Auralization of Wind Turbine Noise: Propagation Filtering and Vegetation Noise Synthesis

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Summary
An auralizator for wind turbine noise consists of an emission synthesizer, a propagation filter, a vegetation noise synthesizer and a suitable reproduction system. This article describes the propagation filtering, considering the specific geometry of a highly elevated source and distant receivers, and the vegetation noise synthesizer. It is shown that the propagation filtering can be implemented efficiently as a series of finite impulse response filters (FIR) with a relative small number of taps. Measurements have revealed that a wind turbine has to be modeled as largely extended source in order to correctly simulate the ground effect. Based on numerical simulations, a model to incorporate energy neutral short-time level fluctuation effects was derived. Due to the source extension, the fluctuations are significantly smaller than expected for a concentrated point source.

The vegetation noise synthesizer uses an emission model that predicts a wind speed dependent volume-specific sound power spectrum for different tree species. The model is steered by a time varying wind speed function that is generated by a random process with a predefined power density spectrum.

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1. Introduction
Auralization has quite a long tradition in room acoustics [1] but has been discovered only recently for environmental noise applications [2, 3]. In its simplest form, an auralization starts with an audio recording taken close to the source. Subsequently the signal is filtered with help of a third-octave band equalizer according to damping values obtained with a spectral propagation model [4]. The approach chosen here is based on a purely synthetic emission audio signal [5] and a subsequent filtering that models each propagation effect individually. This allows for a more flexible adaptation of the emission signal characteristics and a more subtle simulation of the propagation, including possible Doppler-shifts for moving receivers. The auralization tool presented here is part of the project VisAsim [6, 7] that will study the landscape impact assessment of wind farms considering both visual and acoustical stimuli.

Sound propagation from wind turbines to typical listener positions has the distinction of highly elevated sources and large distances to the receiver. The height of the source strongly reduces the sensitivity of the propagation attenuation with respect to meteorological conditions [8, 9]. In our simulations we therefore ignore a possible curvature of propagation paths due to vertical gradients of the effective speed of sound and assume an attenuation independent of the condition of the atmosphere. However, as wind turbine noise occurs during periods with relative high wind speeds, a simulation of the propagation has to consider atmospheric turbulence which corresponds to a non-stationary, fluctuating channel. A realistic listening impression at a receiver position has to be composed of the signal of the turbines and possible environmental noise contributions. Indeed in many situations vegetation noise plays an important role as it grows with increasing wind speed and thus may mask turbine noise at high and very high wind speeds [10, 11, 12].

In section 2 of the paper the propagation filtering of wind turbine noise is discussed in detail for each propagation effect. Hereby the ground effect and fluctuations of the atmosphere that lead to receiver level variations have been investigated extensively. Based on measurements and numerical simulations it can be concluded that a wind turbine has to be modeled as a largely extended source. The point source assumption would significantly overestimate interference effects and level variations. In section 3 the model for the synthesis of vegetation noise is presented. Regarding signal strength, spectral content and wind speed dependency, the model relies on the work by Fégeant [13, 14] and Bolin [15]. Section 4 finally concludes with an outlook for future work.
2. Propagation effects and representation by digital filters

The emission synthesizer [5] delivers a digital audio signal \( e_i[k] \) for each source \( i \) with \( k \) as sample index. This signal is scaled as sound pressure in 1 m distance, assuming that it is radiated by a point source. The propagation effects from the source to the receiver can be understood as a filter that converts the emission signal \( e_i[k] \) into a signal \( r_{ij}[k] \) that corresponds to the sound pressure at the receiver position \( j \). The receiver signal \( r_{ij}[k] \) can be written as superposition of direct and ground reflected sound as

\[
r_{ij}[k] = F_0\left(F_1(e_i[k_e]) + F_2(e_i[k_e])\right),
\]  

(1)

where \( F_0 \) is the filter function that represents the reflection characteristics of the ground and the additional delay as a consequence of the longer propagation path compared to the direct sound. \( F_1 \) is the filter function that simulates geometrical spreading, air absorption and possible further attenuation effects introduced by barriers and foliage. \( F_2 \) finally is a power-neutral filter function that varies randomly over time to simulate fluctuations due to atmospheric turbulence. \( k_e \) corresponds to the propagation delay from source to receiver. In the general case for a moving receiver, \( k_0 \) and the filter functions \( F_0, F_1 \) and \( F_2 \) vary over time \( t \).

