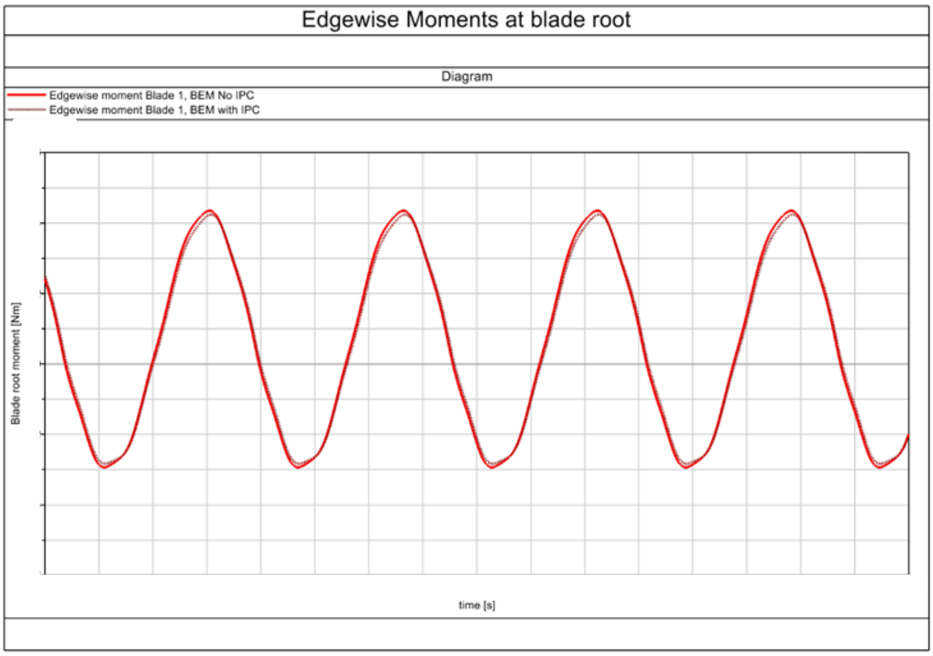
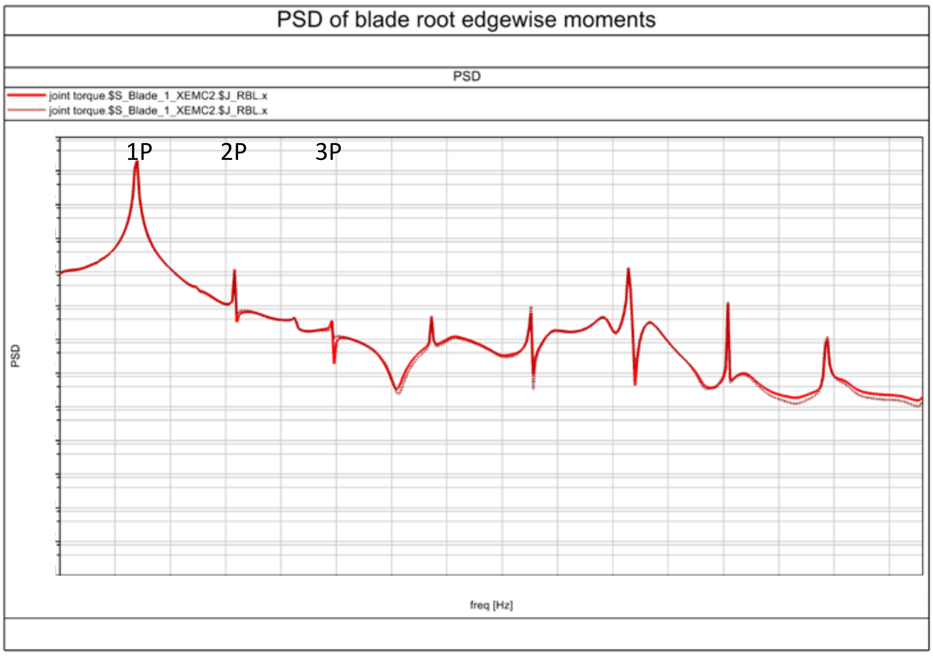


Figure 11: The PSD of the blade root edgewise moments of blade 1, using BEM with the IPC model and without the IPC model.



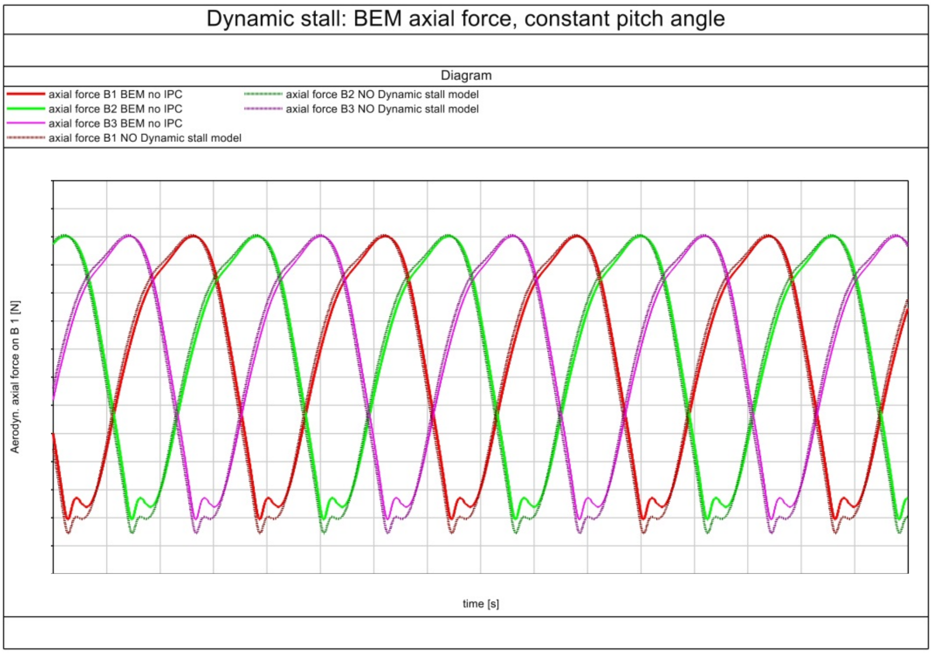
3.5 Dynamic stall effects in BEM model

The dynamic stall model will have a significant effect on the loads on a turbine when there are strong changes in angle of attack. In the case of yaw and also in the case of cyclic pitching blades, the variation in the angle of attack is significant and the dynamic stall model will be very relevant to the calculation. Therefore the simulations using the BEM model have been performed with the dynamic stall model active (first order Snel model) and without dynamic stall. The AWSM calculations (discussed in the next section) have only been performed using the first order Snel dynamic stall model.
The effect of the dynamic stall model on the results of the simulations for a blade at a constant pitch angle and a blade with the IPC model will be discussed in this section.

