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2014 J. Phys.: Conf. Ser. 524 012182
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Analysis of the effect of curtailment on power and fatigue loads of two aligned wind turbines using an actuator disc approach

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Abstract. To study the effects of curtailment on both power production and fatigue loading, actuator disc (ACD) simulations of two turbines aligned in the wind direction are performed with the EllipSys3D code developed at DTU/Risø. A simple non-aeroelastic fatigue load evaluation method for ACD simulations is developed. Blade loads, extracted along a line that rotates in the rotor plane with the rotational velocity of the respective turbine, are used to calculate flapwise bending moments. After applying a rainflow counting algorithm an equivalent moment is calculated. Power curtailment is introduced by increasing the blade pitch angle of the first turbine. Evaluation is made with regards to fatigue load reduction at the second turbine and the change in the total production. Further parameters investigated are the spacing between the two turbines and the level of imposed pre-generated turbulence. The aeroelastic code Vidyn, Ganander [1], is used for validation of the ACD load evaluation method. For this purpose, the EllipSys3D simulations are rerun without the second turbine. Time series of cross sectional velocity fields are extracted at positions corresponding to the former placement of the downstream turbine and used as input for aeroelastic turbine load calculations in Vidyn. The results from Vidyn and the results based on the ACD loads show similar trends. Fatigue loads at the downwind turbine are clearly decreasing as the blade pitch angle of the upstream turbine is increasing. The achievable amount of fatigue load reduction depends on the level of the imposed pre-generated turbulence as well as the spacing between the turbines. The presented method is intended for further development of wind park optimization strategies.

1. Introduction
When turbines operate in the wakes of other turbines there are two main disadvantages. These turbines produce less energy than freestanding turbines and they are exposed to higher turbulence levels. Turbulent wind speed fluctuations are known to be a key parameter for fatigue loading. The increase in fatigue loading due to wake effects is assumed to be proportional to the increase in turbulence intensity, Frandsen [2]. Power curtailment of a turbine reduces the thrust force acting on its rotor and therewith the impulse force acting on the wind flow. A curtailed turbine thus generates a weaker wake, which results in reduced turbulence-induced dynamic loading and increased production for any turbine placed downstream. However, these benefits have to be put in relation to the decreased production of the curtailed turbine.
Research on curtailment strategies for wind farm optimization has been performed by ECN [3] with the main focus on the possibility of increasing the power production.

An initial study on curtailment of individual turbines in a wind farm has been made by Nilsson et al. [4]. It is shown that pitching the blades of the turbines in the first row increases the production of the turbines in the second row. Whether an optimized de-rating strategy could increase the total farm production or not needs further investigation. Even a certain loss in a farm’s total production could be justified by a reduction of fatigue damage, especially in offshore conditions where wake effects are strong and maintenance is expensive. The aim of the current study is to develop a simple non-aeroelastic fatigue load evaluation method for actuator disc (ACD) simulations. The aeroelastic code Vidyn, developed by Teknikgruppen, Ganander [1], is used to validate the presented method and to evaluate the importance of including elastic effects in the analysis.

2. Numerical model and setup

The EllipSys3D code, Michelsen [5] [6] and Sørensen [7], is used to perform ACD simulations of two turbines aligned in the wind direction. The EllipSys3D code is a general purpose Navier-Stokes solver for incompressible flows based on a finite volume approach. Briefly, computations are performed using the LES technique where large eddies are resolved explicitly and eddies smaller then a certain size are filtered out and modeled by an eddy-viscosity based sub-grid scale (SGS) model. For this work the mixed scale model developed by Ta Phuoc [8] is used. The reader is referred to Mikkelsen [9], Ivanell et al. [10], Troldborg et al. [11] and Nilsson et al. [4] among others for more information about the numerical model.

