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Measuring and Analysing the Sound Propagation of Wind Turbines

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Summary

The influence of atmospheric conditions on the propagation of sound emitted from wind turbines is investigated on the basis of measured data. Effective sound speed profiles and gradients are calculated considering atmospheric stability and wind direction. At distances of 154 and 249 m to the wind turbine no meteorological effects on sound propagation but directivity effects of the sound source are observed. Due to the dipole characteristic of the dominant aerodynamic noise source, sound levels at gradients close to zero are lower than at higher absolute gradients. At a horizontal distance of 479 m, the effect of different sound speed gradients on measured sound levels is recognisable. With increasing sound speed gradients, sound waves bend downwards which results in a decrease of propagation loss. Upward bending occurs at strongly negative gradients, where the propagation loss is 6 dB higher than with highly positive gradients. The effect on refraction is less pronounced with weaker gradients.

1. Introduction

From 2007 to 2017, the capacity of onshore wind turbines has increased worldwide from 113 to 497 GW. Further growth is expected, reaching 830 GW by 2023 [5]. With the expansion of wind energy and wind turbines moving closer to local residents, the noise emission of wind turbines and its propagation has come into focus. This work focuses on the influence of meteorological conditions on sound propagation based on measured data.

Earlier studies already showed a large effect of the meteorological conditions on the sound emission and sound propagation. On the basis of long-term measurements van den Berg [11] shows that the

noise levels in the area of a wind farm are higher than expected at night. If the common description of the logarithmic wind profile is used to extrapolate the wind speed from the reference height to the hub height, the nightly wind speeds at hub height are underestimated. In a stable atmosphere at night stronger winds exist at hub height than those predicted by the logarithmic wind profile. As a result, a wind turbine produces more sound than expected from the wind speed at reference height. As described in van den Berg [11], due to the higher noise emissions, the levels at 400 m and 1000 m distance to the wind farm were up to 15 dB higher than expected. Consequently, when calculating wind profiles, it is important to consider not only surface roughness, but also atmospheric stability.
Öhlund and Larsson [9] carried out acoustic and meteorological measurements near to two wind turbine sites in Sweden. No meteorological effects were observed at a distance of 400 m from the nearest wind turbine. At shorter distances the directivity of the turbines predominates. At distances of 1-2 km to a wind farm, variations in sound pressure levels of 6-14 dBA were measured, depending on the sound speed gradient and correspondingly on the refraction. These effects were observed in total sound levels and in all 1/3 octave bands from 63 to 1000 Hz. According to Öhlund and Larsson [9], for high sound sources a certain distance is needed until sound waves are refracted at the strong velocity gradients near the ground. The meteorological effects in relation to refraction increase with distance and become significant at a distance between 400 m and 1000 m.
Based on the studies of van den Berg [11] as well as Öhlund and Larsson [9], the meteorological effects on sound emission and sound propagation are investigated using long-term measurements with three microphones. For this purpose, the theory of sound propagation with focus on the calculation of sound speed profiles will be discussed first. Subsequently, the performed measurement campaign and the evaluation method of the acoustic data are presented. Finally, the measurement results in relation to meteorology effects will be presented and discussed. The contribution ends with a conclusion and outlook.

2. Sound Propagation Theory

Sound propagation in the atmosphere is influenced by air absorption, atmospheric refraction and turbulence. Sound loses energy due to atmospheric air absorption, which is converted into heat. The amount of air absorption strongly depends on the sound frequency, the temperature, and the relative humidity of the air as well as increases with distance and frequency. The calculation of sound attenuation is described in DIN ISO 9613-2 [3]. Thus, depending on temperature and humidity, the attenuation at 4 kHz can be 22.9 to 88.88 dB/km.
As described in detail in the literature, the vertical gradients of the sound speed lead to atmospheric refraction downwards or upwards. The sound waves are bent in the direction of the low speeds. If the wind speed increases with height, and/or a positive temperature gradient is present the sound waves are bent downwards. This leads to higher sound pressure levels at the point of immission. When wind speed decreases with height, and/or there is an adverse temperature gradient, sound waves are bent upwards. As a result, shadow zones with low sound levels can occur. Turbulence scatters sound waves into the shadow zone. The described effects of refraction and scattering are shown in figure 1. Turbulence is described as temperature and wind fluctuations in the atmosphere. They not only lead in scattering of sound, but also cause a displacement of phases and amplitudes.
The focus of this contribution is on the effect of refraction on sound propagation. Since refraction is directly related to sound speed profiles, the calculation of profiles is described. The speed of sound is dependent on temperature and humidity and is also affected by the wind speed. In the direction

