Relevance of aerodynamic modelling for load reduction control strategies of two-bladed wind turbines

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Abstract. A new load reduction concept is being developed for the two-bladed prototype of the Skywind 3.5MW wind turbine. Due to transport and installation advantages both offshore and in complex terrain two-bladed turbine designs are potentially more cost-effective than comparable three-bladed configurations. A disadvantage of two-bladed wind turbines is the increased fatigue loading, which is a result of asymmetrically distributed rotor forces. The innovative load reduction concept of the Skywind prototype consists of a combination of cyclic pitch control and tumbling rotor kinematics to mitigate periodic structural loading. Aerodynamic design tools must be able to model correctly the advanced dynamics of the rotor. In this paper the impact of the aerodynamic modelling approach is investigated for critical operational modes of a two-bladed wind turbine. Using a lifting line free wake vortex code (FVM) the physical limitations of the classical blade element momentum theory (BEM) can be evaluated. During regular operation vertical shear and yawed inflow are the main contributors to periodic blade load asymmetry. It is shown that the near wake interaction of the blades under such conditions is not fully captured by the correction models of BEM approach. The differing prediction of local induction causes a high fatigue load uncertainty especially for two-bladed turbines. The implementation of both cyclic pitch control and a tumbling rotor can mitigate the fatigue loading by increasing the aerodynamic and structural damping. The influence of the time and space variant vorticity distribution in the near wake is evaluated in detail for different cyclic pitch control functions and tumble dynamics respectively. It is demonstrated that dynamic inflow as well as wake blade interaction have a significant impact on the calculated blade forces and need to be accounted for by the aerodynamic modelling approach. Aeroelastic simulations are carried out using the high fidelity multi body simulation software SIMPACK. The aerodynamic loads are calculated using ECN’s AeroModule and NREL’s BEM code Aerodyn13.

1. Introduction
The two blade wind turbine concept has recently reappeared on the wind energy market despite the complex inherent fatigue loads[1]. A reason for this is the potential to reduce the initial installation and maintenance cost and to facilitate the construction of multi-MW turbines both offshore and in complex terrain [2].

To improve the fatigue loading of two-bladed wind turbines, innovative load reduction concepts are being developed for the Skywind 3.5MW prototype within the scope of the LARS (Load Reduction Systems) project. The dynamic fatigue loads of a two-bladed rotor are higher and more complex in comparison to a conventional three-bladed rotor. Because of the opposite blade configuration an uneven rotor distribution of aerodynamic forces will generate hub moments that have to be absorbed by the turbine structure. Such asymmetric aerodynamic loads can be caused by local wind speed...
variations, such as turbulence and sheared inflow, or by an inhomogeneous rotor induction occurring in yawed inflow.

The load reduction concept of the Skywind 3.5MW prototype combines a tumbling rotor with individual pitch control. Design tools must be able to model correctly the aerodynamic forces in such operating cases. The blade element momentum theory (BEM) is not suitable to model inflow situations that result in a non-uniform induction, like yaw misalignment, pitch asymmetry and large out of plane excursions [3]. To account for these limitations semi-empirical correction models are usually implemented in BEM codes. Free wake vortex methods (FVM) provide a better representation of the flow by calculating the local induced velocities from the circulation distribution in the turbine wake. Thus, inhomogeneous induction is calculated inherently with this approach.

In this work the relevance of the aerodynamic approach for the design of a load reduction control concept is evaluated by comparing two state-of-the-art BEM codes against a lifting line free wake vortex code. A coupled aeroelastic multi-body simulation model of the two-bladed Skywind 3.5MW turbine is used as the reference turbine. Based on the sensitivity of the turbine design to asymmetric external loading the different aerodynamic methods are verified against each other for critical load inducing inflow situations. Simulations are performed for sheared and yawed inflow, being the main sources of periodic fluctuations of the local induction during regular operation.

In a further investigation the impact of an advanced aerodynamic approach in possible load reducing operating modes is assessed. To account for the influence of an individual pitching situation a simple cyclic pitch control is investigated. Furthermore the aerodynamic effects of teetering rotor dynamics and their modelling requirements are discussed.

