Prediction of long-range propagation of wind turbine noise using the CNPE method

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Introduction

In the atmosphere, prevailing meteorological conditions have a strong influence on the long-range sound propagation. Wind and temperature gradients result in a geometric refraction and atmospheric turbulence leads to a scattering of sound waves. The impact of these effects on the sound propagation increases with distance. In particular, the prediction of long-range sound propagation and the impact of atmospheric effects are relevant for wind turbine noise. Evaluating these effects, a sound propagation model, which is based on the CNPE (Crank Nicolson Parabolic Equation) method, is developed within the project "WEA-Akzeptanz".
Implementing a wind turbine as a sound source in the CNPE method is an ongoing topic. Various methods exists and are discussed in former publications. A mathematical approach to describe a wind turbine as a single point source located at hub height is introduced in [1]. Additionally, [2] presents an approach for coupling a source model based on Amiet's theory with a parabolic equation code using a back-propagation method. Also, a moving source approach with three point sources located close to the blade tips is shown in [3]. The investigations of this contribution are referred to the latter approach.
In this work, the long-range sound propagation of a single point source and a simplified wind turbine source are compared. Therefore, the sound propagation model is introduced and the implementation of the source model is described. The long-range sound propagation of both sources are compared regarding downwind and upwind situations. At last, the possibility of using a point source to investigate wind turbine noise is discussed. The studies presented here are simplified and used as the very basis for further investigations.

Theory

Long-range sound propagation is strongly influenced by atmospheric conditions like refraction effects as a consequence of wind gradients. This effect is illustrated in Figure 1 with the help of sound rays. In the atmosphere, the speed of sound c is superposed with the speed of wind v_w and results in the effective speed of sound c_{eff}. Due to changing wind speeds within the altitude, the effective speed of sound underlies a change of speed with altitude, leading to refracted sound waves.[4]
In downwind directions, the wind speed is added to the speed of sound. Therefore, the effective speed of sound increases with the height and a downward refracted atmosphere is the consequence. Due to the downward refraction, sound waves are reflected at the ground more often, leading to higher sound pressure levels close to the ground.
Conversely, the wind speed is subtracted of the speed of sound in upwind directions. The effective speed of sound is therefore decreasing with the height, leading to an upward refracted atmosphere. Due to the upward refraction of sound waves, geometric shadow zones occur close to the ground in which the sound pressure levels are reduced.[4]
This contribution focuses on refraction effects in the atmosphere due to a wind gradient. Refraction due to a temperature gradients as well as atmospheric turbulence are not taken into account.

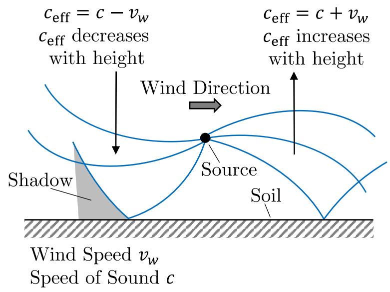

Figure 1: Atmospheric refraction of sound waves (illustrated as rays) as a consequence of wind gradients.

Sound Propagation Model

In this study, the Crank Nicolson Parabolic Equation (CNPE) method is chosen to calculate the sound field. With a neglection of backscattering and focusing only in direction of propagation, it is an efficient and suitable choice for calculation of long range sound propagation. Based on the Helmholtz equation

$$\frac{\partial^2 q}{\partial r^2} + \frac{\partial^2 q}{\partial z^2} + k_{\text{eff}}^2\, q = 0, \tag{1}$$

with the assumption of axial symmetry, a 3D domain is reduced to a 2D domain. Next to the sound field q and the cylindrical coordinates r and z, the effective wave number $k_{\text{eff}} = \omega / c_{\text{eff}}$ includes the effective speed of sound. The latter is approximating the atmospheric wind. The sound propagation is investigated in the far-field because of incorrect results in near-field situations as a consequence of angular limitations in the PE-method. Using the wavelength λ, the calculation domain is discretized with an equidistant grid of $\Delta z = \Delta r = \lambda/8$.
For the boundary condition, the acoustic impedance defines the lower boundary and the upper boundary prevents reflections with perfectly matched layer to simulate free field conditions. By a step-wise extrapolation