3.5.1 Dynamic stall effects for a blade at constant pitch angle

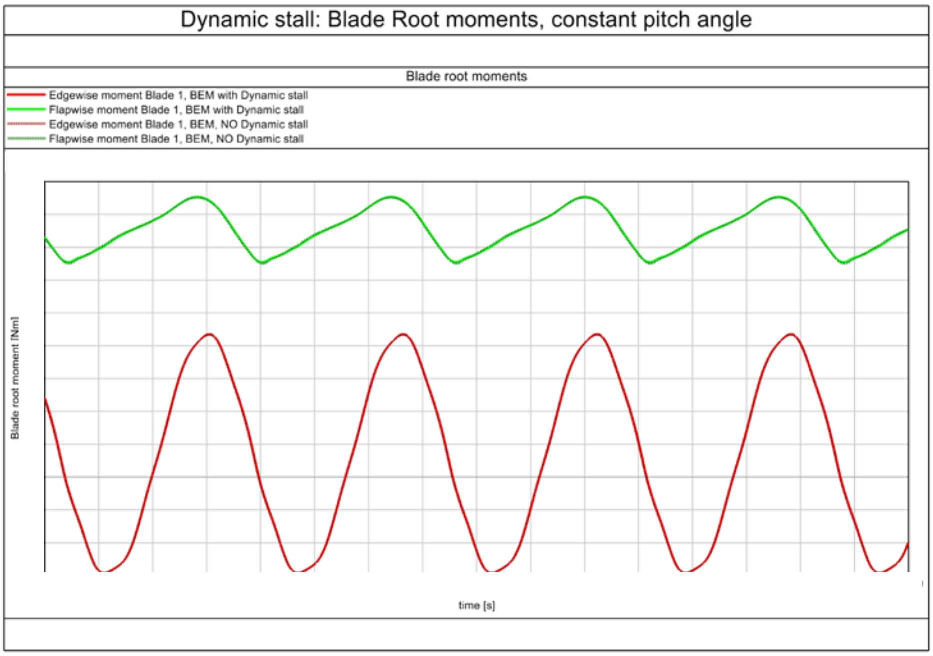
Below the figures illustrate the effect of the dynamic stall model on the variations in the loads.

Figure 12: A short sequence of the axial force on each blade as determined in simulations based on BEM, with ("BEM no IPC") and without ("No Dynamic stall model") dynamic stall for yawed flow and constant pitch angles.



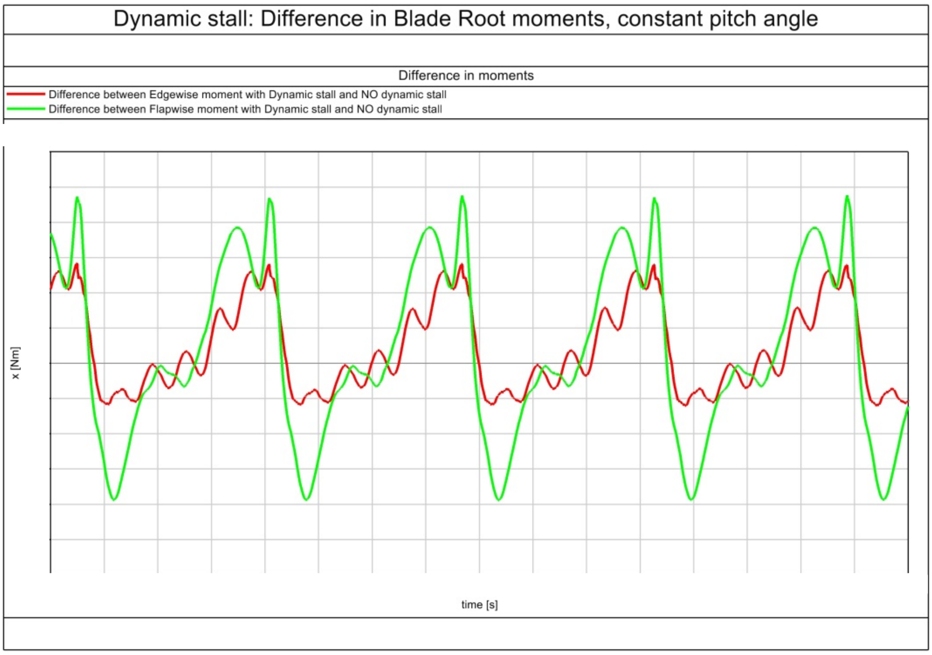
The difference between including the dynamic stall model and a simulation without a dynamic stall model for a blade that operates at a constant pitch angle is illustrated in **Figure 12**, by plotting the calculated axial forces on each blade. This shows that for the constant pitch angle case, the dynamic stall model does not have a large influence on the axial force on a blade.

Figure 13: The blade root moments for a blade 1 at a constant pitch angle, with the dynamic stall model and without the dynamic stall model



The blade root moments are plotted in **Figure 13**. There is again very little difference between the blade root moments calculated with and without dynamic stall model. The difference is made more clear in **Figure 14**, where the difference between the two calculations is shown for both the flapwise and the edgewise blade root moments. This graph shows that there is a cyclic difference due to the dynamic stall model, but looking at the scale of the variations, this is only in the order of less than 1 per cent of the total blade root moments.

Figure 14: The difference between the blade root moments calculated with dynamic stall model and without dynamic stall model



3.5.2 Dynamic stall effects for a model including cyclic individual pitch

The calculations of the rotor with the IPC model included show a clearer difference with the dynamic stall model included or not included, as is illustrated in the graph with the aerodynamic axial force on blade 1 depicted in **Figure 15**. Including the dynamic stall model in the calculation results in a smaller amplitude of the aerodynamic axial force on the blade.
The PSD of the axial force on blade 1 is illustrated in **Figure 16**. This graph shows that there is less vibration in 1P when the dynamic stall model is included, but that other frequency content is increased by including the dynamic stall model in the calculation.
The blade root moments are illustrated in **Figure 17**. The difference between the results obtained using a simulation with the dynamic stall model and a simulation without the dynamic stall model are quantified in **Figure 18**. This again illustrates that there is a difference, but compared to the actual values of the blade root moments, it is very small. Comparing **Figure 18** to **Figure 14** does show that the difference due to the dynamic stall model is, as could be expected, slightly larger for the pitching blade.
These calculations show that the dynamic stall model has a significant effect on the outcome of a simulation and should be included in any load analysis especially in a yawed case. However, it is also known that the whole concept of dynamic stall is still not modelled accurately enough (Holierhoek et al.). It can also be concluded that the effect of dynamic stall is much smaller than the effect of including the IPC model, which

is relevant to know for the comparison between BEM and AWSM, even though they were both used including the same dynamic stall model. As small differences in the results could lead to differences in the dynamic stall effects in the calculations, it is relevant to illustrate that the complete effect of dynamic stall is actually relatively small.

Figure 15: A short sequence of the axial force on each blade as determined in simulations based on BEM, with ("BEM no IPC") and without ("No Dynamic stall model") dynamic stall for yawed flow and pitching blades.