2.1. Doppler shift due to moving receiver

If the position of the receiver varies over time—which is planned in VisAsim [6]—the mapping of the emission signal time axis onto the receiver time axis becomes time-dependent. For a given sound travel time \( \Delta t(t) \) from source to receiver, the index \( k'_e \) of the emission signal \( e \) that is mapped onto the receiver sample with index \( k_e \) is given as

\[
k'_e = k_e - \Delta t(t) \cdot f_s,
\]  

(2)

where \( f_s \) is the sampling frequency. In general, \( k'_e \) obtained by equation (2) is not an integer and therefore not directly usable as sample index. In order to avoid discontinuities for varying \( \Delta t \), an interpolation operation is needed that allows to estimate an emission signal value at arbitrary points in time. The emission signal value \( e \) at index \( k'_e \) is determined here as

\[
e[k'_e] = \left(1 - k'_e + [k'_e]\right) \cdot e[k'_e] + \left(k'_e - [k'_e]\right) \cdot e[k'_e] + 1.
\]  

(3)

where \( [k'_e] \) corresponds to the floor function of \( k'_e \).

The linear interpolation in equation (3) corresponds to a low-pass filter operation and thus introduces an amplitude error at high frequencies. The upper limiting frequency \( f_{s_u} \) (corresponding to the \(-3 \) dB point) of the low-pass filter is lowest for \( k'_e - [k'_e] = 0.5 \). With help of numerical simulations, an average value of 14.9 kHz was found for \( f_{s_u} \), assuming a sampling frequency \( f_s \) of 44.1 kHz. In the context of wind turbines, this high frequency error is acceptable as frequencies above 10 kHz play a minor role at distances of several hundred meters. One reason is air absorption that introduces significant high frequency damping and a principal uncertainty due to its high sensitivity with respect to temperature and humidity. At 200 m distance and 14.9 kHz, air absorption varies by 1 dB/°C temperature change and by 0.5 dB/% change in humidity (ISO9613-1).

2.2. Geometrical spreading

The propagation effect of geometrical spreading is the simplest one to simulate. Depending on the source-receiver distance, a frequency independent scaling of the emission audio signal has to be applied.

2.3. Ground effect

2.3.1. Simulation by a FIR filter

Ground effect is modeled here according to the underlying physical mechanism as interference between direct and ground reflected sound (equation 1). As a simplification it is assumed that the reflection occurs at an infinitely extended plane defined by the topography at the receiver position. The ground reflection differs from the direct sound by scaling with a complex reflection factor and an additional delay. The ground reflected sound is represented as \( F_2(e_i[k]) \) with the filter function \( F_2 \).

\[
F_2(e_i[k]) = \frac{r_d}{r_r} \left( (e_i[k] * q[m]) * g_i[m] \right).
\]  

(4)

Figure 1. Ground effect for grassland (200 Rayls) for a source-receiver distance of 500 m (top) and 1000 m (bottom). The point source is assumed 100 m, the receiver 2 m above ground. The dashed line refers to the exact calculation, the solid line shows the error for a FIR simulation with \( n = 40 \) taps.
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Figure 2. Measured and calculated (point source and extended source assumption) level differences of wind turbine noise evaluated as level differences for a microphone position 1.60 m above ground and close to the ground (0.05 m). The source – receiver distances were 400 m (a), 300 m (b), 250 m (c) and 150 m (d). The height of the nacelle was 95 m, the propagation was over grassy land.

(a)

(b)

(c)

(d)

where \( r_d \) is the source - receiver distance, \( r_r \) is the distance source – ground reflection point – receiver, \( q[m] \) is the impulse response of the spherical wave reflection coefficient \( Q \) [16], \( q[l] \) is the impulse response of a delay by \( l \) samples where \( l = \text{round}(f_s \cdot (r_r - r_d)/c) \), \( c \) is the speed of sound and \( * \) is the discrete convolution operation.

As indicated in equation (4), the linear distortion by the spherical wave reflection coefficient \( Q \) is modeled by a digital filter \( q[l] \). \( q \) is realized here as a FIR filter where the coefficients are obtained by inverse Fourier transformation of \( Q(f) \) and subsequent limitation to a length of \( n \) taps. The FFT length is chosen as 64 k, corresponding to a frequency resolution \( \Delta f = 0.673 \) Hz (\( f_s = 44.1 \) kHz). It is found that for high elevated sources, already a relatively small number of taps is sufficient to reproduce the ground effect with acceptable accuracy. Figure 1 shows the ground effect for the propagation over soft ground (200 Rayls) between a point source 100 m above ground to a receiver 2.0 m above ground. The exact calculation and the simulation with a FIR filter of \( n = 40 \) taps is shown. The accuracy of the FIR simulation is better than 1 dB for the lowest interference dips. The increase of the error at high frequencies in case of the propagation distance of 1000 m is not relevant in an auralisation application, as these signal components become inaudible due to strong absorption by the atmosphere.

