TNO PUBLIC

Westerduinweg 3
1755 LE Petten
P.O. Box 15
1755 ZG Petten
The Netherlands

www.tno.nl

T +31 88 866 50 65

TNO report

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TKI WoZ VortexLoads
Final report

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Author(s)	K. Boorsma, F. Wenz[†], M. Aman[‡], C. Lindenburg[∓], M. Kloosterman[∓] [†] USTUTT-IAG [‡] DNV-GL [∓] LM Windpower

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Since April 1st, 2018 ECN and TNO have joined forces.

Acknowledgement

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Project title	TKI WoZ VortexLoads
Project number	TEWZ117007
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Project period	1st August 2017 - 30th September 2019

The project partners are:

- ECN part of TNO: Project coordinator, applied research
- LM Wind Power: Blade manufacturer
- DNV-GL: Developer of aero-elastic simulation software package Bladed
- GE: Turbine manufacturer
- IAG University of Stuttgart (subcontracted): CFD simulations

Summary

The TKI WoZ VortexLoads project consortium has made a great contribution to more accurate wind turbine design load calculations, paving the way for further reductions in the cost of wind energy. A variety of Computational Fluid Dynamics (CFD) simulations have confirmed the hypothesis that conventional Blade Element Momentum models overpredict fatigue loading for wind turbine design load calculations up to 20% depending on the load case considered. On the other hand the unsteady loading characteristics from lifting line free vortex wake models were shown to agree well with the CFD simulations. A comparison to field data measurements agrees with this observation. New light has been shed on the cause for the observed differences and several model improvements have been developed, both to reduce the computational effort and improve robustness of vortex wake simulations (making these ready for application to certification load calculations) as well as to make BEM models more accurate. The improved modelling and the corresponding aerodynamic load reduction have a potential to reduce blade mass and/or further upscaling of the blades leading to a reduction in LCOE.

Contents

1 Background

Both Dong and ENBW expect that from 2025 on offshore wind in Germany can operate without subsidy. Also in the Netherlands tenders without subsidy are emerging. To meet this goal, large and reliable wind turbines are needed. At that time the size of wind turbines will be in the range of 13-15MW. For a reliable design, dependable aerodynamic models are needed.

At this moment there are roughly three categories of aerodynamic models available:

1. Blade element momentum (BEM) models
2. Vortex-wake models
3. Computational Fluid Dynamics (CFD) models

In the industry, the blade element momentum method is the workhorse for wind turbine certification load calculations. The development of more advanced codes like vortex-wake models for offshore wind turbine applications started in early 2000. Vortex-wake models give a more accurate description of the rotor wake aerodynamics, but are more computationally expensive. Nevertheless with increasing computational power, vortex-wake models are most likely a good alternative for BEM. As part of the EU-project AVATAR [1] a fatigue load comparison round was performed between various aero-elastic codes using BEM and vortex-wake models. Calculations were done for a 10MW rotor during normal operation. The figure below shows the difference with respect to the average for the different BEM and vortex-wake (VRX) models at 8m/s wind speed. Over the blade span a reduction of roughly 15% of blade out-of-plane fatigue equivalent moments is visible for the vortex-wake models. Besides that large differences were found in the implementation of the BEM models. More results are given in the dedicated AVATAR report [2].

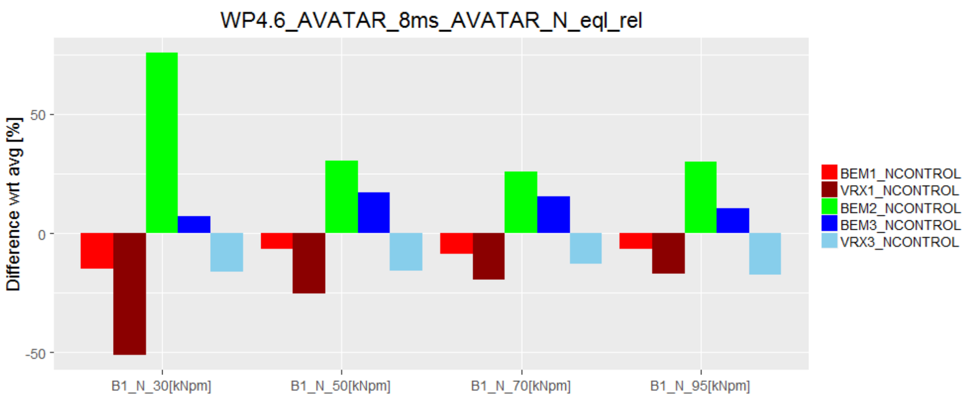


Figure 1.1: Comparison of blade root out of plane fatigue equivalent moments at 0%R, 30%R, 50%R, 70%R and 95%R. from AVATAR d4.6 [2]