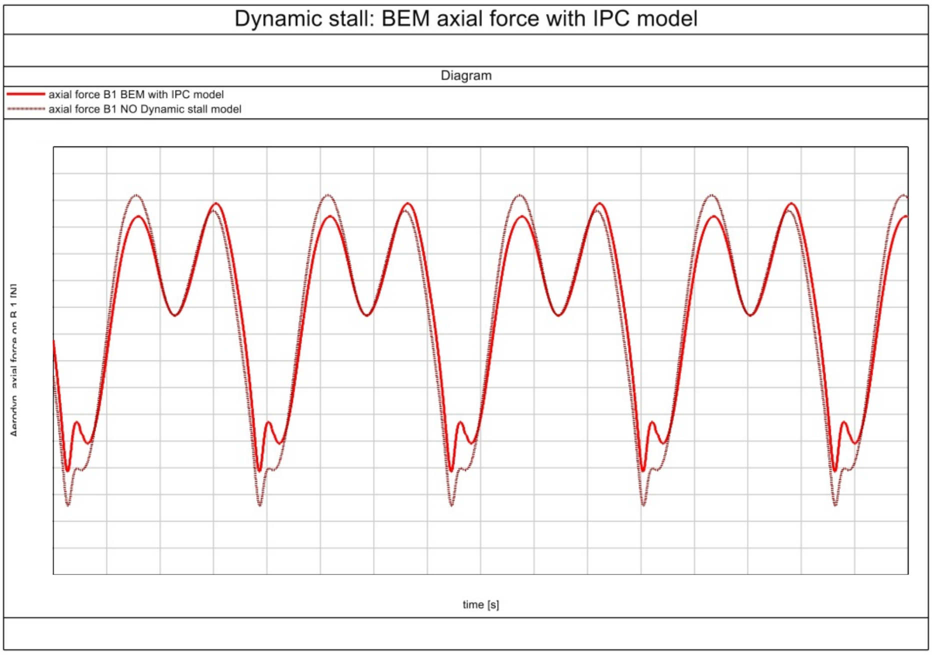


Figure 16: A PSD of the axial force on blade 1 including the IPC model and a dynamic stall model ("BEM no IPC") compared to a calculation with IPC model and without dynamic stall model ("No Dynamic stall model")

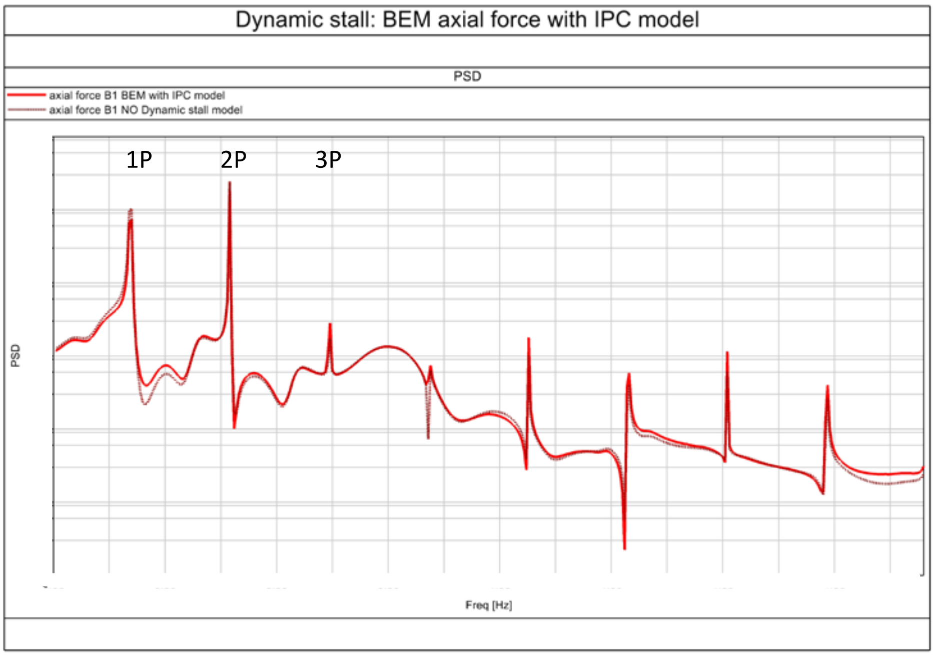


Figure 17: The blade root moments for a pitching blade with and without dynamic stall model

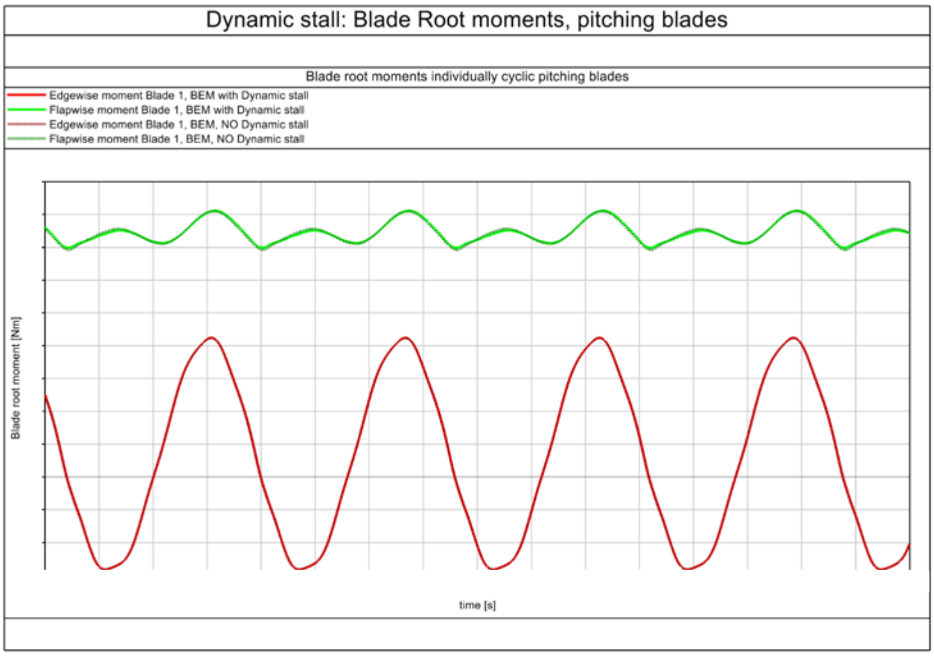
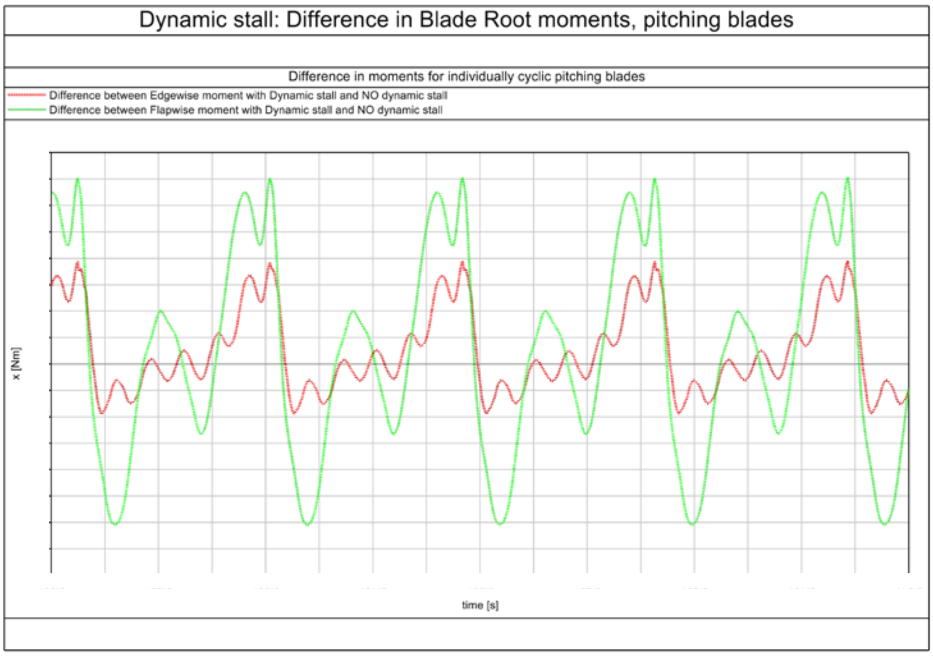


