Analyzing the Sound Propagation of Wind Turbines Based on Measured Acoustical and Meteorological Parameters

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Introduction

Due to the ongoing discussions regarding wind turbine noise, the sound propagation of wind turbines is a research topic receiving a lot of attention. To investigate phenomena affecting sound propagation, an experimental campaign was carried out in 2018, as part of the research project "WEA-Akzeptanz". In this work, the setup of the measurement campaign is shown. In addition, the processing and evaluation of acoustical data are described in detail. Finally, the first results regarding the dependence on meteorological, acoustical and wind turbine parameters are presented. Moreover, wind direction dependence of noise emissions and sound propagation are discussed.

Site Description and Measurement Setup

As part of an extensive measurement campaign, acoustical and meteorological measurements were carried out near to a 2 MW wind turbine. The wind turbine has a hub height of 100 m and a rotor diameter of 100 m. The terrain of the site is flat and the area consists mainly of meadows, which are partly crossed by ditches with reeds. In order to avoid additional extraneous noise from natural sources, acoustic measuring instruments were located at least 10 m away from possible disturbing influences. The site and the position of acoustic instruments is shown in Figure 1. Accordingly, three acoustic measuring stations were placed in 154 m, 249 m and 479 m distance to the wind turbine. The distance of the first measuring point at 154 m corresponds to the reference distance mentioned in IEC 61400-11:2012 [1].

A challenging task for acoustic measurements in the free field is the prevention of wind-induced noises occurring at the microphone. These noises can strongly corrupt the measurement data, especially in the low-frequency range. Using a nose cone, a 90 mm standard windscreen and a 220 mm self-developed secondary windscreen, the wind-induced noise was reduced effectively during the measurements. An example of an acoustic measuring station including windscreens is shown in Figure 2. The height of all sound level meters was 1.70 m. Each measuring station was connected to a solar panel for external power supply. In order to investigate sound propagation, a description of atmospheric conditions is needed. Hence, meteorological parameters were monitored synchronously to sound pressure levels, octave bands and audio. Wind vectors, temperature and humidity were recorded at measurement heights of 2 and 10 m and at a distance of 200 m

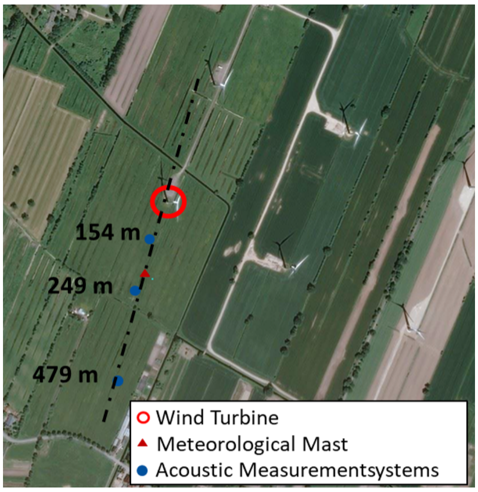

Figure 1: Map of the measurement site including measurement positions,

from the wind turbine (see Figures 1 and 2). Moreover, operating data of the wind turbine, such as output power and rotational speed, were detected.

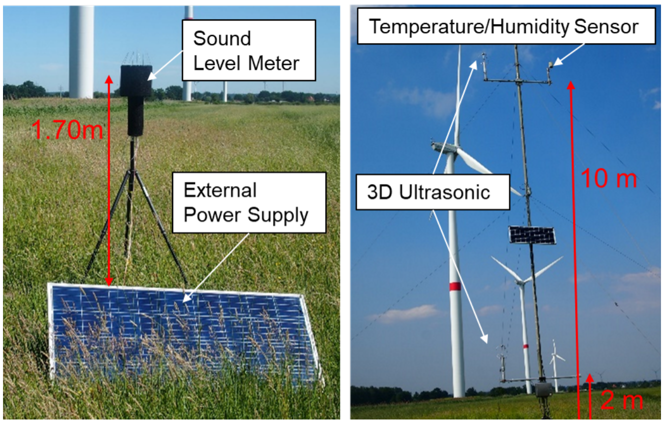

Figure 2: Acoustical measurement station (left) and meteorological mast (right)

Evaluation Methods

Measurements can be affected by disturbances of human activities, overflights or natural sources. In particular, wind-induced sounds from vegetation or animal noises from birds or frogs are natural sources that disturb acoustic measurements. Van den Berg [2] as well as Larsson and Öhlund [3] use the following three criteria to sort out data sets with disturbances and to accordingly select data sets with dominant wind turbine noise:

$$L_5 - L_{95} \leq 4 \text{ dB(A)} \quad (1)$$
$$L_1 - L_{95} \leq 15 \text{ dB(A)} \quad (2)$$
$$L_{eq} - L_{1/3>3150Hz} \leq 1.5 \text{ dB(A)} \quad (3)$$