2.3.2. Source extension

In order to validate the ground effect simulation, four measurements were performed at Mont Crosin, Switzerland over soft ground (grassland). The source was a Vestas V90 turbine (no. 11) with a hub height of 95 m. The receiver was positioned in different distances to the source, firstly close to the ground (0.05 m) and subsequently at a height of 1.60 m. The measurements were evaluated as narrow band spectrum differences between the position at 1.60 m and the ‘close to ground’ position. For the measured geometries, the corresponding level differences were calculated assuming a point source at the hub position. As can be seen in Figure 2 the point source assumption leads to pronounced interference patterns that are not confirmed by the measurements. The relatively weak ground effect dips in the measurements suggest an extension of the source. Indeed this is confirmed by observations of the emission of wind turbines by acoustical cameras [17]. In the following it is assumed that the source has a vertical extension that corresponds to the diameter of the rotor. Corresponding calculations with five different point sources distributed
equidistantly in height reproduce the measurements in Figure 2 reasonably well.

2.4. Air absorption

The simulation of air absorption is realized by a linear phase FIR filter. The filter coefficients are found by inverse Fourier transformation of the air absorption spectrum. To obtain a linear phase filter, the imaginary part (or phase) of the absorption spectrum $H(f)$ is set to 0,

\[
\begin{align*}
\Re[H(f)] &= 10^{-0.05 \cdot A(f)}, \\
\Im[H(f)] &= 0,
\end{align*}
\]

where $A(f)$ is the air absorption at frequency $f$ in dB according to ISO 9613-2. The impulse response $h(t)$ is then determined as

\[
h(t) = IFFT(H(f)).
\]

where $h(t)$ is symmetrical around $t = 0$. $h(t)$ is symmetrical truncation to a finite length of $n$ taps and shifted by $n/2$ samples to obtain a causal filter.

The quality of the air absorption simulation by an FIR filter is expressed as squared difference between the exact solution and the FIR simulation of the air absorption in dB and averaged over the frequency range for which the attenuation due to air absorption is less than 30 dB. Figure 3 shows this error as a function of number of taps $n$ for different source-receiver distances. Air temperature and humidity were set to 10°C and 60%.

As can be seen in Figure 3, the necessary number of taps to obtain a good model of the air absorption increases with increasing source-receiver distance. An FIR filter length of $n = 20$ is sufficient to simulate air absorption with an accuracy better than 1 dB for distances up to 1000 m.

2.5. Attenuation by barriers and foliage

Similarly to the simulation of air absorption, attenuation by barriers and foliage is implemented as a linear phase FIR filter as well. Figure 4 shows the average squared error as a function of the number of taps for the barrier attenuation according to ISO 9613-2 for different values of the path length difference $z$ around the obstacle and through the obstacle. The necessary number of taps increases for increasing $z$. For strongly attenuating barriers ($z \approx 1.0$), an FIR length of $n = 80$ is needed for an accuracy better than 1 dB. Similar filter lengths have to be used to simulate attenuation by foliage.

2.6. Additional reflections

Besides the ground, additional reflecting objects or structures may influence sound propagation from source to receiver. If the sightline is not interrupted, direct and ground reflected sound usually dominate. However if the source is shielded, possible reflections at buildings [18], forests [19] or cliffs [20] have to be considered.

2.7. Atmospheric fluctuations

2.7.1. Introduction

During propagation over larger distances, significant sound pressure level and phase fluctuations occur due to temporally varying inhomogeneities of the atmosphere. The two relevant properties of the atmosphere are temperature and wind speed. Consequences of these fluctuations are level variations and a loss of coherence between direct and ground reflected sound. The decorrelation between the direct and ground reflected sound path is neglected here as an approximation. In the following, the level fluctuations are discussed in more detail.