Figure 18: The difference between the blade root moments calculated with dynamic stall model and without dynamic stall model



3.6 Effect IPC model on AWSM results

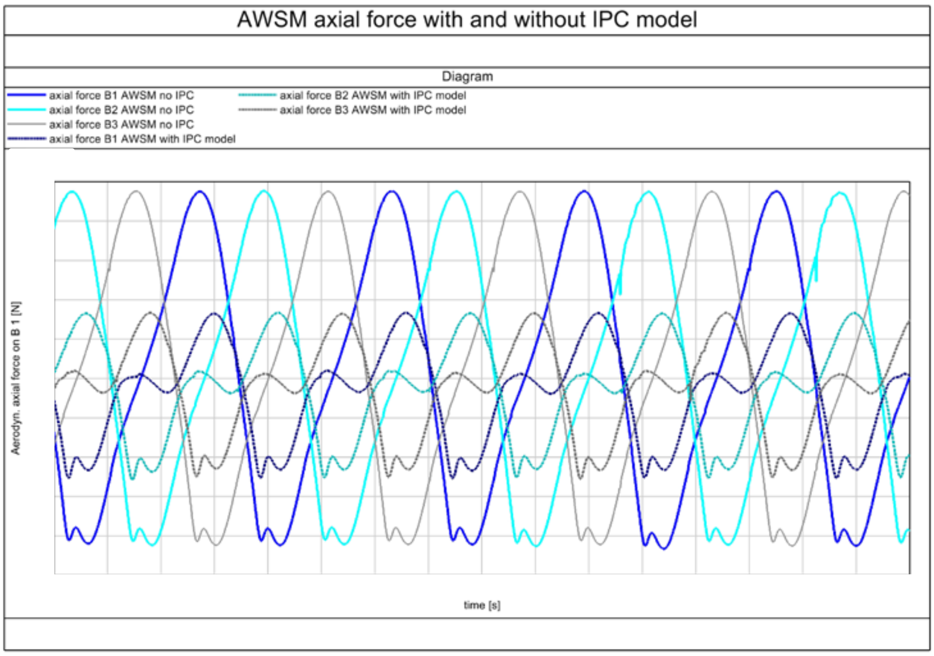
The calculations that were discussed in section 3.4, were also performed using the AWSM aerodynamic option in the ECN Aero-Module. This is a model based on free vortex wake calculations and is based on more physics than the BEM method. Of course this comes at the price of a calculation time that is significantly longer than the BEM calculations.

To derive a BEM model, there are many assumptions used that are not actually valid for a wind turbine and especially in yaw these assumptions are all violated. However, thanks to different engineering models and corrections included in BEM approaches, the end results has proven to be good enough to design wind turbines.

As mentioned before, all calculations using AWSM include the first order dynamic stall model from Snel (Snel).

The axial forces on each blade, as calculated using the AWSM model, with and without the IPC model are illustrated in **Figure 19**. There is again a clear reduction in the amplitude of the variation in axial force when the IPC model is included.

Figure 19: A short sequence of the axial force on each blade as determined in simulations based on AWSM.



The blade root moments in edgewise and flapwise directions are illustrated in **Figure 20** and **Figure 21** respectively. There appears to be very little difference between the two simulations when looking at the edgewise moments, but the cyclic pitching of the blades does result in a significant reduction in the amplitude of the flapwise moments, for the simulation with IPC model it is only 56% of the amplitude with constant pitch angle.

The PSD's of the blade root moments are plotted in **Figure 22** and **Figure 23**.Again, there is little difference visible for the edgewise blade root moments, but there is a clear reduction in the flapwise loads around the 1P frequency.

Figure 20: Blade root edgewise moments for a short sequence as determined in simulations based on AWSM

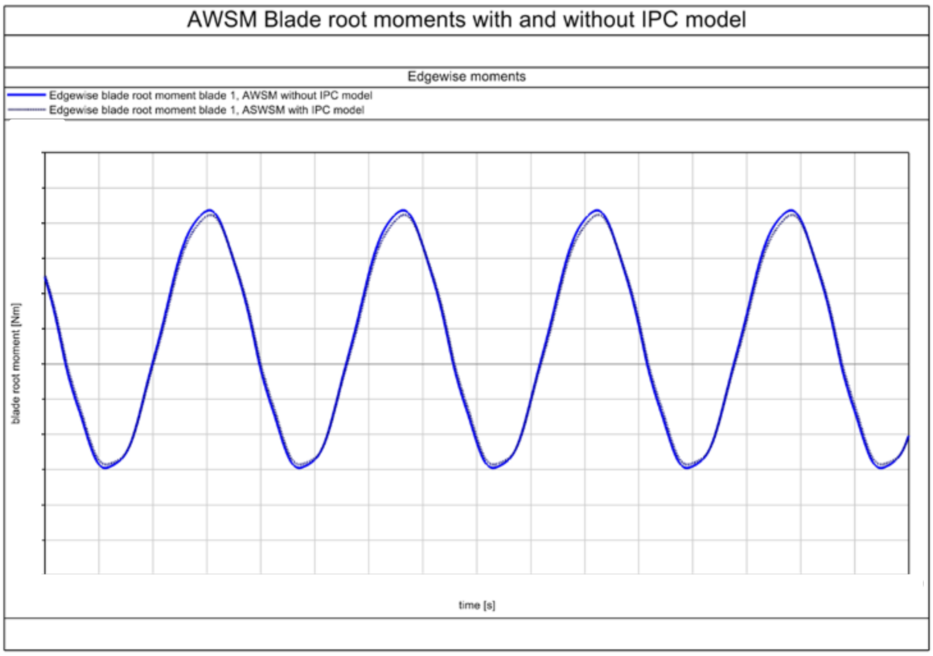


Figure 21: Blade root flapwise moments for a short sequence as determined in simulations based on AWSM

