Effects of wind turbine wake on atmospheric sound propagation

In this paper, we investigate the sound propagation from a wind turbine considering the effects of wake-induced velocity deficit and turbulence. In order to address this issue, an advanced approach was developed in which both scalar and vector parabolic equations in two dimensions are solved. Flow field input was obtained using the actuator line (AL) technique with Large Eddy Simulation (LES) to model the wind turbine and its wake and from an analytical wake model. The effect of incoming wind speed and atmospheric stability was investigated with the analytical wake input using a single point source. Unsteady acoustic simulations were carried out with the AL/LES input for three cases with different incoming turbulence intensity, and a moving source approach to mimic the rotating turbine blades. The results show a non-negligible effect of the wake on far-field noise prediction. Particularly under stable atmospheric conditions, SPL amplification reaches up to 7.5dB at the wake centre. Furthermore, it was observed that when the turbulence intensity level of the incoming flow is higher, the SPL difference between the moving and the steady source is lower.
Turbulence and entrainment length scales in large wind farms

A number of large wind farms are modelled using large eddy simulations to elucidate the entrainment process. A reference simulation without turbines and three farm simulations with different degrees of imposed atmospheric turbulence are presented. The entrainment process is assessed using proper orthogonal decomposition, which is employed to detect the largest and most energetic coherent turbulent structures. The dominant length scales responsible for the entrainment process are shown to grow further into the wind farm, but to be limited in extent by the streamwise turbine spacing, which could be taken into account when developing farm layouts. The self-organized motion or large coherent structures also yield high correlations between the power productions of consecutive turbines, which can be exploited through dynamic farm control. This article is part of the themed issue ‘Wind energy in complex terrains’.

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Wind Farm Wake: The 2016 Horns Rev Photo Case

Offshore wind farm wakes were observed and photographed in foggy conditions at Horns Rev 2 on 25 January 2016 at 12:45 UTC. These new images show highly contrasting conditions regarding the wind speed, turbulence intensity, atmospheric stability, weather conditions and wind farm wake development as compared to the Horns Rev 1 photographs from 12 February 2008. The paper examines the atmospheric conditions from satellite images, radiosondes, lidar and wind turbine data and compares the observations to results from atmospheric meso-scale modelling and large eddy simulation. Key findings are that a humid and warm air mass was advected from the southwest over cold sea and the dew-point temperature was such that cold-water advection fog formed in a shallow layer. The flow was stably stratified and the freestream wind speed was 13 m/s at hub height, which means that most turbines produced at or near rated power. The wind direction was southwesterly and long, narrow wakes persisted several rotor diameters downwind of the wind turbines. Eventually mixing of warm air from aloft dispersed the fog in the far wake region of the wind farm.

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DeRisk - Accurate prediction of ULS wave loads. Outlook and first results

Loads from extreme waves can be dimensioning for the substructures of offshore wind turbines. The DeRisk project (2015-2019) aims at an improved load evaluation procedure for extreme waves through application of advanced wave models, laboratory tests of load effects, development of hydrodynamic load models, aero-elastic response calculations and statistical analysis. This first paper from the project outlines the content and philosophy behind DeRisk. Next, the first results from laboratory tests with irregular waves are presented, including results for 2D and 3D focused wave groups. The results of focused wave group tests and a 6-hour (full scale duration) test are reproduced numerically by re-application of the wave paddle signal in a fully nonlinear potential flow wave model. A good match for the free surface elevation and associated exceedance probability curve is obtained. Finally, the utilization of DeRisk's results in practical design is discussed. (C) 2016 Published by Elsevier Ltd.
Investigating Coherent Structures in the Standard Turbulence Models using Proper Orthogonal Decomposition

The wind turbine design standards recommend two different methods to generate turbulent wind for design load analysis, the Kaimal spectra combined with an exponential coherence function and the Mann turbulence model. The two turbulence models can give very different estimates of fatigue life, especially for offshore floating wind turbines. In this study the spatial distributions of the two turbulence models are investigated using Proper Orthogonal Decomposition, which is used to characterize large coherent structures. The main focus has been on the structures that contain the most energy, which are the lowest POD modes. The Mann turbulence model generates coherent structures that stretches in the horizontal direction for the longitudinal component, while the structures found in the Kaimal model are more random in their shape. These differences in the coherent structures at lower frequencies for the two turbulence models can be the reason for differences in fatigue life estimates for wind turbines.
Simulation of the Flow past a Circular Cylinder Using an Unsteady Panel Method

