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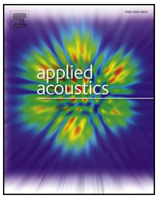

3D-simulation of sound propagation through the wake of a wind turbine: Impact of the diurnal variability

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ABSTRACT

Coupled three-dimensional numerical flow and sound propagation simulations were performed for four different times of a diurnal cycle in the area downwind of a wind energy converter with a hub height of 100 m and a rotor radius of 50 m. The sound propagation from the turbine is subject to vertical and lateral refraction in the wind speed deficit of the wake. The latter is influenced by the varying static stability and turbulence condition of the atmospheric boundary layer. The sound level near the ground is significantly increased by the atmospheric and wake-induced refraction for distances larger than eight times the rotor diameter. This increase is strongest in the morning and evening hours when it locally amounts up to 18 dB. Three-dimensional propagation effects are evident and cannot be neglected. A significant sound-level variation during the turbine revolution is simulated for the evening situation in the far field.

1. Introduction

Wind energy converters emit sound which is mostly produced by the interaction between the rotating blades and the turbulent air that impinges on and flows around the blades (aerodynamic noise; e.g. Kim et al. [22]). Further sound is produced by the generator and diverse auxiliary drives to control yaw and pitch. The problems of wind turbine noise in the environment (emission, propagation, impact on human health) are summarized by Rogers et al. [32] or Tabassum-Abbasi et al. [36]. The perception of wind turbine noise by people (annoyance) is addressed for instance by Pedersen et al. [29]. The local impact of noise depends not only on the sound emission at the turbine, but also on the propagation of the sound waves through the atmosphere. Both emission and propagation are determined by the inflow condition (wind profile, temperature stratification, and turbulence) and the operating condition of the turbine. The propagation is additionally influenced by the specific wake due to the moving rotor blades, e.g. Vermeer et al. [39], and the underlying ground. The wake structure was investigated by Lidar measurements, e.g. Bingöl et al. [3], Trujillo et al. [38] and Käsler et al. [21], and numerical simulations, e.g. Wussow et al. [40], Jimenez et al. [20], Troldborg et al. [37], Gross [13], Sørensen et al. [35], or Gebraad et al. [12].

Only in recent years publications appeared that consider the influence of the wake flow in predicting the far-field sound impact by wind converters. Heimann et al. [17] used a three-dimensional ray-based model which was coupled to two different Reynolds-averaged numerical flow models. They found that the sound impact is very sensitive to details in the meteorological fields. Lee et al. [24] used a 2-dimensional diagnostic wave-based propagation model with axisymmetric approximation and successfully compared the results with measurements. Barlas et al. [1] studied the influence of the wake on the sound impact above plane ground. They used a two-dimensional wave-based sound propagation model that was coupled with a large-eddy simulation (LES) of the air flow. It turned out that during stable stratification the sound level can be strongly underestimated if the turbine wake is not considered. A consistent modelling procedure of the wind turbine noise problem is proposed by Barlas et al. [2] who coupled an aerodynamic emission model for wind turbine noise with a LES flow model to simulate the wake flow with an actuator line approximation of the wind turbine blades, and an acoustic propagation model based on the parabolic equation (PE). A similar approach is followed by Cotté [5]. Since the PE models of [2] and [5] are only two-dimensional they are applied in vertical slices that are connecting emission points near the rotating blade tips with diverse ground-based receiver point around the turbine.

A shortcoming of two-dimensional sound propagation modelling in a vertical plane is the neglect of horizontal refraction due to horizontal gradients of wind and/or temperature. In an undisturbed atmosphere vertical gradients of both wind and temperature prevail and therefore the influence of horizontal refraction is negligible. However, once obstacles such as hills, buildings, trees or wind turbines retard or deflect

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the air flow, horizontal gradients become important. In the case of the wake flow downstream of wind energy converters vertical and horizontal gradients in the wind field are of the same magnitude (e.g. Fig. 7 in Trujillo et al. [38]). This implies that refraction of sound waves not only occurs in the upward and downward directions but also in all other directions (horizontal and slant). Sound waves emerging from the blades into the wake flow therefore pass a three-dimensional system of acoustical lenses leading to local focusing and caustics or to defocusing of the sound rays.

The present paper aims at the numerical simulation of sound propagation in the area downwind of a wind turbine in three dimensions. The three-dimensional wind and temperature fields are provided by precursory large-eddy simulations (LES) which consider the resistance of a wind turbine on the air flow. To cover different situations the results of Englberger and Dörnbrack [10] were used. They refer to four selected times of a full diurnal cycle.

The objective of this study is the elucidation of three-dimensional atmospheric sound propagation effects with the help of three-dimensional numerical simulation. The evaluation is limited to the area downwind of a wind turbine which includes the wake of the rotor. Here the influence of the atmospheric structures on the acoustic refraction is in the focus. Therefore the model fully describes refraction due to wind and temperature gradients in three dimensions. An accurate description of the aero-acoustic source as the result of the interaction between the turbulent air stream and the rotating blades (‘blade-vortex interaction’) is not intended. Nevertheless, the sound emission is realistically prescribed with respect to source position, spectrum and directivity. Moreover, the study does not aim at the time behaviour of sound levels. It rather deals with sound levels averaged over the turbulent time scale. This applies to partial sound levels according to various source positions taken during the revolution of the rotor and the mean sound level over a full rotation.