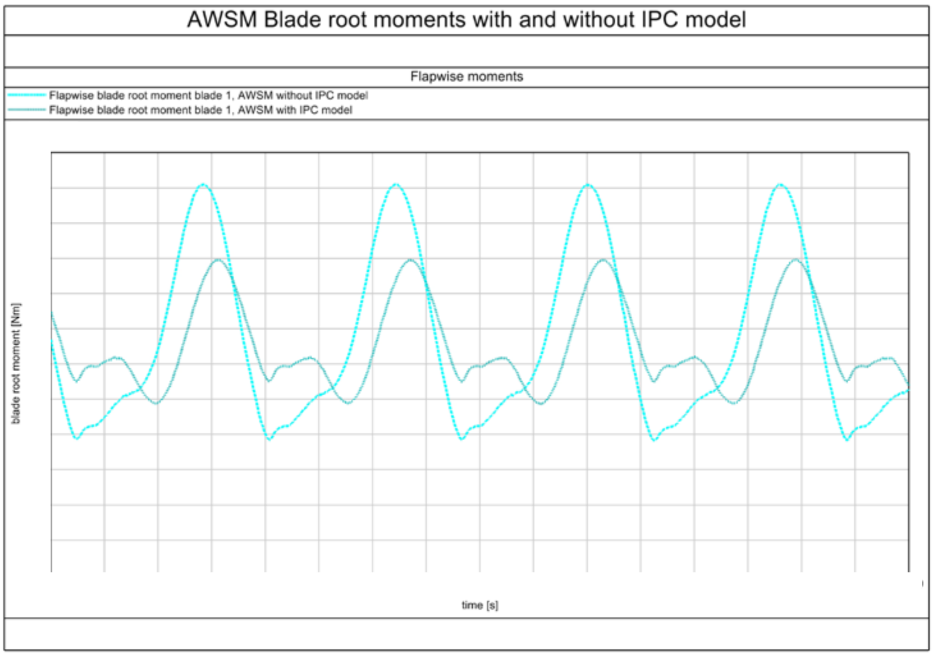


Figure 22: PSD of flapwise moments with and without IPC model

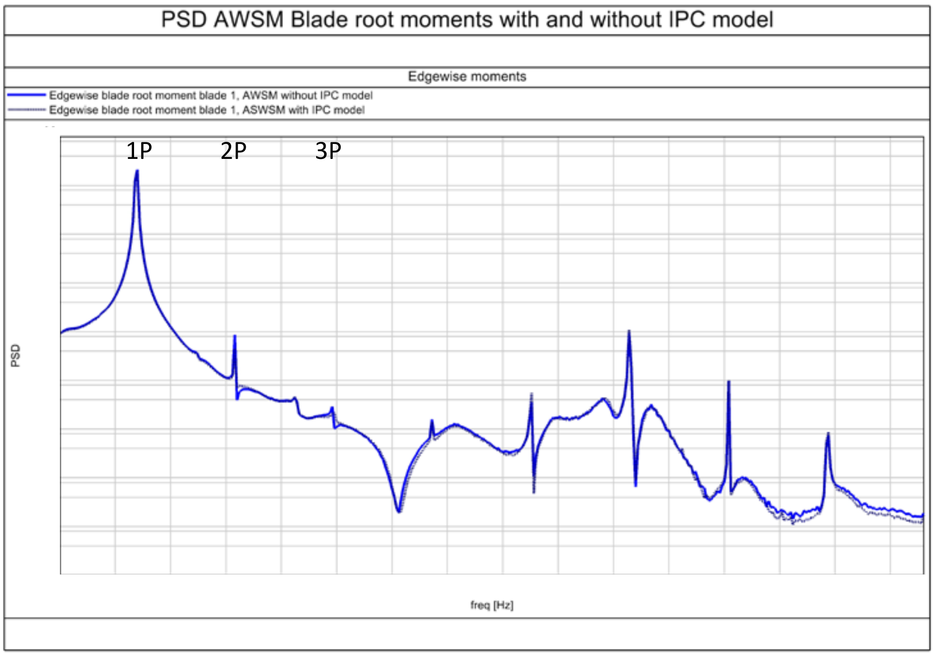
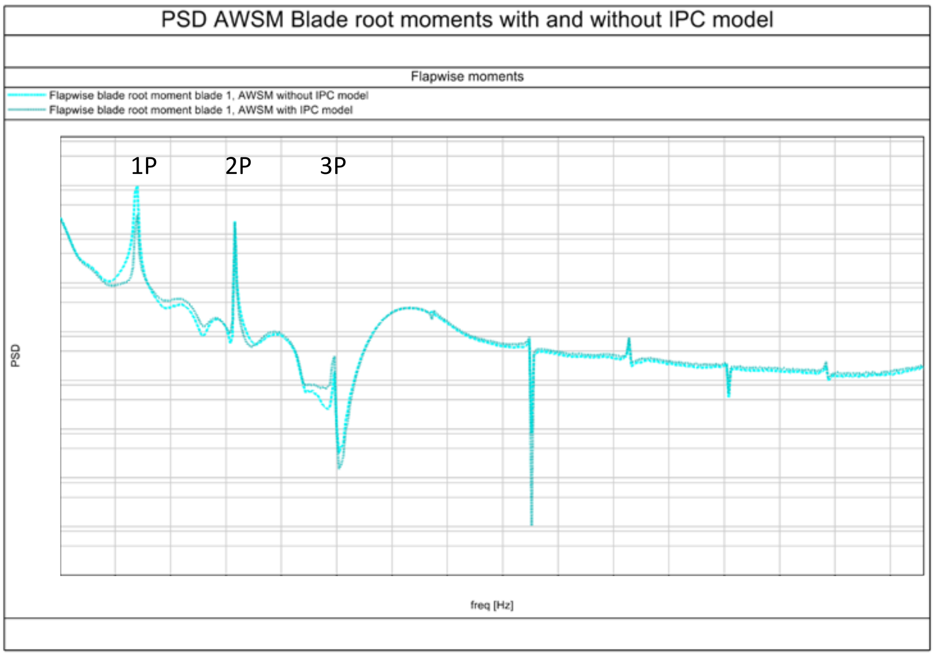