Since the out-of-plane blade moment drives the structural design and the potential for upscaling, it is important to reduce uncertainty in the results of the aerodynamic models. There is a need to identify where the difference originates from and to validate the vortex-wake models for fatigue load calculations. Since the computational power needed for CFD calculations is huge, it is not expected that CFD models will be used for design load calculations in the near future. However CFD models are, because of the detail of the calculated flow field, a good alternative for wind tunnel measurements. Finally for Dutch offshore wind farm developments the improved reliability of the aerodynamic models is important for the future design and application of wind turbines larger than 10MW and for the design of the support structure, where the rotor loads are introduced at the tower top.

This report gives an overview of the TKI WoZ VortexLoads project, both from a technical as well coordinating point of view. Firstly a project description is given in Chapter 2, also containing details about the approach, budget, dissemination and other coordination aspects. Chapter 3 gives a summary of the technical achievements per task. Conclusions and recommendations are given in Chapter 4.

2 Project overview

ECN part of TNO coordinated the TKI WoZ VortexLoads project, which ran from August 2017 to September 2019. A strong consortium was built consisting of the whole technology chain from research to industrial application (LM Wind Power, DNV-GL, GE and IAG University of Stuttgart).

2.1 Objectives and results

The following research questions are central to the TKI WoZ VortexLoads project:

- How well are fatigue loads estimated in turbulent inflow conditions?
- How can we further reduce the uncertainty of aerodynamic modeling in load case simulations?
- How can we facilitate the introduction of vortex-wake models in design standards?

Corresponding to these questions the objective of the TKI WoZ VortexLoads project is to make vortex-wake models ready for application to certification load calculations. And to evaluate the reduction in fatigue loading using a vortex-wake model instead of the blade element momentum model. Improved modeling and a potential reduction of the aerodynamic load results in less material use for manufacturing of blades leading to a reduction in LCoE.

This project delivers validated vortex-wake models for certification of wind turbines by industry. For this a database with results of turbulent inflow CFD test cases is generated. Both blade element momentum and vortex-wake models are used and compared for a selection of fatigue design load cases. The vortex-wake model is implemented in the aero-elastic codes for application to design load calculations by the industry.

2.2 Work plan

The project consisted of five technical work packages. Each work package is coordinated by one of the project partners. The corresponding work descriptions are highlighted below in more detail.

WP1 Numerical wind tunnel tests (CFD) in turbulent inflow
(ECN part of TNO (WP-lead), DNV-GL, LM Wind Power)

In this work package a data base of CFD test cases with turbulent inflow is created. The CFD calculations are performed using the CFD model of the AVATAR blade. The calculations will be performed by the University of Stuttgart as subcontractor. In this work package the following task will be performed:

- Design representative test cases;
- Checking the calculated CFD data for the validation purpose.

WP2 Validation of BEM and Vortex-wake models with numerical tunnel data
(ECN part of TNO (WP-lead), DNV-GL, LM Wind Power, GE)

In this work package calculations with the blade element momentum model and the vortex-wake model are compared with the test cases of the turbulent CFD calculations. No structural dynamics is included. Although the focus is on structural loads the energy production is also compared and reported. Tasks in this work package are:

- Checks on correct modelling of AVATAR blade in aerodynamic codes of partners for simple load cases like for instance uniform wind;
- Simulate selected numerical wind tunnel cases with BEM and vortex-wake codes;
- Compare simulation results of different codes with numerical wind tunnel (CFD) results.

WP3 Validation of BEM and Vortex-wake models with full scale on-site measurements
(ECN part of TNO)

In this work package the aeroelastic models are compared with full scale on-site measurements. Instead of a 10MW wind turbine now a 2MW wind turbine is used for validation. Focus is on the fatigue loading. The work package contains the following tasks:

- Select test cases from full scale on-site EWTW measurements for validation;
- Simulate the selected test cases;
- Validate the models on fatigue loading.