Simulations for this study have been performed using the NREL 5 MW reference turbine which is a well described typical variable speed collective pitch offshore turbine, Jonkman et al. [12]. The radius $R$ of this turbine is 63 m and is used as a parameter throughout this paper. The overall dimensions of the grid used in this study are $93 \times 20 \times 20 R^3$, referring to an $z,x,y$-coordinate system, where $z$ is the streamwise coordinate, $x$ the crosswise coordinate and $y$ the vertical coordinate. An equidistant part with a resolution of $\Delta x = 0.1 R$ and a size of $73 \times 4 \times 4 R^3$ is located in the center of the grid. The grid around the equidistant part is stretched towards the outer boundaries.

The rotors of the turbines are represented by actuator discs using a body force approach. This method significantly reduces the computational demands compared to modeling the full geometry of the rotor since the boundary layer over the blades is not resolved. The information from the flow solver is interpolated to the polar grid of the ACD, in this study consisting of 31 points along the rotor radius and 81 points in the azimuthal direction. A description of the applied ACD method is given by Nilsson et al. [4], indicating that a grid resolution of $0.1 R$ is sufficient in terms of relative power prediction.

3. Turbulence

Pre-generated inlet turbulence is imposed in a plane upstream of the first turbine using the Mann model, Mann [13] [14] in which isotropic von Kármán turbulence is exposed to a linear shear using rapid distortion theory. The result is an anisotropic turbulence that is fitted to the Kaimal spectrum. Simulations are performed with an ambient turbulence intensity ($T I_{amb}$) of 5.15% and 10.26% respectively, where evaluation has been made at the position of the first turbine ($z = 17 R$). $T I_{amb}$ is defined as the standard deviation of the axial wind speed divided by the mean axial wind speed $u_0$. The Mann method gives a box of turbulence consisting of $1024 \times 16 \times 16$ grid points. The box measures $158.7 \times 2.9 \times 2.9 R^3$ and has an equidistant resolution of approximately $0.16 R$ in the $z$-direction, $0.18 R$ in the $x$-direction and $0.18 R$ in the $y$-direction.
The time step of the Mann box is about 0.16 \( R/u_0 \). In the simulations, \( xy \) planes of turbulence are imposed using body forces at \( z = 13R \). The planes are convected downstream by the flow solver. Interpolation is required since both the spatial and the temporal resolution of the Mann box is lower than in the LES. In the current study only two pre-generated turbulence sequences are used for realization of the respective ambient turbulence intensities.

4. Simulation setup
All simulations presented in this study have been performed for a mean wind speed \( u_0=10 \) m/s, without wind shear and for one wind direction only. The first turbine is placed at \( z = 17R \) and the second turbine is placed further downstream. Results are presented for three different spacings between the turbines, namely \( 7R, 10R \) and \( 14R \).

In an initial simulation both turbines operate with a blade pitch angle of 0°. Curtailment is introduced by increasing the blade pitch angle of the first turbine stepwise up to 10°. The blade pitch angle of the second turbine remains at 0° throughout all simulations. One individual simulations is performed for each tested combination of pitch angle, spacing between the turbines and turbulence intensity.

The computational time step \( \Delta t \) is chosen with respect to the Courant-Friedrichs-Lewy (CFL) condition given in equation 1, where \( U \) is the velocity and \( \Delta x \) the grid resolution in the equidistant region of the domain.

\[
\frac{U \Delta t}{\Delta x} < 1 \quad (1)
\]

Assuming \( U \) to be in the order of \( u_0 \), which is set to 1 for normalized computation, implies that \( \Delta t \) needs to be smaller than \( \Delta x \) considering non-dimensionalization. In the current study, the conservative choice of \( \Delta t = 0.25 \Delta x \) accounts for the fact that \( U \) can exceed \( u_0 \) locally. Each simulation involves computations of 20 000 time steps. Evaluation of the effects of curtailment has been made based on data series extracted between time steps 12 635 and 17 716, corresponding to 800 seconds.