2.7.2. Measurements of level fluctuations

During two days in September 2011, several recordings were taken at Mont Crosin in Switzerland. The equipment was made up of a Sound Devices 702T recorder and a B&K 4006 microphone. The signals of two Vestas V90
turbines (no. 11 and 12) with a hub height of 95 m were investigated at a microphone height of 1.60 m in different distances. The microphone signals were analyzed in octave bands with help of a Norsonic Environmental Analyzer 121 and averaged over periods of 100 ms. From the sequence of these 100 ms values, a moving average over a time interval of 5 s was calculated. This slowly varying time history served as reference. Finally the statistics of the level differences of the original 100 ms values and the reference was evaluated and expressed as a standard deviation. The evaluation of the signal power of a band-limited signal over a finite time window is inevitably associated with an uncertainty that depends on the product of bandwidth and averaging time. Consequently the above-described evaluation of the standard deviation cannot be attributed exclusively to fluctuations. Figure 5 shows the standard deviations of the wind turbine noise measurements and for comparison the standard deviations obtained for stationary pink noise.

The evaluations show at low frequencies comparable standard deviations for the wind turbine noise and the pink noise reference. The turbulences begin to dominate only for frequencies above 500 Hz. Furthermore the measurements demonstrate that the standard deviations increase for increasing frequency, distance and wind speed.

2.7.3. Characterization of atmospheric turbulence

In the following, horizontal sound propagation is assumed. Therefore the momentary effective speed of sound \( c \) can be written as

\[
c = c'(T) + v.
\]

where \( c'(T) \) is the speed of sound at temperature \( T \) and \( v \) is the horizontal component of the wind speed vector parallel to the propagation direction from source to receiver.

The characterization of the fluctuations is usually based on the refraction index \( n \). It can be written as

\[
n = 1 + \mu = \frac{c_0 + v_0}{c},
\]

where \( \mu \) is the fluctuating part of the refraction index, \( c \) is the momentary effective speed of sound, \( c_0 \) is the reference speed of sound in a medium at rest at average temperature \( T_0 \) and \( v_0 \) is the average wind speed component in propagation direction.

The momentary temperature \( T \) and the momentary wind speed component \( v \) in propagation direction can be written as sum of the average values \( (T_0 \text{ and } v_0) \) and a fluctuating part \( (\Delta T \text{ and } \Delta v) \): \( T = T_0 + \Delta T \) and \( v = v_0 + \Delta v \). With the approximation of normally distributed fluctuations and under the assumption that temperature and wind speed fluctuations are not correlated, follows for the variance of the fluctuation of the refraction index \( \mu \) [21],

\[
\langle \mu^2 \rangle \approx \frac{\sigma_T^2}{c_0^2} + \frac{\sigma_v^2}{4T_0^2},
\]

where \( \sigma_T \) is the standard deviation of the temperature fluctuations and \( \sigma_v \) is the standard deviation of the wind speed fluctuations. \( T_0 \) is the average air temperature in Kelvin and \( c_0 \) is the speed of sound. Typical values for \( \langle \mu^2 \rangle \) lie between \( 10^{-6} \) and \( 2 \times 10^{-5} \).

The simplest case that can be analyzed assumes homogeneous and isotropic turbulence [22, 23, 21]. For spherical wave propagation, the average squared log-amplitude fluctuation \( \langle \chi^2 \rangle \) and the average squared phase fluctuation \( \langle \phi^2 \rangle \) can be expressed as

\[
\langle \chi^2 \rangle = \frac{(\ln(A/A_0))^2}{\langle \mu^2 \rangle} = \left( \frac{\langle \phi^2 \rangle}{\langle \mu^2 \rangle} \right)^2 rL,
\]

where \( A \) and \( \phi \) are the sound pressure amplitude and phase with turbulence and \( A_0 \) and \( \phi_0 \) are amplitude and phase without turbulence, \( f \) is frequency, \( c_0 \) is speed of sound, \( r \) is the propagation distance and \( L \) is the correlation length. In the vicinity of the ground, \( L \) is in the range of typical 1 to 1.5 m.