The evaluation of local flow parameters and the performance coefficients indicate the limitations of the BEM approach when simulating two-bladed wind turbines. By comparing the structural loads of the turbine the uncertainties in the design process introduced by different aerodynamic models can be estimated and the required level of aerodynamic modelling which is necessary for the development of the load reduction control concept can then be determined.

2. Methodology

2.1. Aerodynamic Modelling

Most available wind turbine design tools consist of an implementation of the blade element momentum method (BEM) or an advanced approach following the lifting line free wake vortex theory (FVM) to account for the external loading. In comparison the FVM offers a better physical representation of the flow but requires a higher computational effort.

None of the modelling approaches calculate explicitly the airfoil boundary layer effects. Therefore, empirical airfoil data needs to be supplied from wind tunnel experiments or two-dimensional numerical simulations. Different models are available to account for the dynamic stall effect ([4], [5]).

2.1.1. Blade Element Momentum Theory. The blade element momentum theory links the local blade forces derived from blade element theory to the total annular induction. The local inflow velocities of a stream tube are determined by solving iteratively the momentum balance of flow retardation and rotor forces. The basic BEM theory is only valid under the following conditions:

- The momentum balance is evaluated for radially independent sliced annuli.
- The induction over the circumference of each annular element is constant.
- Inflow and rotor are orthogonal and the rotor is a plane disc.
- The number of blades is assumed infinite.
- The flow equilibrium is instantaneous without time delay and the fluid is considered non-viscous and incompressible.

Several correction models have been developed to enhance the applicability of the BEM. The empirical Prandtl correction accounts for the finite number of blades. For yawed inflow a skewed wake function corrects the local induction depending on the azimuthal blade position using an
approach derived from the Glauert formulation. A dynamic inflow model accounts for the inertia of the flow in the case of unsteady rotor induction. Most BEM implementations treat the local induction on each blade individually, such that a non-uniform rotor induction is possible.

2.1.2. Free Wake Vortex Method. An alternative, effective aerodynamic modelling approach is the lifting line free wake vortex method. In the FVM the blades are represented as lifting lines and the wake as a lattice of free vortex filaments. The method calculates the shape and contained vorticity of the turbine wake and yields the local induced velocities by solving the Biot-Savart law. The local blade forces can be calculated by using empirical airfoil data. The shed vorticity is then derived by applying the Kutta-Jokouwski theorem [6].

Especially for load cases with high blade wake interaction the FVM permits a more detailed and physically correct display of the local blade forces, without relying on empirical global flow correction models.

2.2. Multi Body Simulation
The structural turbine dynamics are calculated in the commercial multi body simulation software SIMPACK. Its high fidelity approach allows simulating an unlimited number of structural degrees of freedom, accounting for an advanced level of detail of the model. Flexible bodies, like blades, shafts or tower structure, will be represented by their reduced modal shapes. Two interfaces are used in this study to calculate the aerodynamic blade forces. The Aerodyn13 module is a BEM code developed by NREL [7]. The AeroModule of ECN contains both a BEM algorithm and a free wake vortex code called AWSM, both of which have been validated in wind tunnel tests [8].

3. Load inducing effects
A two-bladed wind turbine reacts to external loads like a suspended beam while in contrast the behavior of a three-bladed rotor can be compared to a disc. This implies that an uneven blade load distribution, due to non-uniform inflow, will result in severe fluctuating hub moments in the two-bladed case. An investigation of the impact of aerodynamic modelling has been performed for sheared and yawed inflow.

3.1. Sheared Inflow

3.1.1. Aerodynamic effects. Sheared inflow implies a locally dependent variation of the axial wind speed. A wind turbine rotor is subject to a change of the local inflow velocity depending on its azimuthal position. For a vertical shear the blade in the downright position will experience the lowest inflow velocity and the lowest blade forces. In the upright position the local wind speed and the local blade forces are maximal. The local blade forces will oscillate around a mean value during one rotation. While the disclike behaviour of a three-bladed rotor will mitigate the periodic effects of sheared inflow, the hub loads of a two-bladed rotor will experience large amplitudes due to the opposite blade alignment.