5. Generator-torque controller
The rotational speed of the turbines is continuously adjusted using a control mechanism based on the generator-torque characteristic [15]. A torque-speed curve gives the relation between rotational speed and generator torque. This curve is known for the unpitched turbine. In order to control the turbine in an optimal way even when the blades are pitched, torque-speed curves for every tested pitch angle need to be calculated. The torque-speed curve (Figure 1) is composed of different regions corresponding to the different operational states of the turbine. For a comprehensive description of the torque-speed curve the reader is referred to Jonkman et al. [12]. The main objective of curtailment is to optimize a wind farm operating below rated wind speed. The turbines are therefore assumed to operate in the production optimized region, where the controller follows the optimal torque-speed curve. The generator torque \( T \) is here proportional to the square of the rotor speed \( \Omega \) in order to keep the tip speed ratio of the turbine at its optimal value.

\[
T = k \cdot \Omega^2 \quad (2)
\]

The factor of proportionality \( k \) is defined by the maximum power coefficient \( C_P \) and the corresponding optimal tip speed ratio \( \lambda \). Optimal tip speed ratios and the maximum power coefficients for the different pitch angles are determined in an iterative process applying an in-house developed blade element momentum (BEM) code in the Matlab environment. Based on the relation
between $T$ and $C_P$, where $A$ is the rotor area and $\rho$ the air density

$$T = \frac{C_P \rho A u_0^3}{2\Omega} \quad (3)$$

and the relation between $\lambda$ and $\Omega$

$$\lambda = \frac{\Omega R}{u_0} \quad (4)$$

the respective factor of proportionality $k$ can then be found. Combining equations 3 and 4 gives the following expression for $k$

$$T = \frac{C_P \rho A R^3}{2\lambda^3} \cdot \Omega^2 = k \cdot \Omega^2 \implies k = \frac{C_P \rho A R^3}{2\lambda^3} \quad (5)$$

Having determined $k$ for the respective pitch angle, the speed torque curve for operation in the production optimized region can be computed. Instead of modeling the other regions of the speed torque curve, the optimal region is extended over all rotational speeds. The impact that this simplification has on the results obtained is assumed to be small, however further investigations are suggested.

6. Fatigue loads

Fatigue is the damage accumulation process on a component produced by cyclic loading. Exposing a material to cyclic loading of constant amplitude will cause fatigue failure after a certain number of cycles. In reality amplitudes of cyclic loading are rarely constant. Most components are exposed to random load fluctuations. A common method to quantify the fatigue impact of fluctuating loads is the combination of a rainflow counting algorithm and an damage equivalent load approach, enabling the relative comparison of different load samples. With help of a rainflow counting algorithm [17], fluctuating loads can be separated into load ranges characterized by their size, mean value and weighting. The equivalent load range $L_{eq}$ that, applied with an
equivalent frequency $N_{eq}$, would cause the same amount of damage as the actual load sample can be calculated with the following formula [16]

$$L_{eq} = \left( \sum_i \frac{l_i \cdot n_i}{N_{eq}} \right)^{1/m}$$

(6)

where $l_i$ represents the different load ranges, $n_i$ the respective weighting factor and $m$ the negative reciprocal of the slope of the material specific Wöhler-curve. Typical values for $m$ are 3 for steel components and 10 for the composite material of the blades. Mean-load levels and material specific endurance limits are not taken into account.

All load ranges are listed separately by the rainflow counting algorithm applied in this study. The weighting factor is 1 for a full range and 0.5 for a half range. Equation 6 can therefore be rewritten as

$$L_{eq} = \left( \sum_i \frac{f_i}{N_{eq}} + 0.5 \cdot \sum_j \frac{h_j}{N_{eq}} \right)^{1/m}$$

(7)

where the different full and half ranges are denoted by $f_i$ and $h_j$ respectively.

7. Actuator disc based fatigue load evaluation method

In the current study a simple non-aeroelastic fatigue load evaluation method for ACD simulations is presented. Blade load components acting perpendicular to the disc, are extracted in 31 points along a line that rotates in the rotor plane with the rotational velocity of the respective turbine. The loads are given as a pressure on the disc and need therefore to be multiplied with one third of the circumference corresponding to the radial position of the respective point in order to get a line load on the radius.