The relation in equation (10) expresses that the log-amplitude and phase fluctuations are equal and that they increase with increasing frequency, increasing propagation distance and increasing turbulence. The log-amplitude fluctuation \( \langle \chi^2 \rangle \) can be rewritten as a variance in dB \( \langle \chi^2 \rangle \) as

\[
\langle \chi^2 \rangle = \langle (20 \lg(A/A_0))^2 \rangle = \langle \chi^2 \rangle \cdot \left( 20 \lg(e) \right)^2
\]

\[
= \langle \chi^2 \rangle \cdot 75.4. \quad (11)
\]
The model above predicts for a distance of 400 m with \( \mu^2 = 10^{-6} \) and \( L = 1.0 \) m at 2 kHz a standard deviation of 6 dB and at 4 kHz even 12 dB. These values are much higher than the measured fluctuations in Figure 5. This overprediction of the simple model was already observed by Daigle [21]. Furthermore he pointed out that measurements show a saturation of the log-amplitude fluctuations around \( \langle \chi^2 \rangle \approx 0.33 \) or \( \langle \chi^2 \rangle \approx 25 \) which corresponds to a standard deviation of 5 dB.

In order to further investigate the amplitude fluctuations for the specific case of wind turbine noise propagation, numerical simulations were carried out with a finite difference time domain model [24].

2.7.4. Numerical simulations

The numerical FDTD simulations of amplitude fluctuations due to atmospheric turbulences make usage of the concept of frozen turbulence. Thereby it is assumed that the condition of the atmosphere does not change during a pulse propagation from source to receiver. After many runs with arbitrary fields of the refraction index, statistical quantities can be derived that yield information about the distance and frequency dependency of the global amplitude fluctuations and variations in the ground effect dips due to increasing incoherence between the direct and ground reflected wave. The above observation, that the source has to be regarded as extended over a height that corresponds to the rotor diameter, has to be considered here as well, as this leads to a certain averaging over small-scale local inhomogeneities. The extension of the source is modeled by a series of five point sources distributed equidistantly along a vertical line running through the hub position.

The 2D-FDTD simulation needs a specification of the field of the fluctuating part \( \mu(r,z) \) of the refraction index \( n \). Hereby \( r \) corresponds to a horizontal length coordinate and \( z \) describes height. The fluctuation statistics is then obtained by evaluating many runs with different \( \mu(r,z) \) realizations.

Different turbulence models have been proposed in the literature, see e.g. [25]. In the following, as a simplifying approximation, a Gaussian turbulence model is assumed.

2.7.5. Synthesis of an arbitrary field of the fluctuating part of the refraction index \( \mu(r,z) \)

Following [26], a homogeneous field \( \mu(r,z) \) is assumed in a first step. In this case the spatial variability of \( \mu \) can be characterized by a correlation function with vector \( \vec{z} \) between the two points in space of interest as the argument. This correlation function \( B(\vec{z}) \) is defined as

\[
B(\vec{z}) = \mu(\vec{a} + \vec{z}) \mu(\vec{a})
\]

The bar in equation (12) represents average over time. In general, the field \( \mu(r,z) \) has to be considered anisotropic which means that the correlation function in horizontal and vertical direction will differ.

For both the temperature and wind speed fluctuations, a Gaussian correlation function is assumed. For Cartesian coordinates with \( \vec{z} = x \hat{i} + y \hat{j} + z \hat{k} \) follows

\[
B(x, y, z) = \left[ \frac{\sigma_x^2}{4T_x^2} + \frac{\sigma_y^2}{c_0^2} \left( 1 - \frac{\rho^2}{L^2} \right) \right] \exp(-d^2/L^2),
\]

where \( L \) is the correlation length, \( \sigma_T \) and \( \sigma_v \) are the standard deviations of the temperature and wind speed variation. The variables \( d \) and \( \rho \) are defined as

\[
d = \sqrt{x^2 + y^2 + z^2} \quad \text{and} \quad \rho = \sqrt{x^2 + z^2}
\]

The field can be written as [26]

\[
\mu(r, z) = \sqrt{4\pi \Delta k} \sum_{n=1}^{N} \cos \left( \frac{k_n \cos \theta_n}{k_n \sin \theta_n} \right) \left( \frac{r}{z} \right) + \alpha_n \sqrt{F(k_n \cos \theta_n, k_n \sin \theta_n) k_n},
\]

with \( k_n = n \Delta k \) and \( \theta_n \) and \( \alpha_n \) arbitrary angles between 0 and \( 2\pi \). With the above assumption of a Gaussian correlation function, the spectral density function \( F(k_r, k_z) \) is [26]

\[
F(k_r, k_z) = \frac{L^2}{4\pi} \left( \frac{\sigma_T^2}{4T_x^2} + \frac{\sigma_v^2[k_r^2 L^2 + 2]}{4c_0^2} \right) \exp \left( - \frac{(k_r^2 + k_z^2) L^2}{4} \right)
\]