WP4 Improvement of BEM and Vortex-wake models
(ECN part of TNO (WP-lead), DNV-GL, LM Wind Power)

During the validation in WP2 and WP3 issues may be raised about the aerodynamic models that need to be improved. The following tasks are foreseen in this work package.

- Improve the aerodynamic models based on the outcome of the validation
- Simulate and compare results with validation
- Make improvements of the computational speed of the vortex-wake methods.

WP5 Design load calculations and recommendations for the use of vortex-wake models in the standard
(ECN part of TNO, DNV-GL, GE, LM Wind Power (WP-lead))

In this work package fatigue design load cases during operation are calculated using the aero-elastic codes of the partners. Results of codes of different partners will be compared, where also energy production and ultimate loads are considered. Both blade element momentum and vortex-wake models are used. The experience from the usage of vortex-wake models will be formulated in a set of best-practice recommendations. This work package contains the following tasks:

- Improve interface for smooth integration of aerodynamic codes with structural dynamic code.
- Perform calculations of fatigue design load cases during operation using BEM.
- Select wind conditions with largest contribution to fatigue.
- Perform calculations with vortex-wake model for the selected wind conditions.
- Create best-practice recommendations for the use of vortex-wake models in wind turbine design load calculations.

2.3 Coordination

Apart from the frequent email-traffic, half year meetings were organized to facilitate cooperation between the partners [3, 4, 5, 6, 7]. Here the meeting host has been the coordinating party. Generally speaking these meetings provided a platform to give feedback and enhance the research. A project teamsite was established to facilitate the exchange of data and reports. Apart from organizing the meetings and facilitating contact, the coordinator has had its hand in steering the project results towards the defined deliverables, within the defined temporal and financial boundaries. A yearly progress report has been submitted to the sponsor. The transition from WMC to LM Wind Power, which occured during the running of the project, has been formally declared by a form which was submitted to RvO. Gathering a project team that includes a variety of competences has resulted in a fruitful and pleasant cooperation. Financially, all partners have generally speaking performed their tasks within the allocated subsidy. Here it should be mentioned that a sound definition of the comparison set-up between CFD and lifting line simulations by the consortium has taken more time and budget than anticipated. This has been accommodated by inputting in-kind resources, acknowledging the importance of the work.

2.4 Dissemination

Apart from the numerous technical reports written, several conferences and events have been visited to share project results and obtain feedback from the community. An overview of selected dissemination events and publications is given below.

- Overview presentation during TKI WoZ Matchmaking day 2018, February 2018, Utrecht
- Presentation and paper in “The Science of Making Torque from Wind” conference (TORQUE2018), June 2018 in Milano, Italy [8]
- Presentation and paper (to be published) in “Wind Energy Sciences” conference (WESC2019), June 2019 in Cork, Ireland
- IEA Task 29 meetings where an overview of the progress within TKI WoZ VortexLoads was presented:
  - Meeting at “The Science of Making Torque from Wind”, June 2018 in Milano, Italy
  - Meeting at NREL and University of Boulder, March 2019 in Boulder, US
- Project websites [9, 10]
- The TKI WoZ VortexLoads project resulted in numerous internal publications at the involved project partners