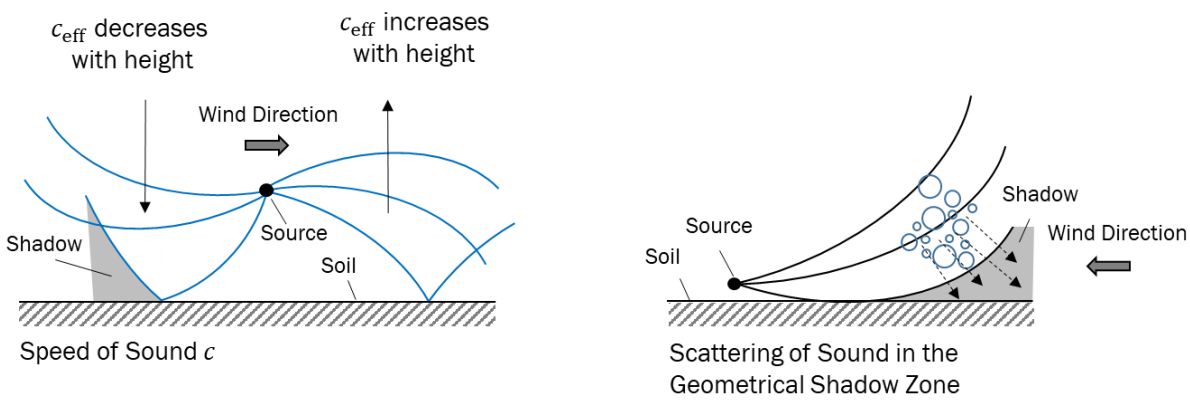


Fig. 1 Left: Atmospheric refraction due to vertical gradients in sound speed Right: Scattering due to turbulences

of sound propagation, the relation between the sound speed $c(z)$, temperature profile $T(z)$ and wind speed profile $u(z)$ in dependence of height z is given by Rossing [10] with

$$c(z) = c_0\sqrt{\frac{T(z)}{T_0}} + u(z), \tag{1}$$

where T is in ℃ and u is in m/s. As explained before, wind and temperature gradients are significant for the refraction of sound. The influence of humidity is of minor importance.
If no measurement data in heights up to 100 m is available, the vertical profiles of wind speed and temperature can be determined using the Monin-Obukov similarity theory. According to this theory, the wind speed components in source-receiver direction and the temperature at height z are determined with

$$u(z) = \frac{u^*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_M\left(\frac{z}{L}\right)\right] \tag{2}$$

and

$$T(z) = T_0 + \frac{T^*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_H\left(\frac{z}{L}\right)\right] + \Gamma. \tag{3}$$

The definitions and the parameter values used in this work are summarized in table 1. The first term of the equation [$\ln(z/z_0)$] represents the turbulences due to mechanic friction. The second term [$\Psi_{M,H}(z/L)$] takes into account turbulences due to thermic friction, and thus the atmospheric stability is considered. This term includes the Monin-Obukhov lenght L, which depends on the heat flow at the ground surface and is particularly important for stability. Turbulent flow quantities such as the Monin-Obukov length are based on measured data and are determined using the Eddy-Corociance method. In order to smooth out random fluctuations in measurement data, atmospheric parameters are calculated with an averaging time of 30 minutes. The determination of L and other parameters listed in table 1 are described in Maas [7]. As shown in table 1, positive values of L represent a stable atmosphere and negative values an unstable one. Under neutral atmosphere $\Psi_M = \Psi_H = 0$

and $L \to \infty$ is assumed. In this contribution, the boundary layer stability conditions are classified in stability classes based on L. For stable and unstable atmospheric conditions, the correction value for the wind profile is calculated using

$$\Psi_M\left(\frac{z}{L}\right) = \begin{cases} 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - \arctan(x) + \frac{\pi}{2} & \text{for } L < 0 \\ -5z/L & \text{for } L > 0 \end{cases} \tag{4}$$

with

$$x = \left(1 - \frac{16z}{L}\right)^{1/4}. \tag{5}$$

For the correction term of the temperature profile the following equation is applied:

$$\Psi_H\left(\frac{z}{L}\right) = \begin{cases} 2\ln\left(\frac{1+x}{2}\right) & \text{for } L < 0 \\ -5z/L & \text{for } L > 0 \end{cases} \tag{6}$$

The equations 4 to 6 are called Businger-Dyer profiles and correspond to measurements from a real atmosphere up to a height of 100 m. By using the calculated wind and temperature gradients (equations 2 to 3), the vertical profile of the sound speed can be determined from equation 1.
Considering the horizontal component of the wind speed in a certain sound propagation direction, Larsson and Öhlund [6] introduced u_{comp} as wind speed parameter in equation 2. The horizontal component u_{comp} can be calculated by

$$u_{comp}(wd) = -|U| \cdot \cos(wd - dir), \tag{7}$$

where the wind direction in °is marked with wd and the direction of sound propagation is dir. A sound propagation in northerly direction is indicated with 0°, $|U|$ is the magnitude of the wind speed.
Conrady et al. [2] and Öhlund and Larsson [9] use the vertical gradient of the effective sound speed

$$\Delta c_{\text{eff}} = \frac{c(z_2) - c(z_1)}{z_2 - z_1} \tag{8}$$

as a measure of refraction. In equation 8 respective sound speeds at two chosen heights z_1 and z_2 are used.