2.7.6. Height dependent correlation length \( L \)

For sound propagation high above ground, the above assumption of a homogeneous turbulence structure with a constant correlation length \( L \) is no longer fulfilled. In [27] measurements are presented that evaluated \( L \) at different heights \( h \) above ground. At 1 m above ground, typical values are \( L \approx 1 \) m, while at a height of 33 m \( L \) increases to about 10 m. Here the following functional relation is used,

\[
L(h) = 0.3h + \exp \left( -0.3h \right)
\]

Furthermore reference [27] gives typical turbulence parameters for different Turner classes. For class 3 that is representative for moderate to strong wind and thus relevant for wind turbines in operation, the parameters are set as follows: \( \sigma_T = 1.3 \text{ m/s} \) and \( \sigma_v = 0.3 \text{ m/s} \). With equation (9) follows \( \mu^2 = 1.5 \times 10^{-5} \).

Assuming a variation of \( L \) with height \( h \), the spectral density function \( F(k_r, k_z) \) in equation (15) is no longer strictly valid. To prove exemplarily that equation (15) can still be considered a good approximation, the spectral density function \( F(k_r) \) with \( k_z = 0 \) was evaluated for the heights \( h = 2 \text{ m} \) (\( \rightarrow L = 1.2 \text{ m} \)) and \( h = 100 \text{ m} \) (\( \rightarrow L = 30 \text{ m} \)) and compared to the Fourier transform of the correlation function \( B(z) \) \( (x = 0, y = 0) \) with height dependent \( L \). As can be seen in Figure 6, the differences are rather small, supporting the applicability of equation (15).

Figure 7 shows an example of a \( \mu \) field realization with height dependent correlation length \( L \) where equation (16) was inserted in equation (15).
Figure 6. Comparison of the spectral density function $F(k_z)$ (dashed line) according to equation (15) and the one-dimensional Fourier transform of the correlation function $B(z)$ (solid line) for a height-dependent correlation length $L$. Left: 2 m above ground, right: 100 m above ground.

Figure 7. Example of a 2D field of the fluctuating part of the refraction index $\mu(r,z)$ for $L$ according to equation (16), $\sigma_v = 1.3$ m/s, $\sigma_T = 0.3^\circ$C, $c_0 = 340$ m/s, $T_0 = 293$ K and $N = 200$ and $\Delta k = 0.05$ m$^{-1}$. The horizontal axis corresponds to the $r$ coordinate, the vertical axis is $z$, both in meters.

2.7.7. Simulation parameters
With the above introduced turbulence parameter values $\sigma_v = 1.3$ m/s, $c_0 = 340$ m/s, $\sigma_T = 0.3^\circ$C, $T_0 = 293$ K, $\mu^2 = 1.5 \times 10^{-5}$, $L(z) = 0.3z + \exp(-0.3z)$, that are considered representative for moderate to strong wind conditions, 14 different $\mu(r,z)$-field realizations (one of them is shown in Figure 7) were determined. For each $\mu(r,z)$-field, the sound propagation was calculated with a 2D-FDTD simulation from five different point sources at heights 45 m, 62.5 m, 80 m, 97.5 m and 115 m to four receivers in 100 m, 200 m, 300 m and 400 m at height of 1.6 m.

2.7.8. Standard deviation of third octave band level fluctuations
Figure 8 shows the fluctuations as a function of frequency for a propagation distance of 400 m. The fluctuations strongly increase with frequency, but show no smooth behavior. This can be attributed to ground effect interferences that lead to frequency dependent sensitivities with respect to an inhomogeneous atmosphere. The standard deviations for the individual point sources range from 5 to 7 dB at 1.6 kHz. However if the already mentioned source extension is taken into account and the average over all five point sources is considered, the resulting standard deviation drops to about 2.5 dB at 1.6 kHz.

Figure 9 depicts the influence of distance on the fluctuations. Here the fluctuations are evaluated as average over all five point sources. The simulation results are compared with measured fluctuations as obtained during the campaign mentioned in section 2.7.2. In tendency the fluctuations increase with distance, however there is no monotonous behavior for all frequencies. The reason for this lies again in the nature of ground effect interferences. For varying propagation distances, the frequencies of constructive and destructive interference change. The comparison of the numerically simulated and measured fluctuations yields reasonable agreement if one considers the large spread of the measurement results. Together with the observations about the ground effect, the results support the finding that a wind turbine has to be modeled as significantly extended source.