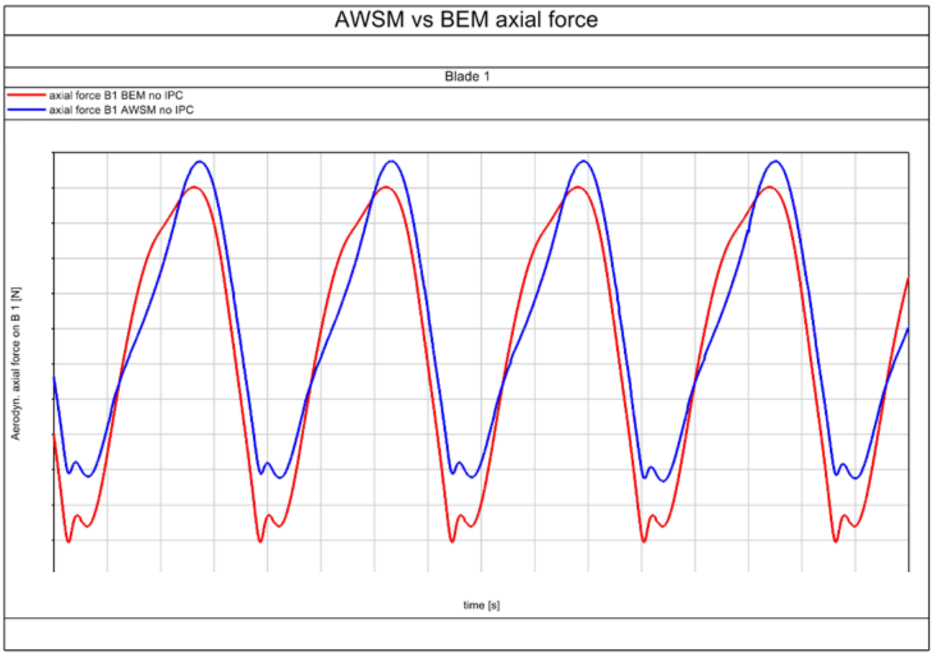
Figure 23: PSD of edgewise moments with and without IPC



3.7 Differences between BEM and AWSM

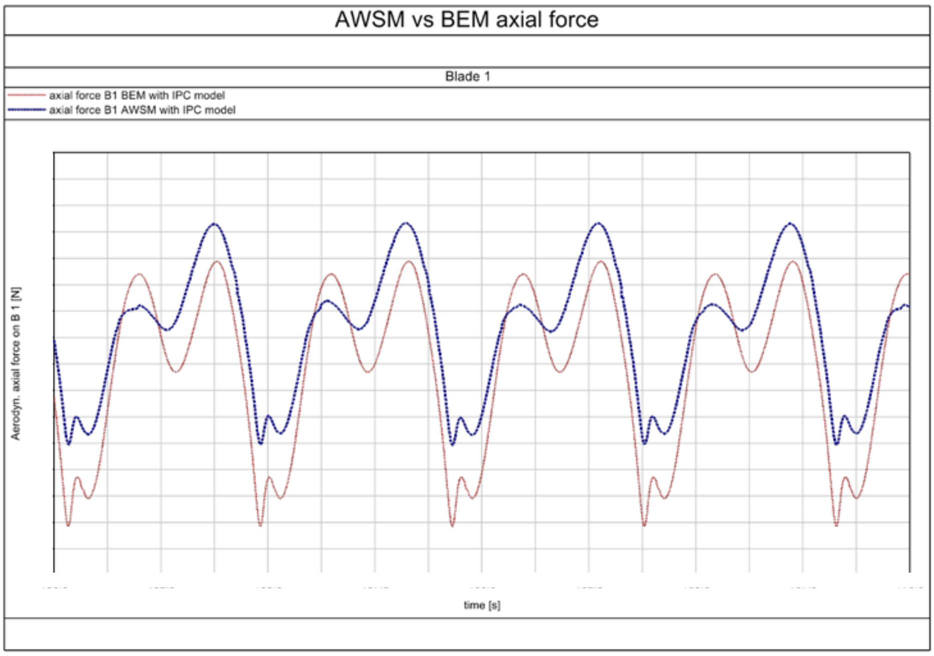
The most relevant outcome of the simulations should be the comparison of the results obtained with BEM and those obtained using AWSM and if there is reason to try to find an additional correction to the BEM equations, or to conclude that it would be recommended to do additional load calculations using a more detailed aerodynamic model, such as AWSM. Therefore the results obtained using BEM and those obtained using AWSM should be compared.
First the aerodynamic axial force for the constant pitch angle cases is shown in

Figure 24: A short sequence of the aerodynamic axial force on blade 1, as calculated for a constant pitch angle using BEM and AWSM



There is a significant difference visible in the graph, between the calculated results using BEM and those using AWSM. Validation of both BEM and AWSM codes has shown that in general AWSM will perform better in strongly yawed cases [Boorsma et al.]. The graph clearly illustrates that the amplitude for the AWSM case is smaller than the amplitude obtained using the BEM model. The average axial force is higher for AWSM than for BEM.
Looking at the aerodynamic axial force on a pitching blade (**Figure 25**), there is also a significant difference between the results obtained using BEM and those obtained using AWSM. The average calculated using AWSM is, just as it was in the case of the constant pitch angle simulations, larger than the average in BEM. The amplitude for BEM is also again larger than the amplitude for the AWSM results.

Figure 25: A short sequence of the aerodynamic axial force on blade 1, as calculated for cyclic pitching blades using BEM and AWSM



Looking at the PSD's of these signals, shows another interesting difference, the peak at 3P is very much present in all results obtained using the BEM model, but almost invisible for the results obtained using the AWSM model, see **Figure 26** and **Figure 27**. Of course looking at the blade root moments is more important for comparing wind turbine loads. In **Figure 28** the edgewise moments are shown for the different simulations, using BEM or AWSM and with constant pitch angle or with the IPC model included. There is very little difference visible in the edgewise moments. However, looking at **Figure 29** with the flapwise blade root moments, there are very clear differences in the results of the different simulations. As expected and discussed in the previous sections, there is a clear reduction in the amplitude of the variations in the flapwise moments when the IPC model is included, but there are also clear differences between the BEM and AWSM results. If there is no IPC model included in the calculation, there is a larger amplitude in the variation of the BEM results that of the AWSM results. This corresponds to the earlier difference shown for the aerodynamic axial force. The effect of the IPC model on these loads is also different for the two aerodynamic models. The difference is illustrated in **Figure 30**, where the flapwise moments calculated with the IPC model have been deducted from the flapwise moments as calculated without the IPC model. This graph shows a clear difference in the maximum reduction in the flapwise moments, it is larger when using BEM than when using the AWSM model. The increase in the loads (resulting in a smaller amplitude) is also larger when calculating with the BEM model than with the AWSM model, as can be seen looking at the negative values of the graph.