of $q(r,z) \rightarrow q(r+\Delta r, z)$ with start at $q(0,z)$, the sound field is calculated. The wave number k_{eff} is a function of the height z and independent of the direction r, which leads to an implementation of refraction. Further descriptions of the used CNPE method can be found in [5] and [6]. The used sound propagation model is verified with a benchmark case of [7] as described in [8].
For every frequency $L_p(f_i)$, the sound pressure level is calculated by

$$L_p\left(f_i\right) = L_w\left(f_i\right) - 10\log_{10}\left(4\pi R^2\right) - \alpha\left(f_i\right) R + \Delta L\left(f_i\right). \quad (2)$$

The last term on the right hand side $\Delta L(f_i)$ describes the transmission loss (TL) which is calculated by the PE-method and shows the alteration of the sound pressure level in the free field due to ground and atmospheric effects [3]. For a generalized analysis, the source power level $L_W(f_i)$ is disregarded. Additionally, in this contribution, the geometrical spreading $(-10\log_{10}(4\pi R^2))$ as well as the atmospheric absorption $(-\alpha(f_i)R)$ are not taken into account.

Source Model

With point sources located close to the blade tip (85 %) a wind turbine can be modeled as shown in [9]. Hence, three incoherent point sources are obtained from a former complex source as shown in Figure 2 (left side). Interpreted into 2D, the three point sources will rotate in and out of the calculation domain. Therefore, in a 2D simulation, those point sources can be moved up and down representing the rotation of a wind turbine. This is shown in Figure 2 (right side).[3]
The locations of the point sources are at the bottom tip height (PSbt at position $h - 0,85R_{\text{WT}}$), at hub height (PSh at position h) and at the top tip height (PStt at position $h + 0,85R_{\text{WT}}$). For simulating a simplified wind turbine source (WTS), those three point sources are summed logarithmic [3]. The introduced wind turbine in Figure 2 is artificial with dimensions referring to an ordinary wind turbine.
Rotational speed and the impact of various flow fields are not taken into account. In addition, there is no weighted spectra for the point sources included. In this contribution, the focus is on refraction effects of different source heights in a time independent situation, which can be seen as a time-averaged investigation of the sound propagation.

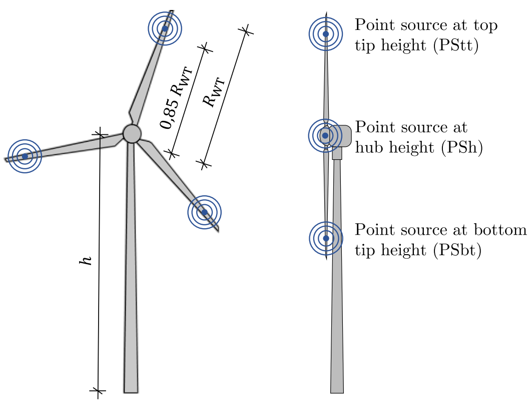

Figure 2: Locations of single point sources of a wind turbine in a 3D situation (left side) and transferred to a 2D situation (right side).

Results and Discussion

In the following, downwind and upwind situations are investigated. For both situations, the simplified wind turbine source is compared to a single point source at hub height for multiple frequencies. Furthermore, the simplified wind turbine source is collated with single point sources at the bottom tip height, the hub height and the top tip height as shown in Figure 2. For the evaluation, the sound propagation in the far-field (> 200 m) is used.

Downwind Situation

Figure 3 shows the transmission loss of a single point source at hub height (PSh) and a simplified wind turbine source (WTS) for 1/3 octave bands with a center frequency of 125 Hz and 500 Hz in a downward refracted atmosphere. For the point sound source at hub height, interference dips as a consequence of ground reflections are noticeable. Depending on the frequency, more precisely on the wavelength, those interference dips varying in incidence and locations.
The transmission loss of the simplified wind turbine source does not show the interference dips as sharp as the compared point source. The summed sources representing the wind turbine as described in the former sections, are leading to inference dips being smoothed. Hence, the simplified wind turbine source shows a lower transmission loss because of the summation of single point sources without adjusted source characteristics.