Table 1 Definition and parameter values used in equations 2 and 3

Symbol	Denotation and Unit	Value
u^*	Friction velocity in m/s	Calculated by Maas [7]
z_0	Roughness length in m	0.08 (see Maas [7])
T^*	Scaling temperature in K	Calculated by Maas [7]
T_0	Air temperature at zero height	283
κ	Von Kármán constant	0.41
Γ	Adiabatic correction factor in °C/m	-0.01 for dry air
L	Monin-Obukhov length in m	Calculated by Maas [7]
		> 0 stable atmosphere
		< 0 unstable atmosphere
Ψ_M	Diabatic momentum profile correction (mixing) function	See equation 4
Ψ_H	Diabatic heat profile correction (mixing) function	See equation 6

3. Measurements and Data Processing

3.1. Site Description and Experimental Setup

Over a period of seven weeks, a measurement campaign was conducted in summer of 2018 next to a wind farm in northern Germany. The focus was on a 2 MW wind turbine with a 100 m hub height and 3-blade propellers of 50 m blade length. The terrain of the site is about 2 m above sea level and the landscape is homogeneous and flat. The area consists mainly of meadows divided by ditches, reeds, and rows of trees. Only one tree with a height of approximately 8 m is located around the acoustic measurement site. Acoustical measurement stations are considered to be 10 m away from natural disturbances such as trees or reeds. The area in which measurements were taken and the contribution of altitude levels in propagation of microphones are illustrated in figure 2.

In the campaign, three sound level meters were placed in 154 m, 249 m and 479 m distance to the wind turbine. The distance of the receiving point at 154 m is equal to the reference distance, as described in IEC 61400-11:2012 [4]. Sound pressure levels, 1/3-octave bands and audio were recorded at each measurement point. Each station consisted of a solar panel for external power supply and a sound level meter including windscreens, as shown in figure 2. Using a standard 90 mm windscreen as well as a 220 mm self-developed secondary windscreen, wind-induced noise was reduced effectively during the measurements. The sound level meters were fixed at a height of 1.70 m. Simultaneously to the acoustic recordings, extensive meteorological measurements were performed to describe the atmospheric conditions. In order to detect wind vectors, temperature and humidity, measurement devices were installed at a height of 2 and 10 m on a meteorological mast (see figure 2). Using Ultrasonic, 3D wind vectors and acoustical virtual temperatures are measured high-resolved. As a result, relevant turbulence parameters described in section 2 can be determined (see Maas [7] for detailed information). The meteorological mast was located 200 m from the wind turbine. Synchronously to acoustic and meteorological parameters, wind turbine operational data such as output power and rotational speed were monitored.