Based on the fact that disturbing sound events strongly influence the sound level in a short period of time, statistical A-weighted percentile sound levels (L_n with n=1,5,95) are used for the criteria (1) and (2). Those criteria are explained by Figure 3, in which minute intervals of the measured statistical sound levels are plotted for approximately two days. In an unstable atmosphere during the day, ambient noise and wind noise are intense. In these situations with high background noise, as shown in Figure 3, the sound levels are highly scattered. At night, the environment is quieter and wind noise is reduced due to the nightly stable atmosphere. The fluctuation of the sound levels is lower and the levels have more constant values. As a result, the noise of the wind turbine is dominant.

With criterion (3), the frequency spectrum of the wind turbine is considered. Due to the air absorption, the high-frequency components in the spectrum decrease with distance. Depending on temperature and humidity, the attenuation at 8 kHz reaches 9 to 29 dB for a distance of 125 m to the wind turbine [4]. Öhlund and Larsson [5] show that energy of vegetation-related sound and noises from animals is dominant at high frequencies. On the basis of a small high-frequency part in the spectrum of a wind turbine, criterion (3) ensures that singing birds, for example, do not influence the measurement data. For demonstration, Figure 3 shows a data set with bird singing.

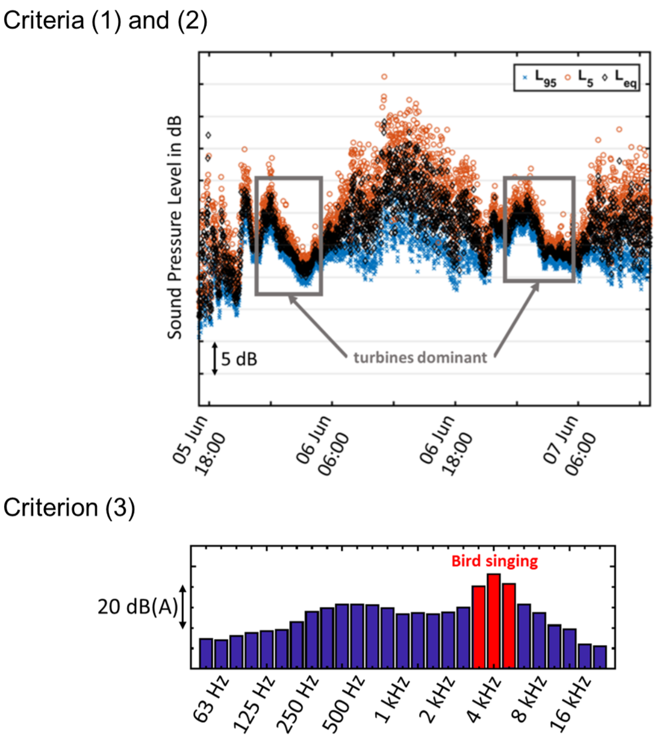

Figure 3: Demonstration of data selection

Using the described criteria, the wind turbine noise is dominant in about 40% of the measurement time. The wind turbine noise is mainly dominant in a stable atmosphere at night. This trend was also observed by Van den Berg [2] and corresponds to the complaints of residents in the area next to wind turbines. The complaints mainly relate to noise in the late evening and at night.

Measurement Results

Meteorological and Wind Turbine Operational Conditions

The noise emission of wind turbines depends on many factors. For instance, noise is emitted as a function of operating parameters such as rotor speed. The operating parameters are directly related to meteorological conditions. For instance, the rotor speed increases with wind speed at hub height and the nacelle position is determined by the wind direction. A distribution of 10-minute averaged values of wind speed at hub height and nacelle position is shown in Figure 4. For better orientation, the acoustic measuring positions and the location of the wind turbine are marked qualitatively. Due to favourable propagation conditions, downwind situations are advantageous for acoustic measurements. For this reason, the wind direction sector for downwind situation is additionally highlighted in Figure 4.

In the time of the measurement campaign, only a weak wind is recognizable in the downwind sector. The database in the downwind direction is small and the highest wind speed at hub height is 9.8 m/s, which is below the rated speed. The presented distribution mainly shows north-westerly winds, so that most of the acoustic data was recorded in crosswind direction to the turbine. In addition, a very weak south wind is noticeable, which represents upwind situations.