3.1.2. Simulation. In Aerodyn13 a rigid turbine configuration is simulated at a constant wind speed with a vertical shear exponent of 0.2. The AeroModule makes use of the logarithmic wind profile, so an equivalent roughness length is necessary to model comparable conditions. By minimization of the quadratic error of the velocity within the rotor dimensions an equivalent roughness length of 0.6 m is found. The rotor speed and wind speed are fixed at rated conditions.

3.1.3. Results. In Figure 1 and Figure 2 the radial distribution of the tangential blade forces in the extreme positions upright and downright are displayed. One can observe that the BEM codes predict higher blade forces in the upper two thirds of the rotor disc, while in the lower third the forces are equal or below the corresponding values of AWSM. This indicates that AWSM calculates a lower
induction far below the turbine hub and closer to the ground, which increases the axial inflow velocity and therefore the resulting forces. The convected vortex sheets of the wake are tilted due to the wind gradient. As a consequence the wake induction not only acts in axial direction, but inherits an upward component. A fluid particle passing the rotor disc in the lower rotor region is less affected by the tilted vortex sheets than a particle passing the upper region. Additionally the upward component of the induction will cause the wake to lift. The lifted wake reduces the concentration of vorticity and consequently the induction in the lower third of the rotor disc. This effect was described in [9].

The highest force amplitudes are for this case predicted by the Aerodyn13 code, which can be attributed to the different description of the wind profile.

![Figure 1: Tangential forces for blade at 0 deg (vertical upright)](image1)

![Figure 2: Tangential forces for blade at 180 deg (vertical downright)](image2)

### 3.2. Yawed Inflow

#### 3.2.1. Aerodynamic effects.

For uniform inflow with yaw misalignment two superimposing effects result in a periodic fluctuation of the local flow, namely the advancing and retreating blade effect and the skewed wake effect. The advancing and retreating blade effect is caused by the vector summation of the tangential blade velocity and the rotor parallel wind velocity component. As a consequence a downwind moving blade will be exerted to lower blade forces than an upstream moving blade. A two-bladed rotor experiences this effect in its opposing extremes while passing the vertical position (at 0° and 180° rotor azimuth), when the horizontal component of the tangential blade velocity is maximal. Both the BEM as the FVM algorithms can inherently account for the advancing and retreating blade effect.

The oblique inflow causes the wake to convect sideways behind the turbine. While the axial velocity of the fluid is reduced by the power extraction, the cross flow velocity is less affected. The wake will therefore skew towards the rotor disc. The concentration of vorticity behind the downwind half of the rotor increases the local induction. Compared to the upwind position the blade forces decrease in the downwind rotor region. This causes an azimuth dependent loading which creates periodic asymmetric load situations on a two-bladed rotor.

BEM theory is only valid for axial inflow and requires a correction model to account for the skewed wake effect. The Aerodyn13 algorithm makes use of the Pitts and Peters formulation of the Glauert’s yawed inflow correction [7]. Optionally the AeroModule BEM offers the application of the enhanced yawed inflow model of Snel and Schepers [10], which mainly acts on the inboard section of the rotor. The FVM accounts inherently for the inhomogeneous induction by calculating explicitly the spatial distribution of vorticity in the wake.

#### 3.2.2. Simulation.

For a number of inflow angles a uniform wind field is applied to a rigid turbine setup. Wind speed and rotor speed are fixed at rated conditions. Dynamic stall and dynamic inflow models are not applied for comparability.
4. Load reduction cases

The load reduction concept of the Skywind 3.5MW prototype combines individual pitch control and an elastic hub mount. Comparable to a teeter hinge the hub mount control system enables a tumbling rotor motion. The aerodynamic effect of cyclic pitch control and a teetering rotor will be investigated in the following sections.