In the present work, an in-house UnSteady Double Wake Model (USDWM) is developed for simulating general flow problems behind bodies. The model is presented and used to simulate flows past a circular cylinder at subcritical, supercritical, and transcritical flows. The flow model is a two-dimensional panel method which uses the unsteady double wake technique to model flow separation and its dynamics. In the present work the separation location is obtained from experimental data and fixed in time. The highly unsteady flow field behind the cylinder is analyzed in detail. The results are compared with experiments and Unsteady Reynolds-Averaged Navier Stokes (URANS) simulations and show good agreement in terms of the vortex shedding characteristics, drag, and pressure coefficients for the different flow regimes.

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Simulations of the Flow past a Cylinder Using an Unsteady Double Wake Model

In the present work, the in-house UnSteady Double Wake Model (USDWM) is used to simulate flows past a cylinder at subcritical, supercritical, and transcritical Reynolds numbers. The flow model is a two-dimensional panel method which uses the unsteady double wake technique to model flow separation and its dynamics. In the present work the separation location is obtained from experimental data and fixed in time. The highly unsteady flow field behind the cylinder is analyzed in detail, comparing the vortex shedding characteristics under the different flow conditions.

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Statistics of LES simulations of large wind farms

Numerous large eddy simulations are performed of large wind farms using the actuator line method, which has been fully coupled to the aero-elastic code, Flex5. The higher order moments of the flow field inside large wind farms is examined in order to determine a representative reference velocity. The statistical moments appear to collapse and hence the turbulence inside large wind farms can potentially be scaled accordingly. The thrust coefficient is estimated by two different reference velocities and the generic CT expression by Frandsen. A reference velocity derived from the power production is shown to give very good agreement and furthermore enables the very good estimation of the thrust force using only the steady CT-curve, even for very short time samples. Finally, the effective turbulence inside large wind farms and the equivalent loads are examined.
Validation of four LES and a vortex model against stereo-PIV measurements in the near wake of an actuator disc and a wind turbine

In this paper we report the results of a workshop organised by the Delft University of Technology in 2014, aiming at the comparison between different state-of-the-art numerical models for the simulation of wind turbine wakes. The chosen benchmark case is a wind tunnel measurement, where stereoscopic Particle Image Velocimetry was employed to obtain the velocity field and turbulence statistics in the near wake of a two-bladed wind turbine model and of a porous disc, which mimics the numerical actuator used in the simulations. Researchers have been invited to simulate the experimental case based on the disc drag coefficient and the inflow characteristics. Four large eddy simulation (LES) codes from different institutions and a vortex model are part of the comparison. The purpose of this benchmark is to validate the numerical predictions of the flow field statistics in the near wake of an actuator disc, a case that is highly relevant for full wind farm applications. The comparison has shown that, despite its extreme simplicity, the vortex model is capable of reproducing the wake expansion and the centre line velocity with very high accuracy. Also all tested LES models are able to predict the velocity deficit in the very near wake well, contrary to what was expected from previous literature. However, the resolved velocity fluctuations in the LES are below the experimentally measured values.© 2016 Elsevier Ltd. All rights reserved.
Wind turbine noise propagation modelling: An unsteady approach

Wind turbine sound generation and propagation phenomena are inherently time dependent, hence tools that incorporate the dynamic nature of these two issues are needed for accurate modelling. In this paper, we investigate the sound propagation from a wind turbine by considering the effects of unsteady flow around it and time dependent source characteristics. For the acoustics modelling we employ the Parabolic Equation (PE) method while Large Eddy Simulation (LES) as well as synthetically generated turbulence fields are used to generate the medium flow upon which sound propagates. Unsteady acoustic simulations are carried out for three incoming wind shear and various turbulence intensities, using a moving source approach to mimic the rotating turbine blades. The focus of the present paper is to study the near and far field amplitude modulation characteristics and time evolution of Sound Pressure Level (SPL).
Effects of Turbine Spacings in Very Large Wind Farms