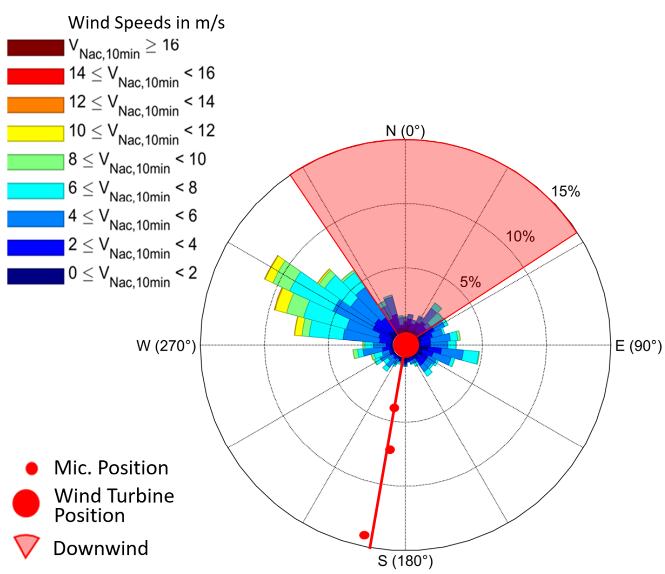

Figure 4: Contribution of measured wind speed at hub height and nacelle position (10-minute averaged data)

Wind Turbine Parameter Dependence of Noise Emission

Measured A-weighted sound pressure levels (L_{eq}) at a distance of 150 m from the wind turbine are used to analyse the noise emission with regards to wind turbine parameters. Wind speed at hub height, output power and rotational speed as well as L_{eq} at 1s intervals are plotted for almost eight minutes in Figure 5. The wind speed varies strongly, whereas power and rotor speed are more smooth due to the control and regulation system of the wind turbine. In response to the operational parameters, L_{eq} varies about 8 dB in the selected time period. Compared to the wind speed, the correlation between output power and L_{eq} or rather rotational speed and L_{eq} is stronger. For this reason, rotor speed is selected as the reference parameter of the turbine for further investigations.

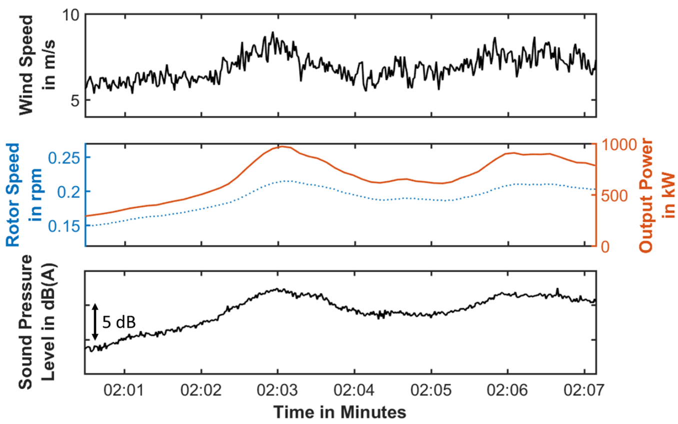

Figure 5: A-weighted sound pressure level and wind turbine operational data at 1 s intervals

Wind Direction Dependence of Noise Emission

In Figure 6, relative L_{eq} at 150 m distance to the wind turbine is plotted against the rotor rotational speed for all wind directions. The datasets were evaluated using the introduced method and only data during stable atmospheric conditions was used. Selected data was fitted using shape-preserving piecewise cubic regression. Besides curves, data points in crosswind direction are plotted. The division of wind directions is illustrated, whereby a low resolution of four 90° wind direction bins are used. Since the results under both crosswind directions were almost identical, both crosswind directions are grouped together as an overall crosswind dataset.

L_{eq} in all directions increase almost linearly, which corresponds to the velocity scaling law given for aerodynamic noise. Due to the low data basis and lack of data at higher rotor speed ranges in the upwind direction, no data-based statement can be made about the emission in the upwind direction. L_{eq} tends to be lower in upwind direction, but this can also be attributed to varying environmental conditions. As investigated by previous researchers, the sound levels in crosswind direction are lower than in downwind direction [7, 8]. This sound reduction is due to the dipole character of the aerodynamic noise, especially the trailing-edge noise. Trailing-edge noise is considered to be the dominant sound source on modern wind turbines. However, in this investigation, the sound reduction in crosswind direction is 2-3 dB(A) and is therefore not as high as pronounced in theoretical predictions of the trailing-edge noise. According to predictions, trailing-edge noise is about 15 dB less in crosswind than in other directions. The large difference to the measured data is due to the fact that in theory only the trailing-edge noise is considered. In the measurements, the total sound pressure level of all sources is taken into account.