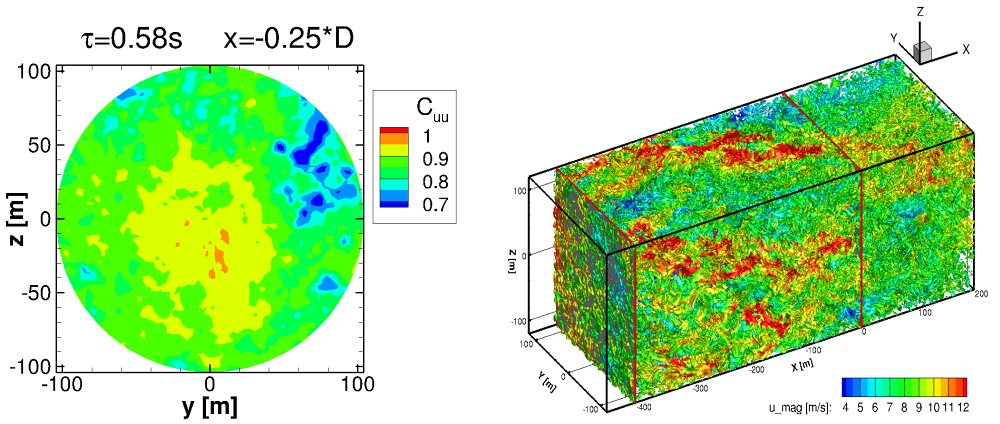
3 Technical Achievements

3.1 WP1 Numerical wind tunnel tests (CFD) in turbulent inflow

A CFD reference solution was calculated with the process chain for simulations of wind turbines developed at the Institute of Aerodynamics and Gas Dynamics (IAG, USTUTT). The main part of the chain is the CFD code *FLOWer*, which is complemented by different pre- and post-processing tools. To account for controller initiated changes in rotation speed and pitch, the variations in rotation speed and pitch were recorded during BEM simulations with controller and prescribed to the CFD simulation via approximated Fourier series.

In cases with turbulent inflow, besides a statistical evaluation, analysing the development of forces over time is an interesting approach which might give more insight. In order to do this a consistent input of background turbulence in the different codes has to be ensured. In CFD, turbulence is altered as it propagates through the domain until it reaches the rotor, while in BEM and vortex-wake models, the flow field, i.e. turbulence, is applied directly to the rotor. Moreover, the propagation in CFD is slowed down in front of the turbine due to the rotor blockage. To allow a time-dependent load comparison between the codes these CFD effects need to be compensated in the lifting-line-code input.

A comparison between the codes was enabled by extracting the turbulent velocity field from empty box (without rotor) CFD simulations at the anticipated rotor position and using it as input to the lifting-line-codes. As a consequence, alterations in turbulence characteristics and decay of vortices due to propagation in CFD were captured in the velocity field. Hence, the turbulence acting on the rotor is identical for CFD and lifting-line codes. The induction of the rotor and the corresponding reduction in propagation speed (axial flow velocity), however, is missing in an empty box CFD simulation. This means in CFD simulations a specific turbulent eddy reaches the rotor position slightly later when a rotor is present compared to a empty box CFD simulation, i.e. in the lifting-line code input. This effect is accounted for by the procedure described in the following.



(a) Cross correlation coefficient between an empty box and rotor CFD simulation at $x/D = -0.25$ for optimized blockage correction

(b) Visualization of wind field deformation from injection to rotor plane

Figure 3.1: Wind field cross correlation and deformation

To investigate how the flow fields of both CFD simulations (with and without rotor) are correlated while approaching the rotor position, the velocity fluctuations u_i' were compared using a cross-correlation. The cross-correlation was evaluated separately for each velocity component in multiple planes perpendicular to the rotor axis upstream of the rotor position. The blockage effect of the rotor could be quantified per plane by shifting the velocity field of the CFD simulation with rotor in time and performing the cross-correlation again. The temporal offset which yields the highest correlation value quantifies the delay in inflow per plane. After averaging the locally varying temporal offsets for each velocity component over the rotor-disk-area in each plane, the values were used to extrapolate the temporal offset τ_0 at the rotor plane by performing a least-square-fit with $\tau(x/D) = a \cdot exp(b \cdot x/D)$. The extracted velocity field from the empty box simulation was shifted by the resulting temporal offset before using it as lifting-line-code input. As a result, a direct comparison of loads over time between CFD and lifting-line-codes is possible.

Overall, six cases were simulated using CFD. The simulation length was decided to be 400 s (with one exception of 200 s) as a compromise between IEC-61400-1 guideline and computational costs. The cases vary with respect to mean inflow velocity, turbulence intensity, turbulent length scale and controller behavior. The structure was kept rigid. The results of the CFD simulations are public and can be requested from IAG, USTUTT. For more details please consult the dedicated TKI WoZ VortexLoads WP1 report [11].

3.2 WP2 Validation of BEM and Vortex-wake models with numerical tunnel data

The CFD simulations from WP1 are carried out to verify the differences in dynamic loading and the resultant fatigue equivalents between BEM and vortex wake codes. Hereto a 'numerical' wind tunnel was set-up subjecting a rigid (or non-flexible) version of the AVATAR wind turbine model. Firstly comparisons in uniform, constant inflow conditions provided a good agreement between all code types, which is a prerequisite for a consistent comparison in more challenging inflow conditions. Sheared inflow conditions demonstrated a difference in the cyclic loading amplitude between BEM and vortex / CFD models. A parameter variation study revealed this difference to scale with the magnitude of the axial induction factor. Turbulent inflow simulations were carried out to verify the influence of turbulence length scale, turbulence intensity and thrust coefficient on the observed differences between the codes.