Assuming that the line load varies linearly between two points, the flapwise blade root bending moment can be calculated by integrating the line loads from tip to root, Hansen [18]. Flapwise bending moments show direct response to wind speed fluctuations and are, in contrast to the edgewise bending moments, not influenced by gravity.

A method like this can never capture the real structural behavior of the turbine but it can give a good indication for possible fatigue load improvements due to curtailment. The advantage of the presented method compared to more advanced models, e.g. an actuator line (ACL) simulation coupled to an aeroelastic code, is the lower computational effort.

8. Aeroelastic analysis

The aeroelastic simulation code Vidyn, Ganander [1] and Schepers et al.[19], developed by Teknikgruppen is used to validate the presented ACD based fatigue load evaluation method and to study the importance of including elastic effects in the analysis.

For this purpose, the EllipSys3D simulations are rerun without the second turbine. Time series of cross sectional velocity fields are extracted at positions corresponding to the former placement of the downstream turbine. Each field consists of $24 \times 24$ points covering the full rotor of the absent turbine. Time series of the local streamwise velocity components are used to determine the inflow for the aeroelastic simulations in Vidyn. In this way the impact that the second turbine has on the flow is not considered in the EllipSys3D simulations but in Vidyn.

Turbine loads are calculated using identical rotor data as in the EllipSys3D simulations. External dynamic loading is caused directly by wind speed fluctuations and indirectly by fluctuations in the rotational speed of the rotor. The generator-torque controller in Vidyn is therefore adjusted to the characteristics of the controller used in the EllipSys3D simulations.
Time series of flapwise blade root bending moments calculated by Vidyn are transformed into one equivalent flapwise bending moment, which can be compared to the equivalent moment determined by the ACD based fatigue load evaluation method.

9. Results and discussion

9.1. Flapwise blade root bending moments

Time series of flapwise blade root bending moments, in the following referred to as flapwise bending moments, calculated with the ACD method are shown in Figure 2. Simulation parameters are $TI_{amb} = 5.51\%$ and a spacing of $7R$ between the turbines. In the right figure, curtailment is introduced by setting the blade pitch angle of the first turbine to $5^\circ$. It can be seen that pitching the blades of the first turbine moderates the fluctuations in the flapwise bending moment at the second turbine while it increases the mean moment. Curtailment can hence be seen as a trade off between load fluctuations and mean loading. Limiting the range of the load fluctuations without making significant changes to their frequency reduces the corresponding equivalent load range.

![Figure 2](image_url)

**Figure 2.** Time series of flapwise blade root bending moments generated with the ACD method for $TI_{amb} = 5.51\%$ and a spacing of $7R$, in the right figure curtailment is introduced by setting the blade pitch angle of the first turbine to $5^\circ$.

9.2. Fatigue load reduction at the second turbine

In Figures 3 and 4 the relative reduction of the equivalent flapwise bending moment at the second turbine is shown as a function of the blade pitch angle of the upstream turbine. Each combination of pitch angle, turbulence intensity an spacing is realized in one simulation. Figure 3 shows equivalent loads that are calculated with a steel typical Wöhler exponent of $m = 3$. The
reduction of the equivalent bending moment is in the following sections referred to as fatigue load reduction. Results are presented as a percentage of the equivalent moment that has been found for the situation without any curtailment.

Results from Vidyn and results obtained with the ACD based structural load calculation method show similar trends, which indicates that elastic effects play a minor role in the analysis of equivalent flapwise bending moments. Fatigue loads at the downwind turbine are clearly decreasing as the blade pitch angle of the upstream turbine is increasing. The achievable amount of fatigue load reduction depends however on the level of ambient turbulence as well as the spacing between the turbines. A lower turbulence intensity causes stronger wake effects due to a slower break down of the wake. Wake effects at the downstream turbine are also dependent on the spacing between the turbines. The smaller the spacing, the stronger the wake effects. Consequently, combining the lower ambient turbulence intensity (5.15%) and the smallest spacing (7R) gives the worst initial situation for the downstream turbine in terms of wake effects and at the same time the most potential for fatigue load reduction.