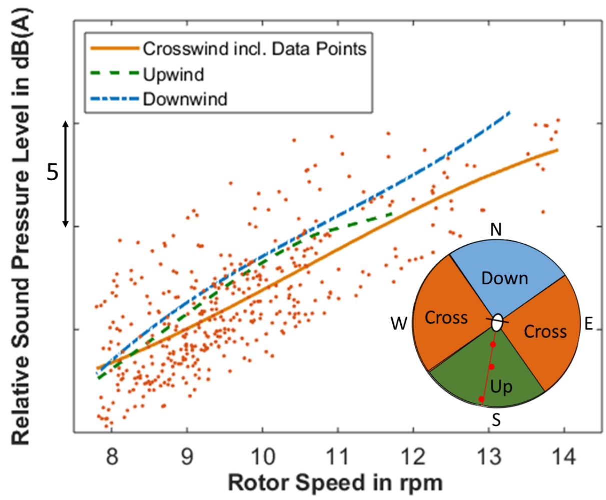

Figure 6: Rotor speed dependence of A-weighted sound pressure level in cross, up and downwind direction using 10-minute averaged data

Wind Direction Dependence of Noise Propagation

In order to investigate the influence of wind direction on sound propagation, 30-minute intervals at stable atmospheric conditions, positive sound speed gradients and rotor speeds of 12 rpm and above were investigated. It is important to have high rotor speeds and thus a high signal-to-noise ratio, because with increasing distance to the turbine, the turbine sound becomes quieter, whereas the influence of ambient noise increases. The effective sound speed profile is calculated with

$$c(z) = c_0 \sqrt{\frac{T(z)}{T_0}} + u(z), \qquad (4)$$

where $T(z)$ is the temperature profile in °C and $u(z)$ presents the wind speed profile in m/s. Both atmospheric parameters are in dependence of the height z [5].

In Figure 7, the decrease of selected relative sound pressure levels over the slant distance from the rotor centre to the receiver are shown for two different sound speed profiles. Moreover, calculated attenuation of geometrical spreading for a point source set at the rotor centre is illustrated. This curve is given for orientation and is not used for discussion, since no effects other than geometrical spreading have been taken into account.

The effective sound speed gradient is larger in downwind than in crosswind conditions. Based on the theory of refraction, lower propagation loss is expected in downwind conditions. The same tendency is observed in the measurement data. Between the first and third position, the L_{eq} decreases by 6.5 dB in downwind, and by 8.7 dB in crosswind direction. The difference in propagation loss is approximately 2 dB. With increasing distance to the wind turbine, the effect of meteorological conditions gets stronger and hence, differences in propagation loss increase. According to Larsson and Öhlund [3], the effect of meteorological conditions start to be important somewhere between 400 m and 1000 m distance from wind turbines.

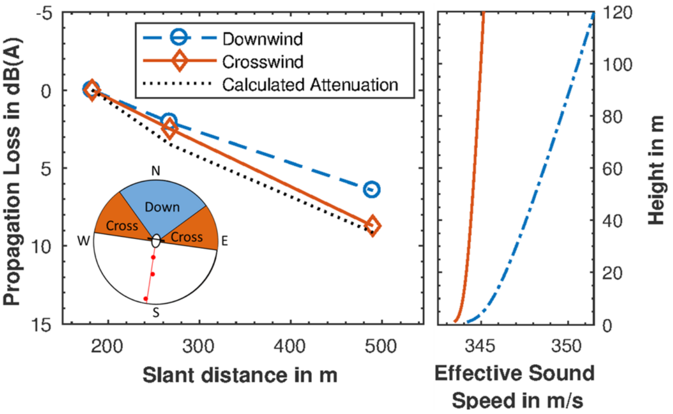

Figure 7: Propagation loss of A-weighted sound pressure level in cross and downwind direction, calculated loss using geometrical spreading for a point source and calculated effective sound speed profile

Conclusions and Outlook

In the summer of 2018, meteorological and acoustic measurements were carried out in the area around an onshore wind turbine. Acoustic parameters were recorded at distances of 154 m, 249 m and 479 m and evaluated with regard to wind turbine parameters and wind direction.

The measured data of the first measuring position was used to assess the noise emission and its dependence on turbine parameters and wind direction. This position corresponds to the distance of the reference measuring point for sound power measurements according to IEC 61400-11:2012. As expected, the measured A-weighted sound pressure level increases with increasing wind speed, power and rotor speed. Due to the high fluctuations of the wind speed, further investigations use the rotor speed as reference parameter of the turbine.

In downwind direction, noise emission is greater than in crosswind direction. This is due to the dipole characteristics of dominant aerodynamic noises, particularly the trailing-edge noise. All measuring positions are used to examine the sound propagation. The sound propagation loss is lower with larger sound speed gradients, i.e. in downwind direction. With increasing distance to the turbine, meteorological effects on sound propagation become more important. Hence, differences in propagation loss increase with distance for various sound speed profiles.

In the future, the results of this study will be verified with measurement data of a second measurement campaign, which is carried out in March 2019 next to a wind farm near to the German-Danish border. Atmospheric conditions have a significant effect on the sound propagation. In future work, this effect will be investigated based on classified atmospheric conditions.

Acknowledgements

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