4.1. Individual pitching

Cyclic pitch control has been used throughout in helicopter industry and is becoming a viable method to mitigate the load contributions of periodic sampling on wind turbines, e.g. wind shear, tower shadow or shaft tilt [11]. These load sources are deterministic and can be reduced by an azimuth
dependent cyclic pitch function. Cyclic pitch control is based on individually pitching blades, so the transient aerodynamic effects of a non-uniform rotor induction caused by independent blade pitch functions need to be addressed.

4.1.1. Aerodynamic effects. If a single blade pitches to feather the bound and trailed vorticity of the blade reduces drastically due to a lower angle of attack. However, the rotor induction reduces only gradually when this vorticity is shed in the wake and so the inertia of the flow prevents the local flow parameters to adjust to the new situation instantly. Since instantaneous equilibrium is a basic assumption of the BEM a dynamic inflow model is required to capture the transient change of the global rotor induction. A dynamic inflow model is only implemented in ECN’s AeroModule BEM [12].

If a consecutive blade passes the tip vortex of the first pitched blade, which contains a significantly weaker vorticity, the change of circulation causes the local axial induction on the following blade to decrease and leads to higher angles of attack. This effect can only be captured by the FVM.

4.1.2. Simulation. In this investigation a generic optimization scheme is used to reduce the change of the angle of attack on a blade profile passing the tower. A periodic cyclic pitch function $\theta_i(\varphi)_{\max}$ was parameterized according to (1), with $\theta_0$ the pitch amplitude of blade $i$, $\theta_l$ the azimuth rotor position of the maximal pitch excitation and $\varphi_d$ the azimuthal width of the pitch manoeuvre.

$$\theta_i = \theta_0 \cos \left( \frac{\pi}{\varphi_d} (\varphi_i - \varphi_0) \right) \quad \text{if } |\varphi_i - \varphi_0| < \frac{\varphi_d}{2}$$

$$\theta_i = 0 \quad \text{if } |\varphi_i - \varphi_0| > \frac{\varphi_d}{2}$$

(1)

Thus, reproducible aerodynamic situations imposed by the pitching manoeuvres can be compared. Two scenarios are presented here to showcase the different modelling effects of the aerodynamic approaches. The first scenario is the so-called ‘smooth’-scenario, where the load variation is effectively reduced to a minimum by smoothing the induction disturbances of the tower shadow through the previously formulated pitch function. The ‘rough’-scenario is a suboptimal solution in which a longer and higher pitch amplitude overcorrects the aerodynamic parameters. Instead of decreasing, due to reduced axial velocity in front of the tower, the angle of attack increases since the blade overpitches to stall. The function of the pitch trajectory is given in Figure 5(a).

4.1.3. Results. The pitch function, the change of the angle of attack and of the axial induction signal for both scenarios are given in Figure 5(a)-(c) and Figure 6(a)-(c). The comparison of the two scenarios reveals the impact of the dynamic inflow model on the BEM results. The dynamic inflow model acts as a damper on the local induction of the blades. It links the annular averaged induction over all turbine blades to the local induction, which is determined separately for each blade. Only if the annular average of the sectional axial inductions changes in time, e.g. during wind gusts or pitch actions, the dynamic inflow model will act on the local inductions such that the rate of change of the global induction is reduced. The global momentum equilibrium is delayed. Without the dynamic inflow model instantaneous momentum equilibrium is calculated for each blade section.

For both scenarios the BEM using the dynamic inflow model delivers a very small deviation of the local induction, because the impulse of the pitching event is considerably small and has little effect on the global induction. In the ‘smooth’-scenario the local aerodynamic coefficients are nearly kept constant, so a consequence of the optimized pitch function is a small deviation of the local induction. This is displayed in Figure 5(c) in the axial induction curve of the FVM as well as the BEM with an inactive dynamic inflow model. The implication is that the axial inflow velocity is only changed by the tower blockage and the function of the local angle of attack is similar during the pitch event.
In the ‘rough’-scenario the decline of the inflow velocity in front of the tower is overcompensated by higher pitch amplitude of 0.8 degrees and a phase lag of five degrees (see Figure 6(a)). The BEM without dynamic inflow model calculates a new time-independent equilibrium state for each time step. Accordingly this yields an increase of the axial induction as a consequence of the higher angle of attack. The aerodynamic parameters calculated by AWSM are on the one hand subject to the increase of bound vorticity at the lifting line, which increases instantly during the pitch manoeuvre. On the other hand the higher shed circulation in the wake adds to the local induction on the consecutive blades. Although the physical theory behind these latter approaches is different, the resulting curves of the induction and angle of attack in Figure 6(b)-(c) look similar. The increase of induction reduces the axial inflow velocity. This partly counteracts the lift of the angle of attack.