2. Flow simulation

2.1. Model

The study deals with a 3-blade horizontal-axis wind turbine with a hub height of $z_{\text{hub}} = 100$ m above ground and an upwind rotor with a radius of $r = 50$ m or diameter of $D = 100$ m (Englberger and Dörnbrack [9,10]). The turbine is located in the origin of the coordinate system at $x_0 = y_0 = 0$ on plane ground (Fig. 1).

The multiscale geophysical flow solver EULAG (Smolarkiewicz and Margolin [34]; Prusa et al. [31]; Englberger and Dörnbrack [9]) is applied in the large-eddy simulation (LES) mode to determine the small-scale flow modification by the rotor in the downwind domain. The turbine-induced force is implemented with the blade-element momentum method as a rotating actuator disc (e.g. Branlard [4]; Englberger and Dörnbrack [9]). A turbulent kinetic energy closure (Schmidt and Schumann [33]; Margolin et al. [26]) is applied.

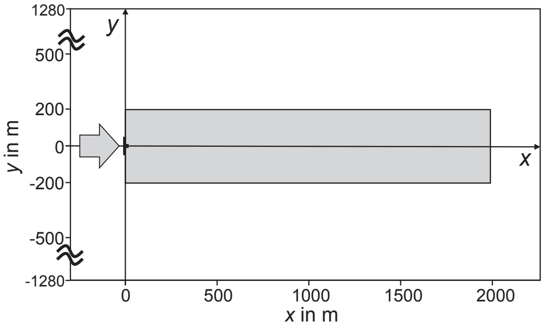

Fig. 1. Plane view of the coordinate system (x, y) and position of the domains of the flow model (outer frame) and the sound propagation model (grey shaded). The grey arrow marks the main inflow wind direction. The position of the wind turbine is indicated by the black symbol in the origin ($x = y = 0$).

The flow model domain comprises 512 × 512 numerical meshes in the horizontal with a resolution of 5 m (Fig. 1). In the vertical the computational domain extends up to $z = 420$ m with a resolution of 5 m in the lowest 200 m and 10 m above.

As large-scale initial condition a wind is assumed to blow with 10 m/s parallel to the x-axis so that the rotor plane of the turbine lays in the y-z-plane. Further, the wind-turbine simulations are conducted with synchronized turbulent inflow data of a diurnal-cycle driven boundary-layer flow over a homogeneous surface with a constant drag coefficient of 0.1 (Englberger and Dörnbrack [10]).

Four meteorological situations are considered. They represent four different times of a day during a full summer solstice mid-latitude diurnal cycle over grass-covered ground with undisturbed short- and longwave radiation: midnight (00 LT), morning (05 LT), noon (12 LT), and evening (18 LT). LT stands for ‘local time’. The situations 00 LT and 12 LT represent a stable and a convective boundary layer, respectively. The situations 05 and 18 LT represent the transition from night to day and vice versa. They are defined to be representative of the time period in which the heat flux changes sign, whereas the convective boundary layer corresponds to the heat flux maximum (here: 140 W/m^2) and the stable boundary to its minimum (here: −10 W/m^2). Further details of the flow simulations, the implementation of the diurnal cycle, and the simulation results are fully described in [9].

For the subsequent acoustical simulations average wind ($\overline{u}$, $\overline{v}$, $\overline{w}$) and temperature ($\overline{T}$) are stored as three dimensional fields for each of the four situations (00, 05, 12, and 18 LT). $\overline{u}$, $\overline{v}$, and $\overline{w}$ are the average wind components in x, y, and z-direction, respectively. $\overline{u}$, $\overline{v}$, $\overline{w}$, and $\overline{T}$ are averaged over 50 min, i.e. the full large-eddy simulation time after a 10-min initial spin-up time. In addition to wind and temperature the three-dimensional distribution of the turbulent kinetic energy ($\overline{E}$) is provided. The water vapour concentration (humidity) is not modelled.

2.2. Results

Fig. 2 shows the vertical profiles, for each of the four simulations, of the 50-min average sound speed

$$\bar{c} = \sqrt{\frac{c_p}{c_v} R_d \overline{T}} \tag{1}$$

in the undisturbed upwind domain of the wind turbine. The average sound speed $\bar{c}$ is determined from the simulated average temperature $\overline{T}$ where c_p and c_v are the specific heat capacities of air at constant

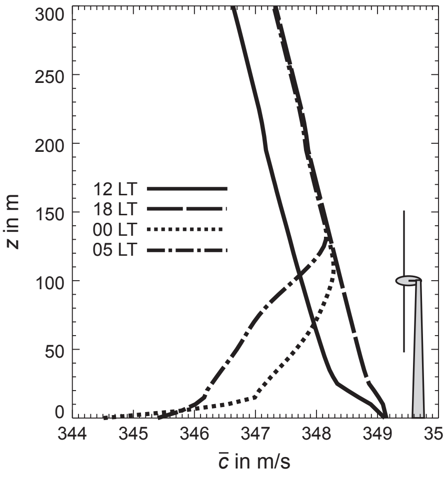

Fig. 2. Vertical profiles of the simulated 50-min average sound speed $\bar{c}$ in the upwind area of the wind turbine at $x = -200$ m, $y = 0$. The line styles indicate the time of the day (LT = local time).