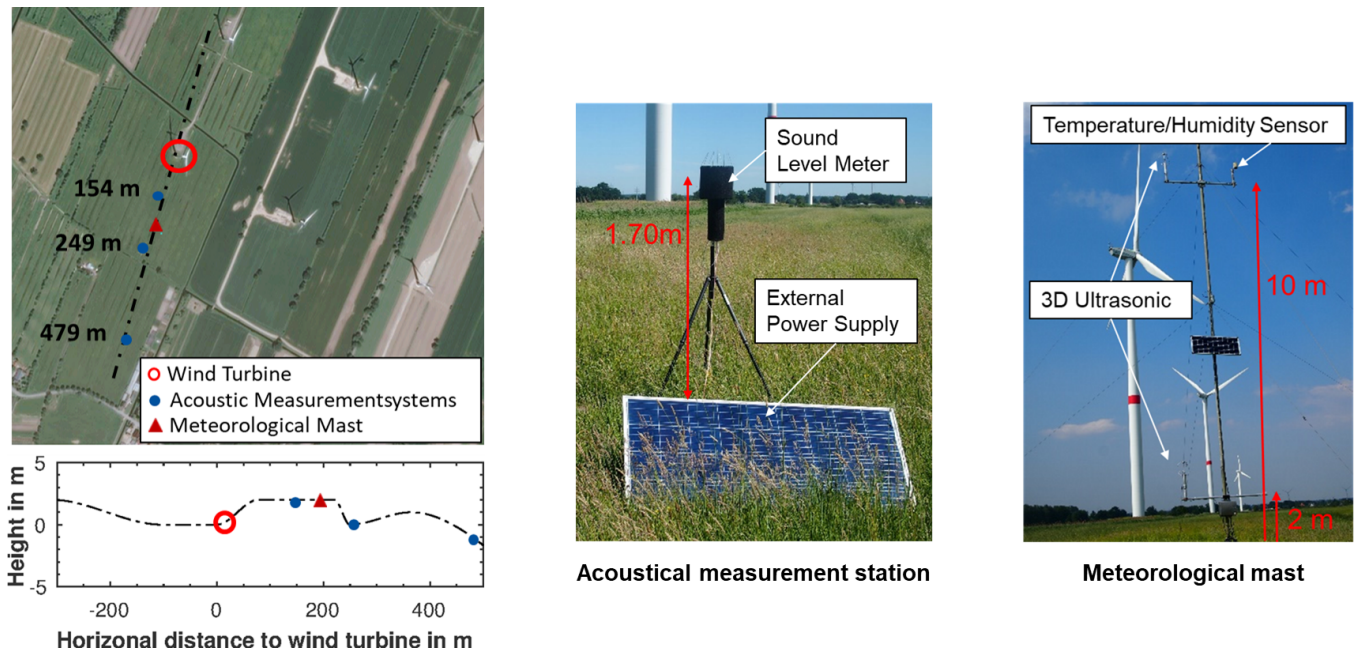


Fig. 2 Overview of the experimental setup

3.2. Selection of Data

While evaluating the acoustic measurements it is important to select data sets with dominant wind turbine noise, without disturbances from human activities, flyovers or from natural sources. Natural sources are mostly wind-induced sound from vegetation, and sound from animals such as bird-singing or frogs. Previous authors, especially named by van den Berg [11] and, Larsson and Öhlund [6], introduced criteria to avoid disturbances and to select data sets when the wind turbine sound is dominant. The criteria are described as follows:

$$L_5 - L_{95} \leq 4 \text{ dB(A)} \tag{9}$$

$$L_1 - L_{95} \leq 15 \text{ dB(A)} \tag{10}$$

$$L_{eq} - L_{1/3>3150Hz} \leq 1.5 \text{ dB(A)} \tag{11}$$

In criteria (1) and (2), statistical A-weighted percentile sound levels (L_n with n=1,5,95) are used. Those two criteria are based on the fact that disturbing sound events significantly affect the measured sound level during a short time period. To describe the criteria, 1 minute intervals of measured statistical sound levels are plotted for about two days in the left figure of 3. As illustrated, excess background noise shows high scattering in the sound level. In the case of dominant wind turbine noise, the sound levels fluctuate less and are more constant.

Criterion (3) represents the sound energy component in the frequency spectrum of a wind turbine. The high frequency components of wind turbine noise are strongly absorbed over distance. Based on investigations from Bolin [1], Öhlund and Larsson [9] show that wind-induced sound from vegetation at higher frequencies has more sound energy than the spectrum of a wind turbine. Typical background noises at the site, such as those from vegetation and bird-singing, dominate at high frequencies. This is also seen in right figure of 3, where an example of measured A-weighted 1/3 octave band during

bird singing is shown. Using the A-weighted equivalent sound pressure level L_{eq}, criterion (3) insures that, for example, bird-related noise does not influence the measurement data.