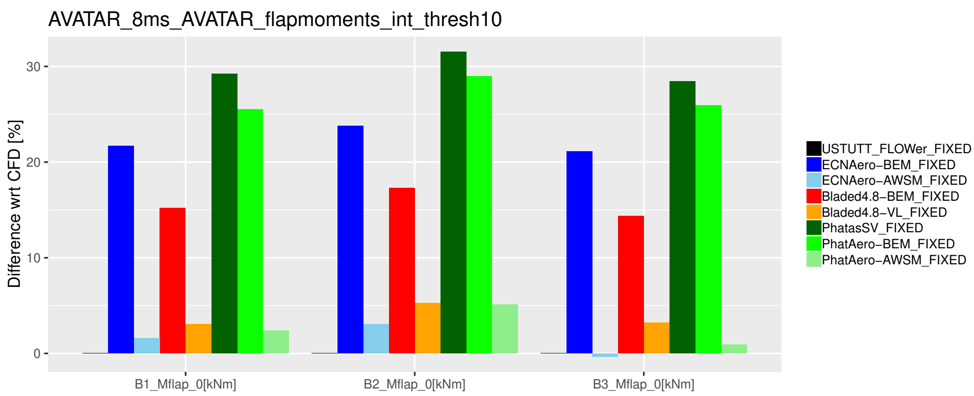
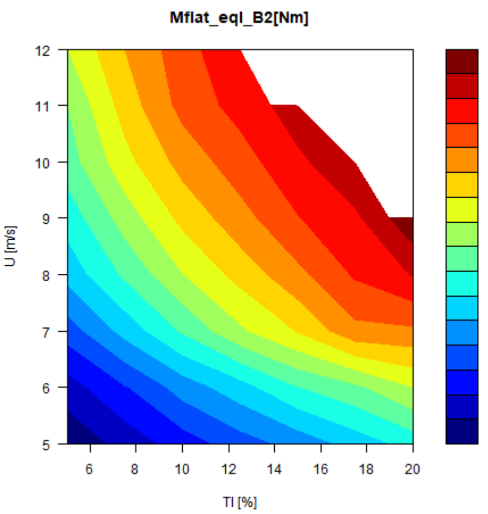


Figure 3.2: Relative comparison of integrated staircase plot values for the flapwise blade root moment, starting at a threshold of 10 counts

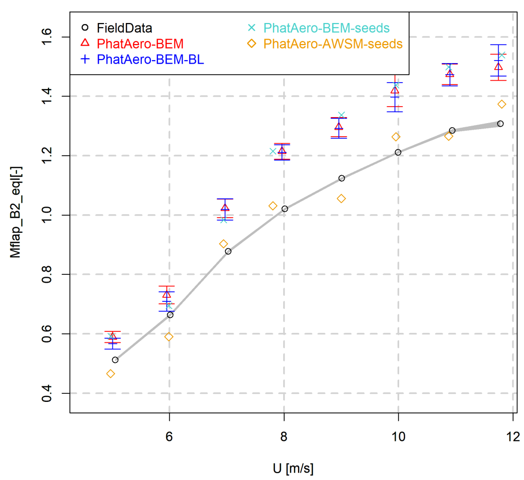
Concluding it can be stated that a variety of CFD simulations have confirmed the hypothesis that conventional BEM models overpredict fatigue loading for wind turbine design load calculations. The differences were shown to be partly related to the shed vorticity modeling. However, both for the shear and turbulent inflow cases a difference between BEM with a shed vorticity model on the one hand and vortex wake models on the other hand remains. Poor tracking of induced velocities with apparent wind speed variations as experienced by the blade was shown to be the underlying cause for the differences between the models, becoming increasingly important for higher thrust coefficients. It is recommended to have a further look into the cause for this difference. In addition to that it is recommended to perform a validation in a real rather than a 'numerical' wind tunnel, featuring a rotor in representative inflow conditions. For more details please consult the dedicated TKI WoZ VortexLoads WP2 report [12].