The Dynamic Wake Meandering model (DWM) by Larsen et al. (2007) is considered state of the art for modelling the wake behind a wind turbine. DWM assumes a quasi-steady wake deficit transported as a passive tracer by large atmospheric scales. The approach is also applied to wake interaction within wind farms, although certain aspects of the complex wake interaction are not captured, see Churchfield et al. (2014). Recent studies have shown how turbines introduce low frequencies in the wake, which could describe some of the shortcomings. Chamorro et al. (2015) identified three regions of different lengths scales. Iungo et al. (2013) related low frequencies to the hub vortex instability. Okulov et al. (2014) found Strouhal numbers in the far wake stemming from the rotating helical vortex core. Simulations by Andersen et al. (2013) found low frequencies to be inherent in the flow inside an infinite wind farm. LES simulations of large wind farms are performed with full aero-elastic Actuator Lines. The simulations investigate the inherent dynamics inside wind farms in the absence of atmospheric turbulence compared to cases with atmospheric turbulence. Resulting low frequency structures are inherent in wind farms for certain turbine spacings and affect both power production and loads.
Quantifying variability of Large Eddy Simulations of very large wind farms

Large Eddy Simulations are inherently dynamic as the largest scales are resolved and the smallest scales are modeled temporally. This raises challenges for simulations including very large scales such as atmospheric flows, which require very long simulation times. Simple averages fail at capturing these dynamics and potentially yield misleading interpretations concerning the capabilities of different models when tested in blind tests or in benchmarking exercises such as Wakebench, where results from different flow models are compared. This article will present results from very large wind farm simulations using Actuator Disc (AD) and Line (AL) models for two different turbine spacings with turbulent inflow. The results of each numerical flow model include a certain variability, and it will be examined if different models result in comparable probability distributions.
Simulation of wind turbine wakes using the actuator line technique

The actuator line technique was introduced as a numerical tool to be employed in combination with large eddy simulations to enable the study of wakes and wake interaction in wind farms. The technique is today largely used for studying basic features of wakes as well as for making performance predictions of wind farms. In this paper, we give a short introduction to the wake problem and the actuator line methodology and present a study in which the technique is employed to determine the near-wake properties of wind turbines. The presented results include a comparison of experimental results of the wake characteristics of the flow around a three-bladed model wind turbine, the development of a simple analytical formula for determining the near-wake length behind a wind turbine and a detailed investigation of wake structures based on proper orthogonal decomposition analysis of numerically generated snapshots of the wake.
Comparison between PIV measurements and computations of the near-wake of an actuator disc

Experimental stereoscopic PIV measurements in the wake of a two-bladed rotor and a porous actuator disc are compared to numerical simulation of an actuator disc. Compared to previous literature, the focus of the present analysis is on the near wake, where the actuator discs fail to represent the complex flow structures correctly, which affects the downstream representation of the full wake behind a real rotor. The near wake region is characterised by the instability and breakdown of the tip-vortex helical system, which constitutes the onset of a stronger mixing process. The comparison focuses on the turbulent structures in the shear layer at the borders of the wake through the analysis of the Reynolds stresses and by employing POD on two separate regions. The analysis shows that the actuator discs fail to capture the details of the complex flow behind a rotor, but that the experimental and numerical actuator discs are generally comparable at a certain distance behind the actuator disc. This project is intended to provide the basis for understanding the origin of the limitations of the current wake models based on the actuator disc assumption.

General information
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Comparison of Engineering Wake Models with CFD Simulations

The engineering wake models by Jensen [1] and Frandsen et al. [2] are assessed for different scenarios simulated using Large Eddy Simulation and the Actuator Line method implemented in the Navier-Stokes equations. The scenarios include the far wake behind a single wind turbine, a long row of turbines in an atmospheric boundary layer, idealised cases of an infinitely long row of wind turbines and infinite wind farms with three different spacings. Both models include a wake expansion factor, which is calibrated to fit the simulated wake velocities. The analysis highlights physical deficiencies in the ability of the models to universally predict the wake velocities, as the expansion factor can be fitted for a given case, but with not apparent transition between the cases.