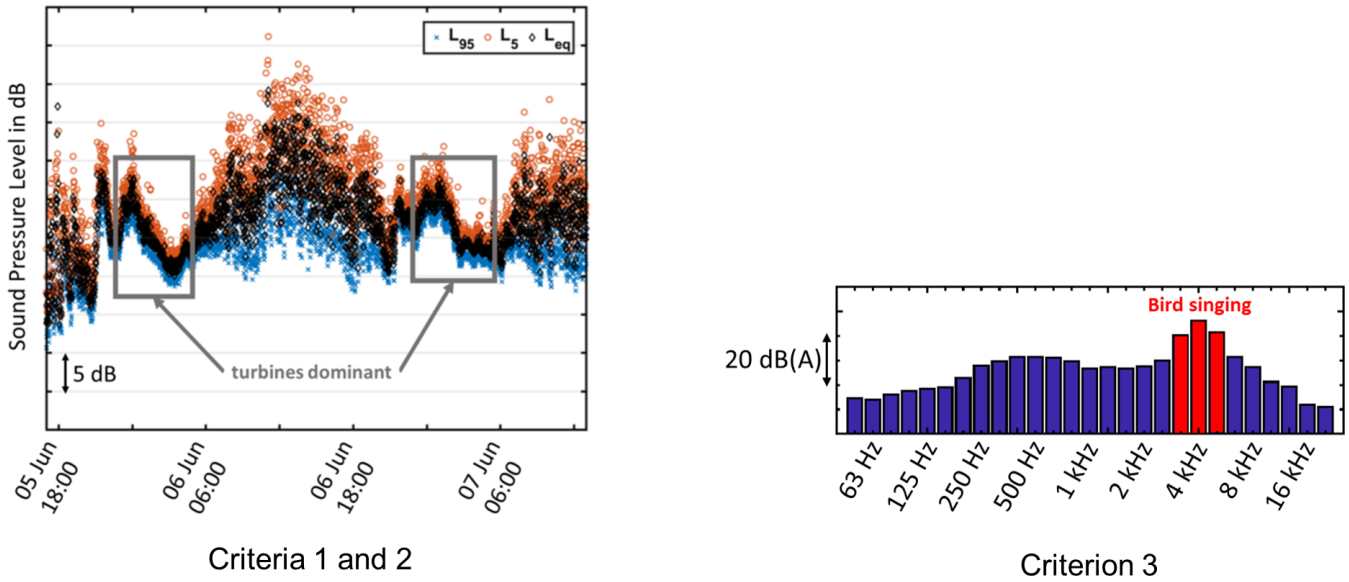


Fig. 3 Criteria 1 and 2: Measured statistical sound pressure levels per minute at 150 m from the wind turbine
Criterion 3: Measured A-weighted 1/3 octave band per minute at 150 m from the wind turbine while bird singing

For approximately 40% of the measuring time, the wind turbine sound was dominant. It is noticeable that the noises are mainly dominant at night and less during the day. This trend was also found by van den Berg [11], and corresponds with the complaints of residents in the area next to wind turbines. The complaints mainly relate to noise in the late evening and at night.

3.3. Method for Evaluating Sound Propagation

As shown in figure 3, the influence of ambient noise is large during the day at unstable atmospheric conditions. During the day the environment is more active then at night. Moreover, the wind speed at the ground is higher in an unstable atmosphere than in a stable one. Accordingly, the danger of measuring wind-induced noises is greater. Consequently, only data sets at stable atmopheric conditions are used for evaluating the sound propagation. Moreover, only data sets with rotor speeds of 12 rpm and above are selected. Since the sound propagation is investigated in all wind directions, the data is divided in four wind direction bins - Downwind, Crosswind 1, Crosswind 2 and Upwind. The division of wind direction is illustrated in figure 4.
Calculating the wind profiles the wind component in sound propagation direction u_{comp} is considered (see section 2). The high relevance of this component is visualized in figure 4. This figure shows the calculated effective sound speed for different wind directions in a stable atmosphere. If u_{comp} from equation 12 is not used to calculate the sound speed profile, it is assumed that the propagation direction of the sound is equal to the wind direction. As shown in the left picture, positive sound

velocity profiles are derived without directional correction - even in upwind situations. If the direction is corrected so that the propagation direction of the sound is not the same as the wind direction, a realistic negative sound velocity profile is obtained in upwind situations. In this contribution the sound propagation direction dir, for the calculation of u_{comp}, is 192.52°.

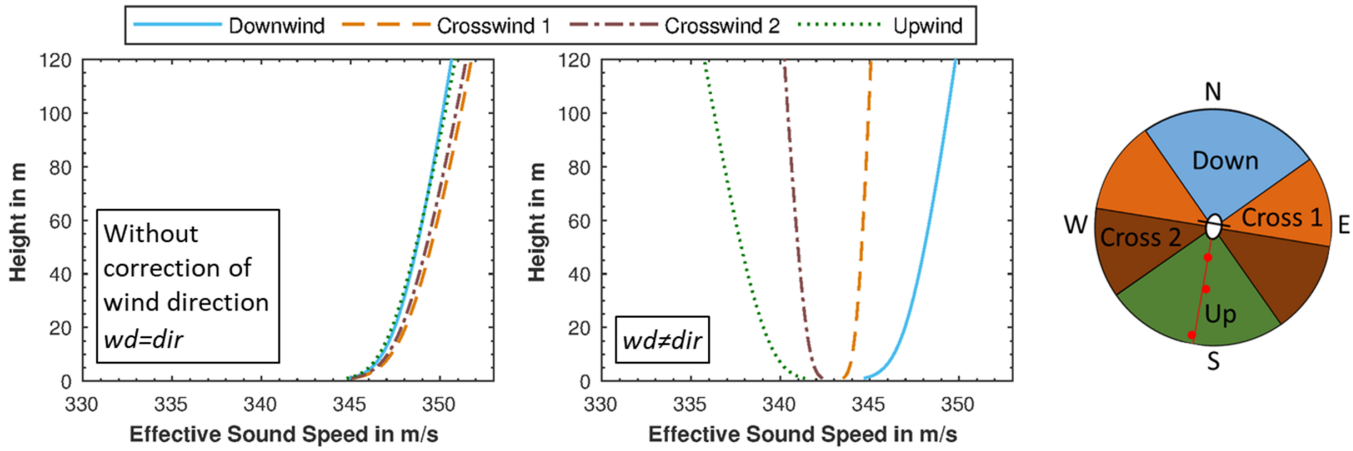


Fig. 4 Calculated effective sound speed profiles for different wind directions and during stable atmospheric conditions
left figure: without correction of wind direction
right figure: with correction of the wind direction using equation 12