3.3 WP3 Validation of BEM and Vortex-wake models with full scale on-site measurements

Within the framework of the TKI WoZ VortexLoads project, a comparison was made between predicted and measured fatigue loads of a 2.5MW turbine at the EWTW test site. Over 7 years of measurements were analysed to obtain relevant statistics over 100.000 ten minute samples, of which about 25.000 remained after filtering out unwanted conditions (e.g. disturbed inflow). The data was bin averaged with respect to turbulence intensity and wind speed, after which dedicated simulations for each wind speed bin were ran at 10% turbulence intensity. A representative seed was chosen for each wind speed bin, which was simulated using the PhatAero-AWSM vortex wake code. The resulting load comparison shows BEM to over predict the fatigue equivalent flapwise blade root moments similar to the comparison against CFD, where the vortex wake model comes closer to the measurements (Figure 3.3(b)).



(a) Field data variation with wind speed and turbulence intensity



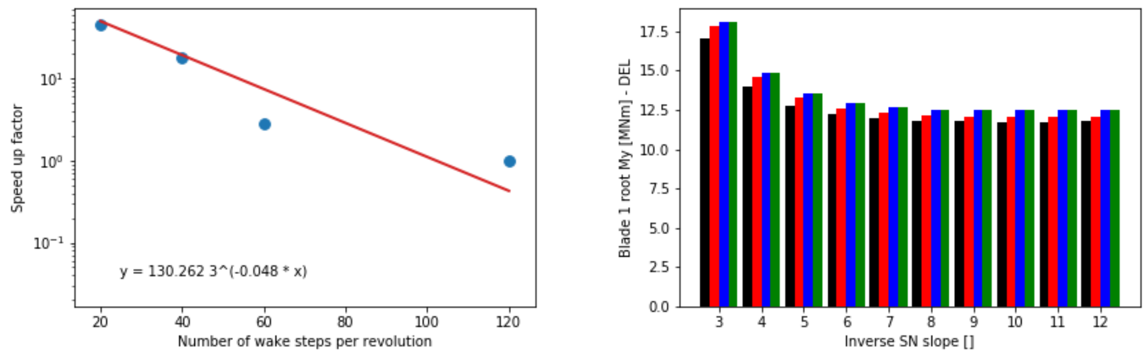
(b) Comparison between field data and simulations at TI=10% as a function of wind speed (all values are non-dimensionalized using the average of the field data results over the wind speed bins)

Figure 3.3: Visualization of damage equivalent flapwise blade root moment

Care should be taken drawing conclusions on the basis of these results, since it is felt that comparing aero-elastic simulations to the used field data set is subject to many uncertainties (inflow, control, model data, compensating errors etc.) that cannot always be verified. A great effort was made however to eradicate most of these, e.g. by running simulations for a large number of seeds and using a large number of measurement samples. It is recommended to set-up a dedicated field test in an effort to further reduce these uncertainties. Here one can think of using nacelle LiDAR to characterize the inflow conditions in more detail for synthetic wind field creation in combination with pressure sensors to measure sectional aerodynamic loading. For more details please consult the dedicated TKI WoZ VortexLoads WP3 report [13].

3.4 WP4 Improvement of BEM and Vortex-wake models

Within the framework of work package 4, improvements to both BEM and free vortex wake codes have successfully been implemented with the end goal to make wind turbine design load calculations more accurate. Here we can distinguish improvements to BEM type codes, which focus on engineering models and their implementation to make these more accurate. A model to account for the influence of the blade shed vorticity has been successfully implemented based on the time history of the vortices in the wake of each blade element. Application of this model was shown to bring BEM simulation results closer to the free vortex wake simulations at a relatively small extra computational expense. Another approach that has been researched is the definition of a representative streamtube wind speed in non-uniform inflow conditions for improved induction tracking. Although the first result of this approach both in sheared and turbulent inflow are very promising (in combination with shed vorticity modeling, the fatigue load difference with vortex wake codes almost disappears), more research is necessary on this topic to come to a more conclusive implementation, assuring not to unintendedly cover up other effects such as shed and trailed vorticity variation.



(a) Speed up factor for the AVATAR model in turbulent wind with varying vortex wake time step

(b) Damage equivalent flapwise blade root moment for AVATAR model in turbulent wind with varying vortex wake time step. 20 steps per revolution (black), 40 “ (red), 60 “ (blue), 120 “ (green)

Figure 3.4: Effect of varying wake update frequency on computational effort (left) and accuracy (right)

The improvements to free wake vortex codes focus on ways to reduce the computational effort associated with running them. Distinguishing between wake update frequency and aerodynamic sample time was shown to have a great potential in reducing CPU time (Figure 3.4). Limiting the number of free wake points and total wake length are obvious candidates to save computational time. Progressively skipping shed vortices in the far wake was shown to have a great reduction potential, with a minimal impact on the accuracy of (un)steady loading characteristics. For optimum computation speed it is vital to make use of the vector-parallel architecture in modern-day CPU’s to carry out multiple floating-point operations per clock cycle. This was achieved by laying out the data contiguously in memory and by writing loops that modern compilers can vectorise, resulting in a computational effort of about 20 times the simulation time for vortex wake codes. For more details please consult the dedicated TKI WoZ VortexLoads WP4 report [14].