2.7.9. Correlation between different third octave bands
The above evaluation yielded the frequency dependency of the fluctuation amplitudes. For the propagation simulation, additional information is needed about the coherence of the fluctuations in different frequency bands.

For that purpose for each $\mu$-field realization $i$, a reference value $L_{ref,i}$ was determined as the energetic sum
of the 6 third octave band receiver levels from 500 Hz to 1.6 kHz. This band was chosen as it covers the frequency range of highest fluctuations. Subsequently the correlation between this reference and the corresponding receiver levels $L_{j,i}$ in each third octave band $j$ was calculated and evaluated as coefficient of determination ($R^2$). As can be seen in Figure 10, there is a high correlation of the fluctuations in the frequency bands above 500 Hz. This suggests that, at least in the upper frequency range, the fluctuations can be considered synchronous. As the fluctuations below 500 Hz are relatively low, this synchronicity is assumed here over the complete frequency range for simplicity. Consequently the fluctuations can be modeled as a global, time-varying filter function $F_t(t)$.

2.7.10. Implementation of the global fluctuation filter function

Simplifying the frequency dependency of the fluctuations and assuming synchronous fluctuation of all frequency bands, the level variations can be modeled by a time dependent high-shelf filter function $F_t^0(t)$ with amplitude response,

$$ \left| F_t^0(f) \right| = \left( A(t) - C_{off} \right) \cdot \left[ 1 + \exp \left( \frac{\ln(81)}{f_1 - f_2} \left[ f - 0.5(f_2 + f_1) \right] \right) \right]^{-1} [\text{dB}]. $$

$A(t)$ [dB] is steered by a random process and $f_1$ and $f_2$ are the frequencies for which the high-shelf function reaches 10% and 90% of $A(t) - C_{off}$. As $A(t)$ in dB varies equally around 0, an additional offset correction $C_{off}$ is needed to adjust for energy neutral fluctuations. From the numerical simulations the following parameter setting has been derived: $f_1 = 2500/\sqrt{d} \text{ [Hz]}$ and $f_2 = 20000/\sqrt{d} \text{ [Hz]}$ with $d$: horizontal distance between source and receiver in meters. Here $A(t)$ is scaled for a resulting standard deviation of 2.0 dB, considering the fact that the synthesized emission signal already contains a significant portion of the propagation fluctuation.

With the above introduced concept of frozen turbulence in mind, information about the spectral content of the random process $A(t)$ can be derived in principal with help of a series of FDTD simulations. Hereby a random field of refraction index is generated and shifted by a certain off-
set for each subsequent run. The level history at a given receiver point can then be interpreted as a time function where the time axis is defined by the offset and an assumed representative wind speed.

As this method would be very time consuming, a simplifying approximation was used instead. For that purpose the local level variation was evaluated for a row of 100 equidistantly distributed receiver points. Figure 11 shows the level as a function of distance from the source. These level variations are caused by changes of the field of refraction near the receiver. A similar effect can be expected near the source, so as a first order estimate one can assume that the variations as seen in Figure 11 would occur on a distance axis scaled by a factor of 0.5.

For a certain wind speed, the number of turning points per second. Assuming a representative wind speed of 6 m/s, the evaluation yields approximately 4 turning points per second.

The random process $A(t)$ is generated by low-pass (order 3) filtered white noise. The upper limiting frequency $f_u$ is set to 2 Hz in order to match the number of turning points as observed in the FDTD simulation. This upper limiting frequency is considered valid for an average distance range of several hundred meters. For larger distances, $f_u$ is expected to lower accordingly.

3. Vegetation noise synthesis

Wind turbine noise at residents locations is usually accompanied by vegetation noise. For a realistic sound setting including possible masking effects, the synthesis of vegetation noise is therefore indispensable. This section describes a model that generates an audio signal as produced by trees and bushes. This signal is essentially broadband noise that originates from contacts between leaves and from vortex shedding around branches and twigs or - in case of conifers - around needles [13].

3.1. Relation between wind speed and specific sound power

3.1.1. General

The model proposed by Fégeant [13, 14] and Bolin [15] describes the acoustical emission of vegetation as a frequency dependent sound power $\Delta W(f)$ per cubic meter and per Hz bandwidth,

$$\Delta W(f) = C_R \cdot S \cdot \left( \frac{u}{c} \right)^{2\chi} \cdot \Gamma(f).$$  \hspace{1cm} (18)

$C_R$ is a radiation constant, $S$ is the leaf area density ($m^2/m^3$), $u$ is the wind speed representative for the vegetation, $c$ is speed of sound, $\chi$ is a wind speed coefficient and $\Gamma(f)$ is a normalized spectrum function. $C_R$, $S$, $\chi$ and $\Gamma(f)$ depend on the type of vegetation. In a specific situation the total radiated sound power is found by scaling with the vegetation volume and integration over the frequency band of interest.