Figure 26: PSD of the aerodynamic axial force on blade 1 for constant pitch angle, using BEM and AWSM

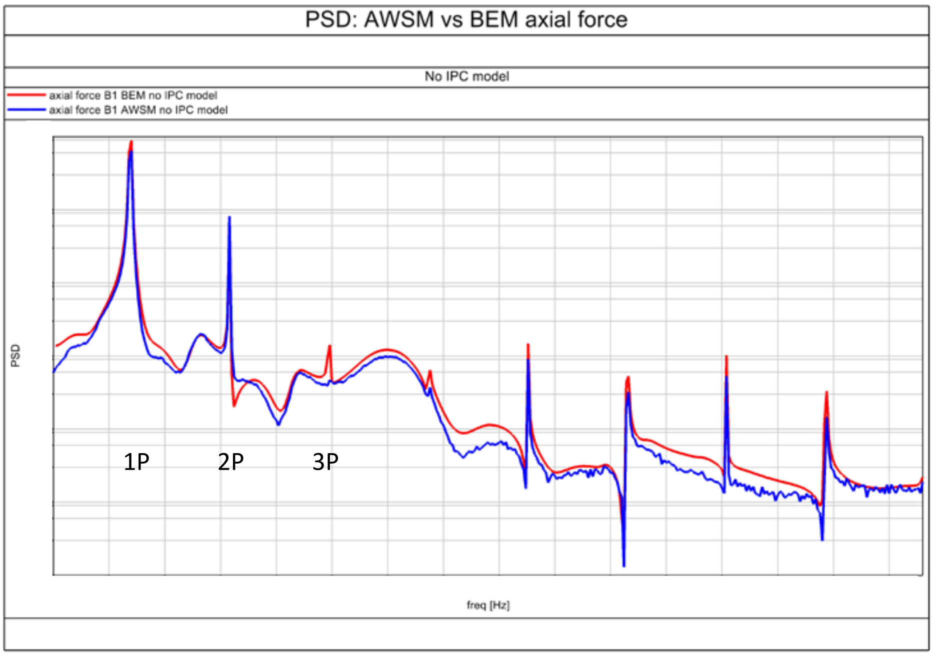


Figure 27: PSD of the aerodynamic axial force on blade 1 for cyclic pitching blades, using BEM and AWSM

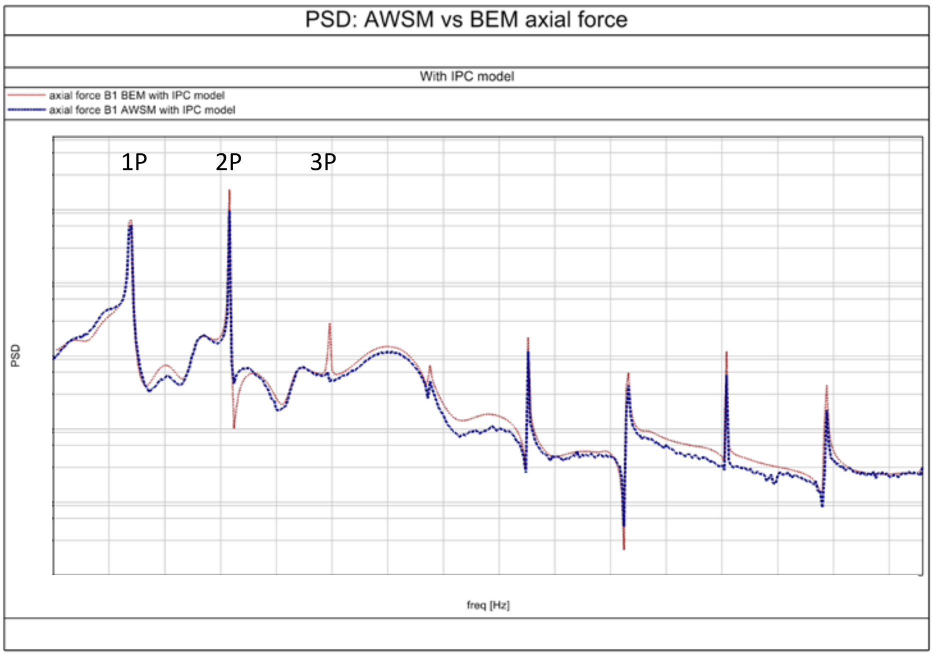


Figure 28: Edgewise moments on blade 1 as calculated using BEM and AWSM, for constant pitch angle and pitching blades

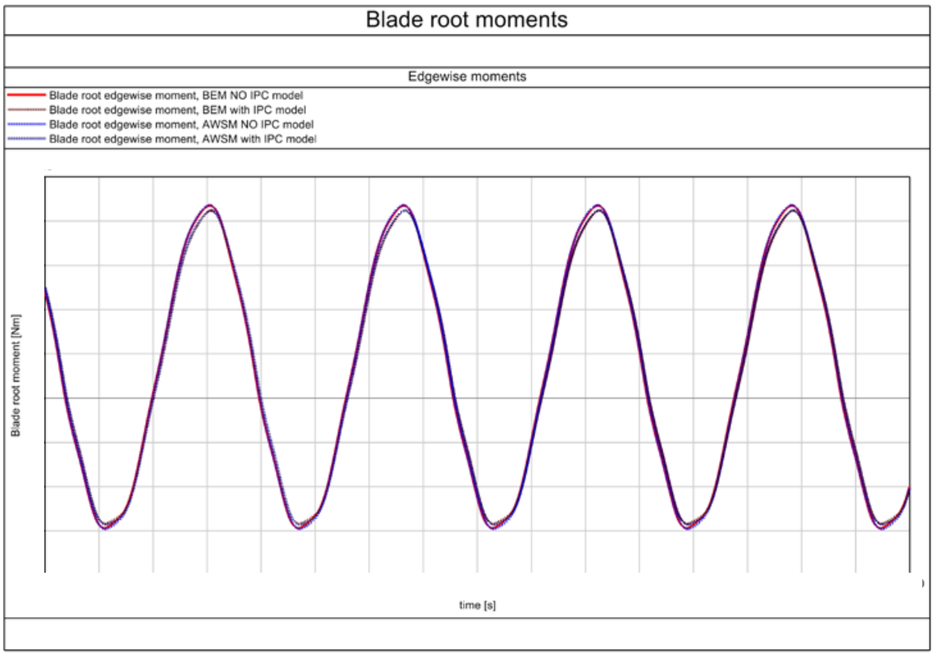


Figure 29: Flapwise moments on blade 1 as calculated using BEM and AWSM, for constant pitch angle and pitching blades

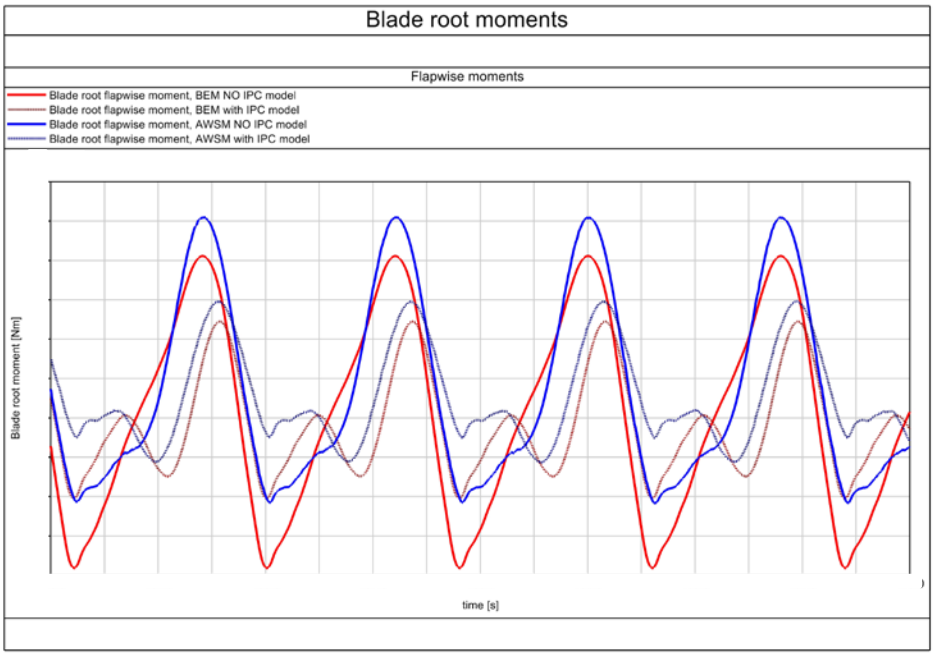


Figure 30: Difference in Blade root flapwise moments due to adding the IPC model, for BEM and AWSM respectively