3.5 WP5 Design load calculations and recommendations for the use of vortex-wake models in the standard

Within the TKI WoZ VortexLoads project investigations are done into the application of vortex wake models to calculation of wind turbine design loads.Several design recommendations in terms of conditions and load cases for which the use of vortex wake programs give additional value compared with the BEM based design programs are given. Scoping analyses have been performed with both BEM based programs and the Vortex Wake program AWSM for the entire fatigue load set. Although only a set of normal production load cases is calculated with AWSM it is expected that the reduction in overall fatigue damage by using the program AWSM may be up to 5% for the AVATAR rotor, which can be translated either in a blade mass decrease or blade length and power increase. Within the TKI WoZ VortexLoads project, the existing BEM based program has been extended with an algorithm that describes the influence of the local blade wake; the 'Blade Shed Vorticity' contribution. This algorithm gives an overall fatigue load reduction of about 2% compared with the BEM based programs without this Blade Shed Vorticity contribution. It is noted that the given percentages are obtained for the AVATAR turbine featuring a low induction rotor and may vary depending on the design operating axial induction.

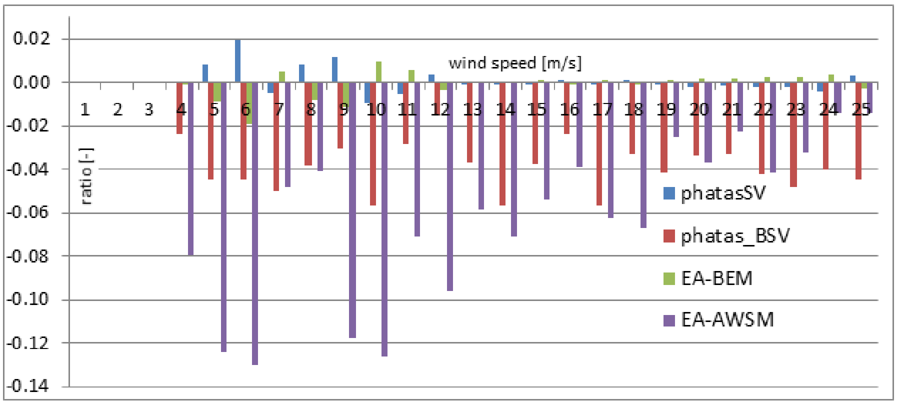


Figure 3.5: Ratio of blade root flap fatigue loading relative to the average of phatasSV and PhatAero(EA)-BEM as a function of wind speed

During the research within the TKI WoZ VortexLoads project several options have been added to facilitate efficient communication between structural dynamic and aerodynamic calculations to reduce overall computational time. Also some scoping analyses have been performed into the recommended settings to perform a reasonable accurate calculation with the Vortex Wake programs. These settings may still give a serious amount of computation time, but it was kept in mind that the choice of a vortex wake calculation instead of a BEM based calculation is based on a more accurate calculation.

From the results of this work package the following conclusions can be drawn:

- Vortex wake programs require some knowledge and aerodynamic expertise to perform an accurate calculation. Given this expertise, the vortex wake program AWSM was tested to be reliable for the cases considered while it also has shown to be robust for serious up- and down- scaling of wind turbine dimensions.
- The interaction between structural dynamics and aerodynamics was successfully improved in the program phat-AERO which communicates with the ECN-Aeromodule. This significantly reduces the overall computational effort needed for running an aero-elastic code with a vortex wake model.

- The difference in overall fatigue from a load set calculated with a vortex wake code and a load set calculated with BEM based programs may be up to 5% for the AVATAR rotor.
- Extending a BEM based model with a shed vorticity extension brings the overall fatigue load prediction closer to a vortex wake model for the same turbine, resulting in about 3% difference.

For more details please consult the dedicated TKI WoZ VortexLoads WP5 report [15].