A differing behaviour is observed for the BEM including the dynamic inflow correction. Since the locally induced velocity is linked to the slow change of global induction the rise of the angle of attack is not moderated by an increased local induction. The resulting blade forces calculated by this approach overshoot the ones of the reference methods similar to the angle of attack.

The higher level of physical representation allows the FVM to better predict the interaction of shed and bound vorticity and the resulting induction during a pitch event. It is shown that a pitch change has an instant effect on the local induction. The use of a dynamic inflow model in a BEM code will neglect this immediate change of induction and therefore leads to differing angles of attack. In practice this implies that a controller command intended to increase the blade force will result in a smaller pitch angle. For cyclic pitch control deactivating the dynamic inflow model leads to similar results as with the FVM. However the exact distribution of vorticity is not respected in this approach and may lead to differing results when the inflow variations are not stationary and azimuth-dependent. The use of the dynamic inflow model is recommended in any way to capture the effect of a transient global rotor induction, e.g. wind and rotor speed variations and collective pitching.

![Figure 5(a)-(c): ‘Smooth’ scenario: Pitch function, angle of attack and axial induction at 85\% blade length over one rotation](image1)

![Figure 6(a)-(c): ‘Rough’ scenario: Pitch function, angle of attack and axial induction at 85\% blade length over one rotation](image2)
4.2. Teetering rotor
A typical load reduction measure for two-bladed wind turbines is a teeter hinge, which allows decoupling the rotor forces and the hub moments. For small teeter excursions the dynamic loads on the turbine are mitigated effectively. A teeter motion contradicts the basic assumption of the BEM, which assumes the blades to be in the rotor disc and the flow field to be in an equilibrium state. The kinematic of a teetering rotor is visualized in Figure 7.

4.2.1. Aerodynamic effects. The flow around a blade profile is in this case influenced by two physical effects which are visualized in Figure 8. On the one hand the axial wind speed component \( \vec{v}_w \) is superimposed with the axial blade section motion \( \vec{v}_r \). For an upwind moving blade section the resulting axial inflow velocity \( \vec{v}_{res} \) is increased, which increases the angle of attack. Below the stall margin the lift coefficient, which dominates the resultant of the profile forces \( \vec{F}_{res} \), will consequently increase in a first approximation linearly. Since for high tip speed ratios the vector of the resultant of the profile forces only has a small tangential component, a rotation of the resultant vector around the quarter chord location will mainly affect the tangential force component. The reduction of the normal force component \( \vec{F}_N \) is compensated by higher lift coefficients and a higher inflow velocity. The tangential force component \( \vec{F}_T \) is magnified by all three mechanisms: the rotation of the resultant force, a higher lift coefficient and a higher inflow velocity. This yields a nonlinear dependence of the angle of attack.

\[ \text{Figure 7: Rotor kinematics for a 1P-teeter frequency.} \]

\[ \text{Figure 8: Inflow velocities and forces on a upwind (dashed lines) and downwind (solid lines) moving profile} \]

The change of normal force during the forward and backward motion of the rotor causes a change of local induction, which will again influence the blade section forces. If no dynamic inflow model is applied a BEM code calculates the new equilibrium instantaneously. Physically the effect of changed induction only becomes fully apparent after some time when the changed vorticity was shed in the wake. The lifting line FVM accounts for this effect intrinsically.