Figure 3. Relative fatigue load reduction based on the equivalent flapwise bending moment at the second turbine as a function of the blade pitch angle of the first turbine, calculated with Wöhler exponent of \( m = 3 \).

In Figure 4 equivalent loads have been calculated for a Wöhler exponent of \( m = 10 \), accounting for the composite material of the blades. The choice of the material specific Wöhler exponent \( m \) is found to have a major impact on the results obtained. From equation 6 it can be seen that the larger \( m \) the larger the influence of load cycles with large amplitude. Many of the larger cycles have their origin in slow variations of ambient wind speed and the resulting change in rotor speed. These variations are hardly affected by curtailment, but they characterize the evaluated load sequence. It is clearly seen that a larger number of realizations is needed in order to reach
a sufficient level of statistical significance in the determination of a potential load reduction.

Figure 4. Relative fatigue load reduction based on the equivalent flapwise bending moment at the second turbine as a function of the blade pitch angle of the first turbine, calculated with a Wöhler exponent of $m = 10$.

9.3. Change in total production due to curtailment

Increasing the pitch angle of the first turbine results in a loss in production for the first turbine and a gain in production for the second turbine. For all simulated combinations of pitch angle (up to $10^\circ$), spacing ($7R$, $10R$ and $14R$) and $TI_{amb}$ (5.15 and 10.26 %) the loss in the first turbine is found to be larger than the gain in the second turbine resulting in a negative effect on the total production for all investigated cases. The total production loss expressed as a percentage of the production for the situation without curtailment is presented in Figure 5. Larger spacing between the turbines gives a larger relative total production loss. It is the gain in the second turbine’s production that makes the difference. A small spacing corresponds to stronger wake effects in the initial situation and gives consequently higher potential for a relative gain in production due to curtailment. The impact of the spacing on the results obtained is moderated for the higher value of $TI_{amb}$.

By combining the results presented in Figure 3 and Figure 5, the effects of curtailment on power and fatigue loads at the downstream turbine can be analyzed. Considering an ambient turbulence intensity of 5.15%, a spacing of $7R$ and the blades of the first turbine being pitched to $2^\circ$, a fatigue load reduction in the order of 10 to 14% can be reached with a total production loss of about 2%. It has to be emphasized that these results are of preliminary character and based on highly theoretical conditions.
Figure 5. Relative total production loss for different spacings between the turbines as a function of the blade pitch angle of the first turbine. $TI_{amb} = 5.51\%$ (left) and $TI_{amb} = 10.26\%$ (right)

10. Conclusions
The presented work is performed as a pre-study for an extended analysis of curtailment strategies. A simple non-aeroelastic fatigue load evaluation method for ACD simulations is presented. It is indicated that ACD-LES tools set up for wind farm analysis, can be successfully used for an approximate evaluation of load consequences related to inflow conditions, control and wind farm topology. However, a grid sensitivity study needs to be performed in future work.

Elastic effects are found to play a minor role when analyzing equivalent flapwise bending moments. Fatigue loads at the downwind turbine are clearly decreasing as the blade pitch angle of the upstream turbine is increasing. Both the level of ambient turbulence as well as the spacing between the turbines have an influence on the achievable amount of fatigue load reduction. The effect on the total power production is found to be negative for all simulated cases, which could be justified by the advantages of fatigue load reduction. The difficulty here is to exactly define the fatigue load reduction that can be achieved by curtailment and to value the expected savings in operation and maintenance.

In this study the flapwise blade root bending moment is chosen to represent fatigue loading. Other structural parameters, like tower top thrust loads, will be included in following studies. The generator-torque control strategy for curtailed turbines can be further developed. Future research is intended on partial wake situations.

ACD disc simulations are expected to be the main tool for further development of wind park optimization strategies. The limitation that ACD simulations imply with regard to detailed wake characteristics needs to be considered when investigating turbulence-induced dynamic loads. Performing the presented curtailment study as an ACL simulation, could give valuable information about the influence more detailed wake characteristics could have on the results obtained.

Acknowledgments
The EllipSys simulations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at the National Supercomputer Centre in Sweden (NSC).
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