The sound generation and radiation of wind turbines depends on many factors. For example, the turbine conditions and the environmental conditions have a direct effect on sound generation. In order to avoid additional error impacts due to inaccurate emission data of the wind turbine, the measured values at the first microphone position are used as a reference to examine sound propagation. The propagation loss is therefore estimated by

$$\Delta L_i = L_1 - L_i, \tag{12}$$

where L_i is the averaged A-weighted sound pressure level in dB at the microphone position i. Hence, L_1 is the averaged A-weighted sound pressure level at the first microphone position at 154 m distance to the wind turbine.

4. Results

In this section the environmental conditions during the measurement period are summarized. The sound propagation is investigated as a function of different gradients of the sound speed and hence, different sound speed profiles. Herein, only data sets during stable atmopheric conditions and rotor speeds of 12 rpm and above are used.

4.1. Meteorological and Wind Turbine Operational Conditions

Wind turbines emit sound as a function of operating parameters, which are dependent on meteorological conditions. During the measurement campaign, wind speed and wind direction were measured with an anemometer located on the nacelle behind upwind rotor. The rotating wings might have an influence on the measured meteorological data at hub height. A distribution of 10-minute averaged values of wind speed and nacelle position is shown in figure 5. In addition, the acoustic measurement positions and the location of the wind turbine are marked. During the period of acoustic measurements wind mainly flew from north-west to the south-east. A lot of acoustic data was therefore collected in the crosswind direction to wind turbine. In the downwind direction, the database is very small and the highest wind speed at hub height is 9.8 m/s, which is below the rated speed.

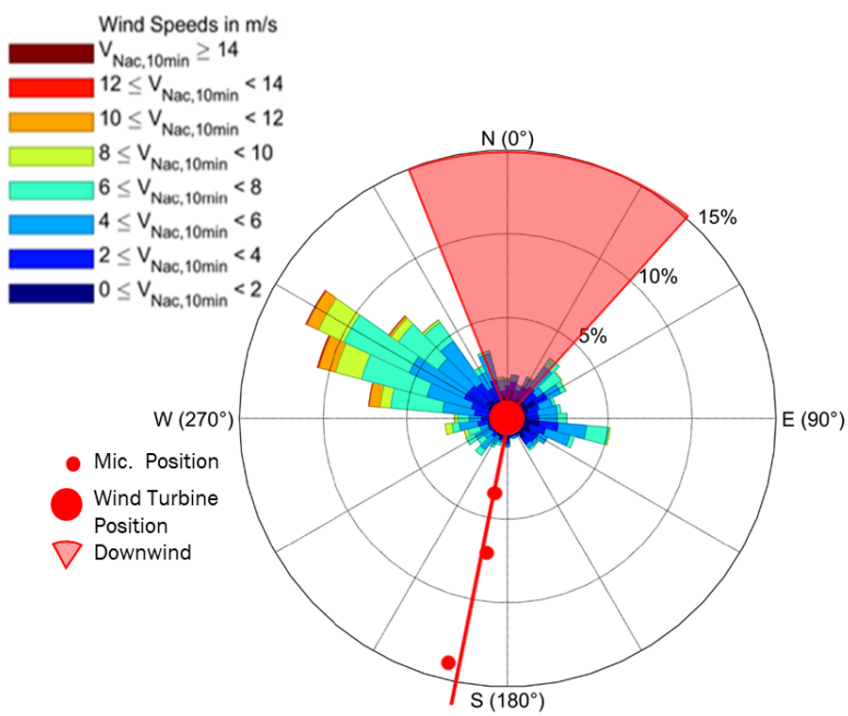
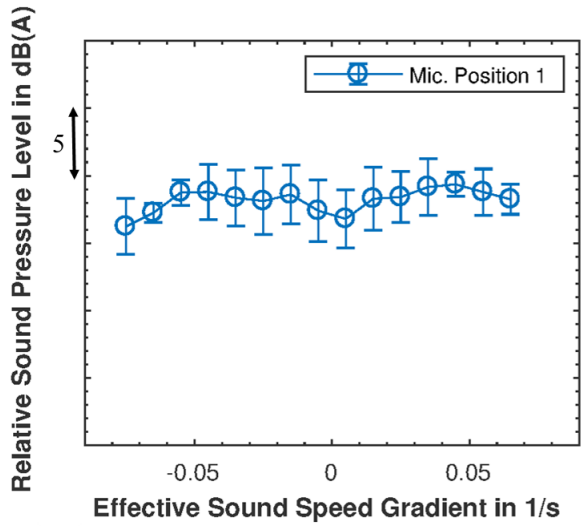