4.2.2. Simulation. To evaluate the influence of the aerodynamic approach a rheonomic sinusoidal teeter motion was imposed on the rotor with a varying teeter frequency. Rotor and wind speed are fixed at rated conditions. No dynamic stall model is applied. Results are shown for an excursion amplitude \( \psi \) of six degrees and 1P-periodic teeter frequency (see Figure 7).
4.2.2. Results. In Figure 9 the rotor torque signal over one rotation is displayed. The torque amplitudes of the AWSM and AeroModule BEM codes exceed significantly the compared Aerodyn13 signal, which cannot capture the dynamic inflow phenomenon. The consequence of the time lag of wake induction is a smaller oscillation of the induced velocity on each blade section. Considering the case without a dynamic inflow model the induced velocity acts as a damper which reduces the oscillations of the angle of attack. When the angle of attack is increased on an upwind moving blade the normal forces and consequently the induced velocity generally increase, which will in the same iteration reduce the axial inflow velocity and the angle of attack. However, activating the dynamic inflow model will result in higher oscillations of the angle of attack and the resulting forces. As mentioned before the impact of a variation of the angle of attack on the tangential forces is nonlinear and much higher than on normal forces. Thus, oscillation amplitudes are significant for the torque and less relevant for the thrust.

The evaluation of various inflow cases with tetering rotor in Figure 10 yields the necessity to apply an aerodynamic approach which includes the dynamic inflow effect. Even so significant differences can be found when comparing the rotor torque calculated by the lifting line FVM and the BEM including dynamic inflow correction model. The AeroModule BEM will consistently overpredict the aerodynamic torque, and therefore the power output, for various combinations of excursion amplitude and teeter frequency.

5. Conclusion
Modern two-bladed wind turbines make use of a combination of measures to reduce the dynamic fatigue loading. An innovative approach to reduce these loads is to enable additional rotor movement using teeter hinges and tumbling hub mounts. In addition, cyclic pitching is becoming a suitable approach for the mitigation of periodic sampling. An accurate prediction of the aerodynamic forces under these operational modes is required to predict realistic operational behavior of the wind turbine. The blade element momentum method (BEM) is the most common aerodynamic design tool, but it has its inherent shortcomings at inflow conditions that are especially critical for the design of load reduction systems of two-bladed wind turbines.

In this paper two state-of-the-art BEM codes are compared using an advanced lifting line free wake vortex code (FVM) for relevant load scenarios. The two-bladed rotor configuration is particularly sensitive to non-uniform induction, which is only inherently accounted for by the free wake vortex method. Using coupled aeroelastic multi-body simulation the predicted loads deviate for sheared and yawed inflow, where the blade vortex interaction and the self-induction of the wake play an important role. Relative standard deviations of the yaw moments differ by a factor two between the BEM and the
FVM code. It can be deduced that the lifting line FVM is the preferred aerodynamic design tool for inflow situations with strong wake interaction.

Load reduction concepts like individual pitching and teeter hinges affect the vorticity distribution in the wake by changing the local angle of attack. In a BEM approach the inertia of the flow needs to be accounted for by a dynamic inflow model. The dynamic inflow model effectively reduces the rate of change of the local induction, which leads to higher oscillations of the angle of attack and the blade forces. The simulation of a cyclic pitch controller to compensate the influence of the tower shadow indicates that local blade forces are overpredicted when using the dynamic inflow model. However, the neglect of a dynamic inflow model in the teetering rotor case not only yields lower blade force oscillations and lower fatigue loads compared to the FVM results, but as well lower mean power coefficients.

The deviations of the two BEM codes compared to each other are partly higher than their respective deviation to the free wake vortex code. This shows that, while being fast and robust, different BEM implementations can significantly affect the outcome of a load analysis. A further investigation of the validity of the aerodynamic modelling is required with the help of CFD analysis and operation measurement data.

Acknowledgment

The project LARS is part of the OpTiWi (OpTimization of Wind turbines) project and is funded by the German federal ministry of environment and nuclear safety BMU. SIMPACK AG is acknowledged for providing the multi body simulation software and Skywind GmbH for providing model data. This analysis makes use of the AeroModule by ECN.

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