To investigate the sound propagation behavior of the simplified wind turbine source (WTS) and single point sources in different heights, Figure 4 shows the corresponding transmission loss for a 1/3 octave band of 500 Hz. The point sources are located at the bottom tip height (PSbt), the hub height (PSh) and the top tip height (PStt).
As shown in Figure 4 the interference dips are also depending on different source heights. Therefore, for the

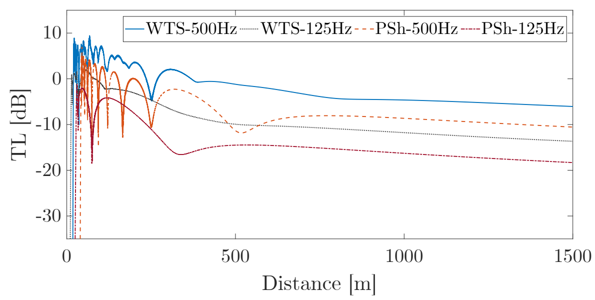

Figure 3: Transmission loss (TL) for a simplified wind turbine source (WTS) and a point source at hub height (PSh) in a downwind situation.

point source located on the top tip, the most interference dips are occurring. For the simplified wind turbine source, those interference dips are again smoothed out. As a result, the transmission loss of the point source at bottom tip height has the most similarities compared to the simplified wind turbine source due to the missing interference dips. Like before, the transmission loss of the simplified wind turbine source is lower because source characteristics are not considered. The transmission loss of the three single point sources are converging in greater distance (> 1000 m). For the investigated sound heights in this contribution, this leads to the assumption that in downwind direction the source height is not decisive in a greater distance. The wake flow is not considered in this study and could lead to different results.

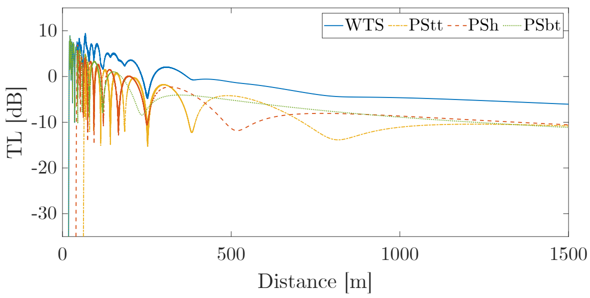

Figure 4: Transmission loss (TL) for a simplified wind turbine source (WTS) and point source at the top tip height (PStt), hub height (PSh) and bottom tip height (PSbt) in a downwind situation for a 1/3 octave band with a center frequency of 500 Hz.

Upwind Situation

Figure 5 illustrates the transmission loss of a point source at hub height (PSh) and a simplified wind turbine source (WTS) for 1/3 octave bands with a center frequency of 125 Hz and 500 Hz in an upward refracted atmosphere. Compared to Figure 3 similar interference dips occur in the near field. Like before, because of the summation of sources the simplified wind turbine source is having, the transmission loss is lower. Due to the upward refracted atmosphere, in a greater distance the transmission loss is decreasing strongly, indicating the geometric shadow zone. This shadow zone is formed more intense for higher frequencies. Furthermore, the shadow zone depends on the source height. Therefore, the transmission loss of the simplified wind turbine with summed sources at different heights is not decreasing as strong as the point source at hub height. Consequently, this leads to higher sound pressure levels in a greater distance even though a shadow zone exists.