4 Conclusions and Recommendations

The consortium has made a great contribution to more accurate wind turbine design load calculations, paving the way for further reductions in the cost of wind energy. To this means fatigue load predictions from vortex wake models have been validated using CFD calculations. Further, a dedicated procedure has been established to ensure consistent time dependent CFD and lifting line based calculations for turbulent inflow cases. Subsequently steps have been made towards making the more accurate vortex wake models ready for application to certification load calculations. Here one can think of guidelines in terms of recommended computational settings, load case selection (for which cases is added benefit expected) and reduction of computational time. On the other hand, improvements to BEM models have reduced the uncertainty associated with this traditional computational method. The long route towards achievement of these objectives is outlined further below.

Making a meaningful comparison between CFD (numerical wind tunnel) and lifting line codes has appeared to be quite a challenge in terms of inflow alignment. However a promising engineering approach was devised which allowed successful comparisons in the time domain between these code types. A test matrix was defined covering representative operational and inflow conditions, bearing the CPU requirements in mind. The fatigue load reduction from BEM to vortex type codes as observed in the EU.AVATAR project has been confirmed by these dedicated CFD simulations. Partly this is explained by the shed vorticity effect which is implicitly included in the vortex wake type codes, but poor tracking of wind variations by induction for BEM remains an issue. It is recommended to further study this aspect to further reduce uncertainties in BEM modeling. In addition to that very similar results were obtained between several vortex type codes originating from different institutions. A variety of load cases has shed more light on this subject, showing a correlation of the observations with axial induction factor.

In addition to the comparison against CFD simulations, a validation was made against measured fatigue loads of a 2.5MW turbine at the EWTW test site. Over 7 years of measurements were analysed to obtain relevant statistics over 100.000 ten minute samples, of which about 25.000 remained after filtering out unwanted conditions. The data was bin averaged with respect to turbulence intensity and wind speed, after which dedicated simulations for each wind speed bin were ran at 10% turbulence intensity. The resulting load comparison shows BEM to over predict the fatigue equivalent flapwise blade root moments, where a vortex wake model comes closer to the measurements. However care should be taken drawing conclusions, since it is felt that comparing aero-elastic simulations to the field data set is subject to many uncertainties (inflow, control, model data, compensating errors etc.) that cannot easily be verified. A great effort was made however to eradicate most of these, e.g. by running simulations for a large number of seeds and using a large number of measurement samples. It is recommended to set-up a dedicated field test in an effort to further reduce these uncertainties, allowing a better validation. Here one can think of using nacelle LiDAR to characterize the inflow conditions in more detail for synthetic wind field creation in combination with pressure sensors to measure sectional aerodynamic loading.

Several improvements were developed to boost the performance of BEM (engineering extensions to include more physics) and vortex wake models (reduction of computational effort). For the vortex wake models the reduction of wake update frequency, vectorization, wake grid coarsening were implemented and analysed. For BEM type models a separate blade shed vorticity model was developed and research was performed into ways to improve local induction tracking. The result is that larger rotors may be designed with lower uncertainty.

Scoping analyses have been performed with both BEM based programs and the Vortex Wake program AWSM for an entire fatigue load set. Although only a set of normal production load cases is calculated with AWSM it is expected that the reduction in overall fatigue damage by using the program AWSM may be up to 5% for the AVATAR rotor, of which about half was attributed to shed vorticity effects. Several recommendations have been given to set-up a realistic calculations with vortex wake type codes in terms of number of wake points, time step and interfacing to a structural dynamics module. A more extensive exploration of design load calculations and the added value of vortex wake calculations still is to be performed, not only focusing on fatigue loads but also on extreme loads and power production. Based on past experience it is anticipated that differences are to be expected in non-uniform and yawed inflow conditions especially when operating in high thrust coefficients. Acknowledging the observed differences between the codes it could be considered to develop official guidelines for more accurate aerodynamic load calculation by a certifying body (such as DNV-GL).

Concluding a very successful validation of lifting line codes against a 'numerical' wind tunnel and field data has been performed in this project, and subsequently these models have been improved and made ready for design load certification leading to a significant cost reduction and/or upscaling potential. A validation study similar to the cases studied in this project in a physical wind tunnel is recommended as 'proof of the pudding'. Nowadays wind tunnels are available that can create non-uniform inflow conditions in a controlled way. In addition to that small scale instrumentation has progressed, allowing us to measure detailed unsteady sectional loading on small scale turbines that can be fitted in a wind tunnel.

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