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Reduced order model of the inherent turbulence of wind turbine wakes inside an infinitely long row of turbines

The turbulence in the interior of an idealised wind farm is simulated using Large Eddy Simulation and the Actuator Line technique implemented in the Navier-Stokes equations. The simulation is carried out for an 'infinitely' long row of turbines simulated by applying cyclic boundary conditions at the inlet and outlet. The simulations investigate the turbulence inherent to the wind turbines as no ambient turbulence or shear is added to this idealised case. A Reduced Order Model for the highly turbulent flow deep inside a wind farm is proposed based on a Proper Orthogonal Decomposition. The reconstructed flow is shown to capture the large scale motions of the highly turbulent flow.
Simulation and Prediction of Wakes and Wake Interaction in Wind Farms

The highly turbulent wake and the wake interaction of merging wakes between multiple wind turbines are modelled using Large Eddy Simulation (LES) in a general Navier-Stokes solver. The Actuator Line (AL) technique is employed to model the wind turbines, and the aeroelastic computations are fully coupled with the flow solver. The numerical simulations include the study of the far wake behind a single turbine, three idealised cases of infinitely long rows of turbines and finally three infinite wind farm scenarios with different spacings. The flow characteristics between the turbines, turbine performance, and principal turbulent quantities are examined for the different scenarios. The study focuses on the large coherent structures and movements of the wake behind and between wind turbines. The large coherent structures are analysed using Proper Orthogonal Decomposition (POD). POD constitutes the basis for two proposed dynamic wake models of the turbulent wake deep inside large wind farms. The first model is based on a direct reconstruction using POD, while the other model (REDOMO) is based on an additional reduction by only including the most dominant frequencies. The flow fields derived from the two wake models are assessed and verified by comparing turbine performance and loads to those derived from the flow extracted from the numerical simulations. The most comprehensive model yields excellent agreement for small and intermediate turbine spacing, while the simpler version is unable to resolve the complex dynamics due to severe temporal filtering. The models have difficulties capturing the more extreme and spurious events for larger turbine spacings. The performance is also compared to stochastically generated Mann turbulence, which gives better results for larger spacings. The comparison also reveals how much information should be retained by the POD models to add more value than simply applying homogeneous turbulence as inflow.

Analysis of turbulent wake behind a wind turbine

The aim of this study is to improve the classical analytical model for estimation of the rate of wake expansion and the decay of wake velocity deficit in the far wake region behind a wind turbine. The relations for a fully turbulent axisymmetric far wake were derived by applying the mass and momentum conservations, the selfsimilarity of mean velocity profile and the eddy viscosity closure. The theoretical approach is validated using the numerical results obtained from large eddy simulations with an actuator line technique at 0.1% and 3% ambient turbulence level and ambient wind velocity of 10 m/s, and 0.1% ambient turbulence level and ambient wind velocity of 7 m/s. The obtained results showed that neglecting the nonlinear term of velocity in the momentum equation in the far wake region cannot be a fair assumption, unlike what is generally assumed in most of text books of fluid mechanics. Therefore the theoretical determination of the power law for
the wake expansion and the decay of the wake velocity deficit may not be valid in the case of the wake generated behind a wind turbine with low ambient turbulence and high thrust coefficient. Although at higher ambient turbulence levels or lower ambient wind velocities (higher thrust coefficients), this trend may be improved due to the faster recovery of the wake and therefore closer values to the theoretical approach may be obtained. In addition, the assumption of self-similarity behavior of the mean velocity profile, when scaled with center line velocity deficit, could be correct in the far wake region of a wind turbine and low ambient turbulence levels.

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Reduced Order Model of Wind Turbine Wakes

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Simulation of the inherent turbulence and wake interaction inside an infinitely long row of wind turbines
The turbulence in the interior of a wind farm is simulated using large eddy simulation and the actuator line technique implemented in the Navier–Stokes equations. The simulations are carried out for an infinitely long row of turbines simulated by applying cyclic boundary conditions at the inlet and outlet. The simulations investigate the turbulence inherent to the wind turbines as no ambient turbulence or shear is added to this idealised case. The simulated data give insight into the performance of the wind turbines operating in the wake of others as well as details on key turbulent quantities. One of the key features of wakes behind wind turbines is the dynamic wake meandering, which is shown to be related to the wind turbine spacing and the vortex shedding from the turbine as a bluff body. The flow is analysed and reconstructed by applying proper orthogonal decomposition.

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Period: 15/09/2016 → 14/09/2019
Number of participants: 4
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Simulation and prediction of wakes and wake interaction in wind farms

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