The influence of different source heights on the occurrence of shadow zones is shown in Figure 6. As well as in Figure 4, the transmission loss for the simplified wind turbine source (WTS) and point sources at three different heights (bottom tip height (PSbt), hub height (PSh), top tip height (PStt)) for a 1/3 octave band of 500 Hz are presented. In general, the shadow zone forms in a

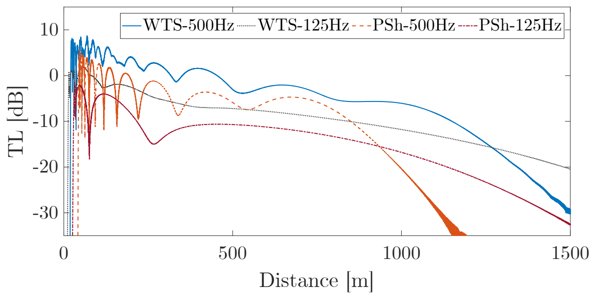

Figure 5: Transmission loss (TL) for a simplified wind turbine source (WTS) and a point source at hub height (PSh) in an upwind situation.

shorter distance the lower the source is located, as seen in the strong decrease of the transmission loss. In the mid-range of propagation distance, the simplified wind turbine source has a lower transmission loss like in the before presented results. Even though, this is not the case for a greater distance because the summation of the single point sources is influenced by the differences in the formation of shadows zones. Here, the point source at top tip height is decisive for the transmission loss of the simplified wind turbine source due to the formation of shadow zone in a greater distance.

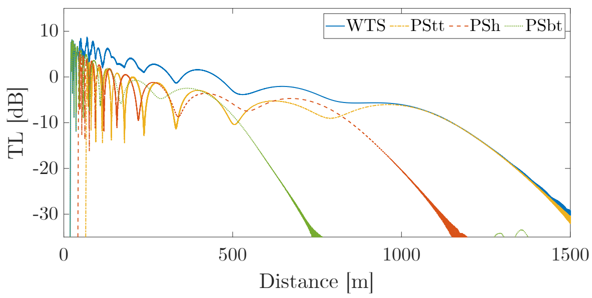

Figure 6: Transmission loss (TL) for a simplified wind turbine source (WTS) and point source at the top tip height (PStt), hub height (PSh) and bottom tip height (PSbt) in an upwind situation for a 1/3 octave band with a center frequency of 500 Hz.

Conclusion and Outlook

In this contribution, a basic study of long-range sound propagation is made for comparison of a simplified wind turbine source with single point sources. Therefore, a simplified wind turbine source is implemented to the Crank Nicolson Parabolic Equation (CNPE) method based on a logarithmic summation of single point sources close to the tip of a rotor blade. The sound propagation of this simplified wind turbine source is compared to single point sources at the bottom tip height, the hub height and the top tip height of a wind turbine for a downwind and an upwind situation.

In general, due to the summation of point sources representing a simplified wind turbine source, interference dips in the sound propagation are smoothed out. In a downwind situation, a lower sound source (at the bot-

tom tip height) has less interference and therefore the most similar sound propagation to the simplified wind turbine source. Additionally, the transmission loss of all single point source heights are converging in greater distance, which leaves the assumption, that the height of sources investigated here, are not decisive in downwind direction.
In upwind direction, the formation of the geometric shadow zone depends on the source height. The shadows zones are formed in greater distance for higher sound sources, resulting in higher sound pressure level when compared to lower sources. Here, the simplified wind turbine source shows similar refraction patterns as the single point source on top tip height, which leads to the assumption, that the highest sound source is most relevant for the investigated upward situation.
To conclude, the studies presented in this contribution show a correlation of wind direction and source modeling. The modeled wind turbine source has a relevant impact on the long-range sound propagation and the need of such a source depend on the wind direction. The various outcome of downwind and upwind situations indicate that in crosswind situations it also is likely to obtain different results. It is presumed that in crosswind situations the sound source at hub height is most dominant.
In this contribution, a time-averaged situation was investigated as a basis for long-range sound propagation studies of wind turbine noise. Rotational speed leading to a time-depending signal and source characteristics are not taken into account. Additionally, various flow fields and wake flow of wind turbines are not considered. Hence, those remarks will be considered in future investigations. Furthermore, source power level, air absorption and geometric spreading will be taken into account.

Acknowledgments

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