Fig. 5 Contribution of measured wind speed at hub height and nacelle position during the measurement campaign (10 minutes averaged data)

4.2. Sound Propagation

As in [2] and [9], the vertical gradient of the effective sound speed Δc_{eff} is used to evaluate the refraction of sound waves (see equation 8). In this contribution, the gradient Δc_{eff} between 120 and 1 m is calculated and divided into 0.01 Δc_{eff}-bins. A strong positive gradient is calculated in downwind conditions and a strong negative gradient is calculated in upwind conditions. Gradients close to $\Delta c_{\text{eff}} = 0$ indicate crosswind conditions.

Before the refraction of sound waves at different distances to the wind turbine is examined, an overview of the measurement uncertainties at the first microphone is given. For this purpose, the mean value and standard deviation of the sound-level data-sets per Δc_{eff}-bin are illustrated in figure 6. In addition, the number of 1-min data sets, which were selected according to the method described in section 3.2, is summarized in a table. As already known from figure 5, the data sets in crosswind direction predominate. The standard deviation of all data sets of the first microphone is less than 2.5 dB(A). As the distance to the wind turbine increases, the number of data sets decreases and the standard deviation becomes comparatively higher.



Δc_{eff}	No. of Data
-0,075	204
-0,065	59
-0,055	29
-0,045	**328**
-0,035	322
-0,025	297
-0,015	536
-0,005	**439**
0,005	624
0,015	**296**
0,025	270
0,035	275
0,045	61
0,055	60
0,065	**120**

Fig. 6 Mean value, standard deviation and amount of the sound-level data-sets per Δc_{eff}-bin at the first microphone

The average sound levels at all microphone positions for calculated effective sound speed gradients are shown in figure 7. In addition, the distance between the measuring position and the wind turbine is given. At the first two microphones with a distance of 154 and 249 m, lower levels are measured at Δc_{eff} close to zero than at high absolute gradients. This is not due to refractions, but represents the directivity of the wind turbine. Due to the dipole characteristic of the aerodynamic source, less sound is emitted in crosswind direction than in upwind and downwind direction. Based on the same measurement campaign, this behaviour is explained in Martens et al. [8].

At the 3rd measuring position at a horizontal distance of 479 m from the turbine, higher levels are measured with highly positive gradients than with more negative gradients. The difference between $\Delta c_{\text{eff}} = 0.065$ and $\Delta c_{\text{eff}} \approx 0$ is about 5 dB. This property is not only due to the directivity of the wind turbine, but also due to a downward bending of the sound waves. There are no differences between

the levels at negative Δc_{eff} and $\Delta c_{\text{eff}} \approx 0$. The level at negative Δc_{eff} has accordingly decreased with distance in comparison with data at $\Delta c_{\text{eff}} \approx 0$. This indicates an upward refraction of the sound waves.

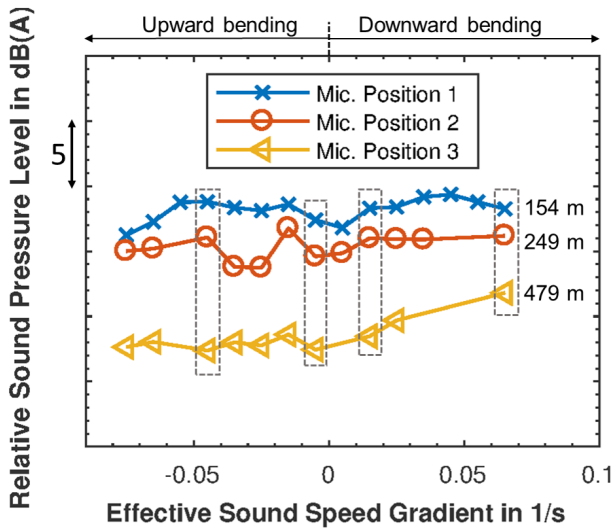


Fig. 7 Averaged A-weighted relative sound pressure levels for different effective sound speed gradients and distances to the wind turbine