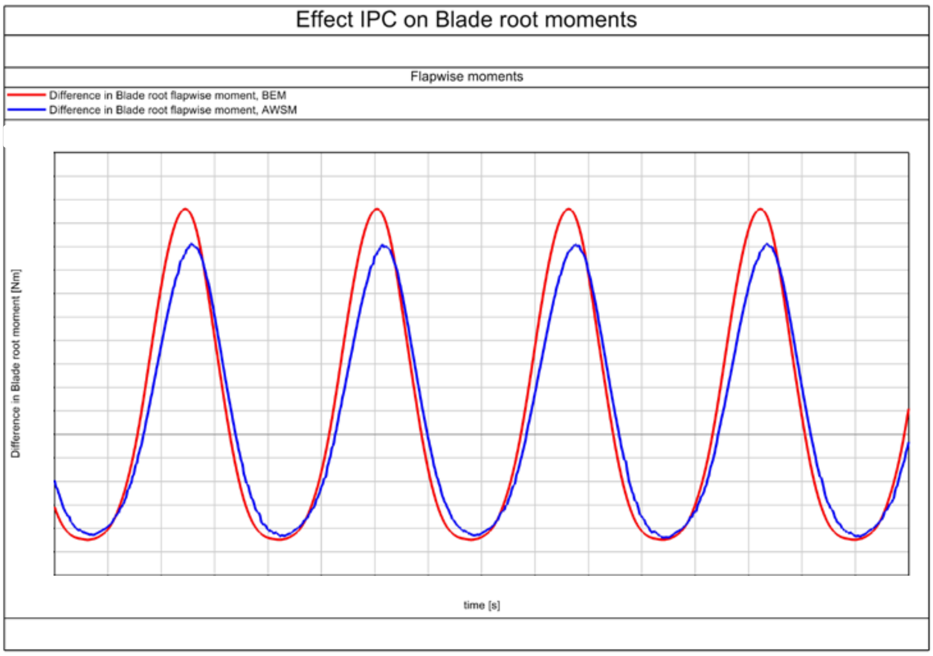
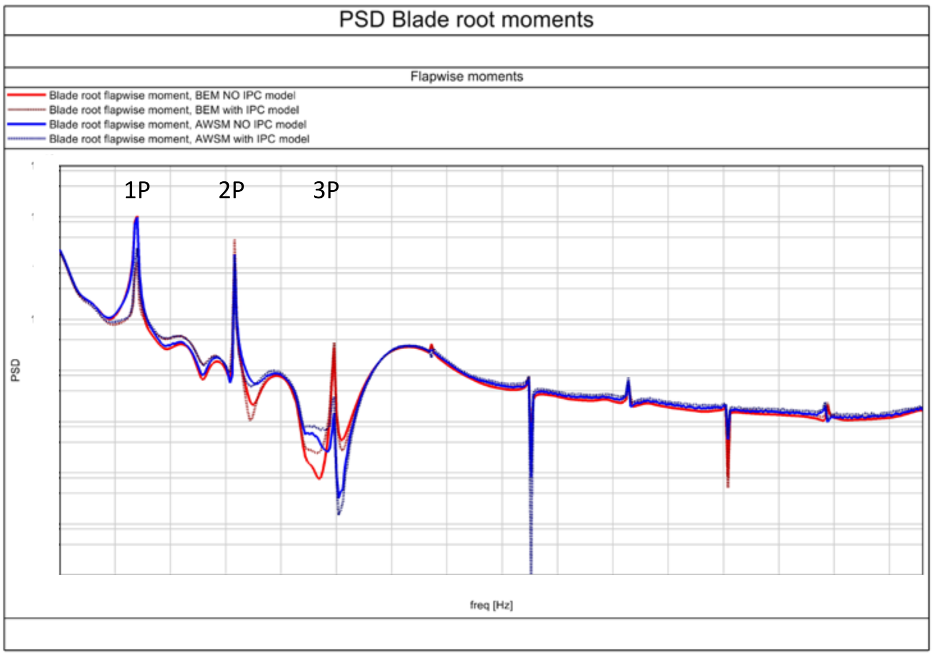


Figure 31: PSD of the flapwise moments at the blade root of blade 1, for fixed pitch and pitching case, using BEM and AWSM



The PSD in **Figure 31** indicates that the main differences in the results comparing BEM to AWSM are in the range just after 2P and around 5P.

4 Conclusions

The main results of the comparisons discussed in this report can be summarised as follows:

- The average flapwise blade root moment when using AWSM is slightly higher than when using BEM. This is due to the fixed wake approach that has been used in these calculations, in order to limit the calculation time somewhat only one free wake point was included.
- The effect of the IPC model on the blade root flapwise moments and the aerodynamic axial loads is smaller when using the AWSM model than when using the BEM model.
- A dynamic stall model has a significant effect on the loads for a blade that undergoes a cyclic changing angle of attack (e.g. due to yaw), but the effect is smaller than the effect of IPC itself.

The use of a more advanced aerodynamic code such as AWSM, preferably with the optimal settings concerning accuracy (so enough free wake points) should be considered when performing simulations of a turbine that includes IPC. The differences found in this report were in general not too large, but the more accurate simulations become, the more optimal a wind turbine design will be. From a practical point of view, it will not be possible to use AWSM for all load cases, so one should select those load cases with the largest difference between the flow conditions of the individual blades. In future perhaps it will be possible to add a more advanced engineering model to BEM to further improve the reliability of BEM.

References

H. Snel. *Heuristic modelling of dynamic stall characteristics*. In European Wind Energy conference, October 1997, Dublin Castle, Ireland, pages 429–433, 1997

J.G. Holierhoek, J.B. de Vaal, A.H. van Zuijlen, and H. Bijl. *Comparing different dynamic stall models*. Wind Energy, 16(1):139–158, 2013.

http://www.SIMPACK.com/

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

K. Boorsma, F. Grasso, J.G. Holierhoek, *Enhanced approach for simulation of rotor aerodynamic loads*, EWEA OFFSHORE 2011 Amsterdam, December 2011