Further discussion on the effect of sound speed profiles on sound propagation is based on four examples. The data at $\Delta c_{\text{eff}} = -0.045, -0.005, 0.015$ and 0.065 are used as examples, because those data sets are available for all measuring positions and have a comparatively large set of data (see marking in figure 6 and 7). In figure 8 the calculated sound speed profiles of the selected Δc_{eff}-bins are illustrated (right) and the respective propagation losses are plotted over the slant distance (left). In addition, the propagation losses due to geometric spreading is shown. This data is calculated by

$$\Delta A_{div} = \left(20log\left(\frac{d_1}{d_0}\right)\right) - \left(20log\left(\frac{d_i}{d_0}\right)\right), \tag{13}$$

where d_i is the distance from the source to the microphone i and d_0 the reference distance, which is set to 1. Effects of the ground or sound absorption are not taken into account.

The measurement results are consistent with the theory presented in section 2 and confirm the trend shown in figure 7. With increasing effective sound speed gradients and correspondingly growing positive sound speed profile, less sound is attenuated over distance. The more negative the sound speed gradient, the higher propagation loss over the distance. In figure 8, this tendency is especially seen at a distance of 490 m, where the difference between the first and last microphone is plotted. With strongly negative gradients, the propagation loss is 6 dB higher than with strongly positive gradients.

In comparison with the calculated propagation loss using geometrical spreading, an additional 3 dB attenuation of the sound is recognizable with strongly negative sound speed gradients. In comparison, 3 dB higher average levels are measured for strongly positive gradients. The same tendency, but less pronounced, is observed at the propagation losses of the gradients close to zero. Here, the slope of the sound speed profiles is smaller, so that the sound waves are bent less upwards or downwards.

As a result, the propagation loss deviates less from the theoretical value. The effect of refraction is particularly pronounced with strongly positive and strongly negative gradients and increases with distance.

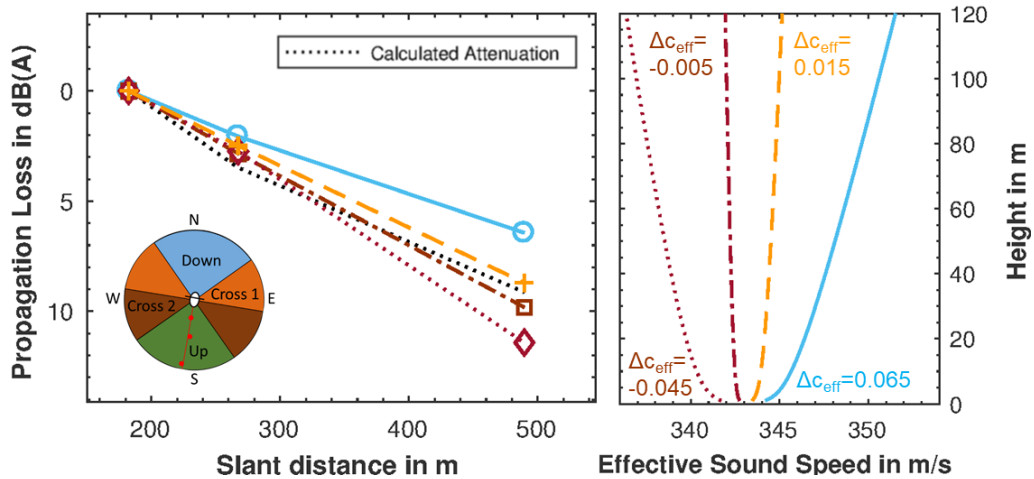


Fig. 8 Relative sound pressure level measured 154 m, 249 m and 479 m distance to the wind turbine during times of different effective sound speed gradients

5. Conclusion and Outlook

The sound propagation of wind turbines is affected by effective sound speed gradients, which are determined by temperature and wind speed profiles considering atmospheric stability. In theory, upward bending occurs with negative sound speed gradients while sound waves bend downwards with positive sound speed gradients. Hence, higher sound levels are expected with positive sound speed gradients. Measured acoustical data in 470 m distance to the wind turbine agree with the theory. A-weighted sound pressure levels with strongly positive sound speed gradients are 6 dB higher than with strongly negative gradients. This effect is less pronounced with weaker gradients and is not observed at shorter distances. At distances of 150 and 240 m to the wind turbine low sound levels were measured with gradients close to zero, which indicates crosswind situations. The measured values at those distances represent the source directivity of the wind turbine.

In future work, the results of this contribution will be verified with acoustical and meteorological data of a second measurement campaign. In this campaign, microphones are located in the statistical main wind direction, and larger distances up to 1150 m from the wind turbine to the receiver are realized. With a larger data base in downwind direction, the effect of the atmospheric stability on sound emission and sound propagation will be investigated in detail. A focus will also be on the influence of the turbulence intensity in the atmosphere.

Acknowledgements

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