For the parameter setting in equation (18), the following classes of vegetation are distinguished,

- deciduous trees with foliage,
- deciduous trees without foliage,
- coniferous trees.

3.1.2. Parameter setting for deciduous trees with foliage

The normalized spectrum function is given as

$$\Gamma(f) = C_1 f^{-1} + C_2 \exp \left( -C_3 (f / f_0)^2 / f_0^2 \right).$$  \hspace{1cm} (19)

where the parameters for $\Gamma(f)$ and $\Delta W$ are given according to Table I.
3.1.3. Parameter setting for deciduous trees without foliage

The normalized spectrum function is given as

$$\Gamma(f) = C_d f^{-2} + \exp \left( -\lambda_{d1}(\log(f/f_{d1}))^2 \right).$$  \hspace{1cm} (20)

where $f_{d1} = 0.2u/0.005$, $C_d = 6E4$, $\lambda_{d1} = 3$ and the parameters for $\Delta W$ are given according to Table II.

3.1.4. Parameter setting for coniferous trees

The normalized spectrum function is given as

$$\Gamma(f) = \exp(-\lambda_1(\log(f/f_1))^2) + C_c \exp(-\lambda_2(\log(f/f_2))^2).$$  \hspace{1cm} (21)

where $f_1 = 0.2u/d_n$, $f_2 = 0.2u/d_z$ and the parameters for $\Gamma(f)$ and $\Delta W$ are given according to Table III.

It should be noted that the model exhibits a pronounced dependency of the spectrum from wind speed for deciduous trees without foliage and for coniferous trees. Fluctuations of the wind speed will thus not only alter the amplitude but the spectral content as well.

### 3.2. Wind speed variation over time

According to [15] and [28], the following spectrum $S$ of the wind speed fluctuation is assumed,

$$nS(n) = \frac{105f}{u^2_n} \left(1 + 33n\right)^{3/2}.$$  \hspace{1cm} (22)

where $n = fz/\bar{u}$, $z$ is height above ground, $\bar{u}$ is the average wind speed at height $z$, $u_n$ is the friction velocity with $u_n = 0.4\bar{u}/\ln(z/z_0)$ and $z_0$ is the surface dependent roughness length. A time signal that represents the momentary wind speed is generated by FIR filtering white noise according to the spectrum $S$ from equation (22).

### 3.3. Wind speed inside vegetation areas

The wind speed inside an area of vegetation differs from the one in the open field. The differences can be observed in the vertical profile and in the magnitude of the wind speed. The attenuation as a function of penetration depth $x$ is usually described by an exponential decay. For our application, the models proposed by [13] and [15] are greatly simplified by assuming a general functional relationship for all kind of vegetation according to

$$u(x) = U_{\text{open-field}} \cdot e^{-0.04x}.$$  \hspace{1cm} (23)

where $u(x)$ is the wind speed representative for the vegetation at depth $x$ and $U_{\text{open-field}}$ is the free field wind speed at 10 m height and blowing upwind to the forest.

With help of equation (18) and the normalized spectrum functions, the wind speed is transformed into sound power. This leads to symmetrical level variations for positive (increasing wind speed) and negative (decreasing wind speed) fluctuations. Due to inertia effects of the movement of branches and leaves, it can be expected that a positive fluctuation should lead to a more steep level increase than the level decrease in case of a negative fluctuation. This is included in the simulation by an exponential averaging of $u$ with two different time constants. Based on listening tests the time constant for positive signal slopes is set to 0.2 s while for negative slopes the time constant is set to 1.0 s. It should be noted that this averaged wind speed $\tilde{u}$ has no longer a direct physical meaning but serves as quantity used in equation (18). Figure 12 shows an example of $u$ and $\tilde{u}$ at a depth of $x = 15$ m for an open-field wind speed of 8 m/s and a roughness length $z_0 = 0.3$ m.

### 3.4. Audio signal synthesis

The audio signal synthesis of vegetation noise starts with the generation of a wind speed time history according to paragraph 3.2. Based on the momentary wind speed, a
4. Conclusions and future work

A model has been presented to perform the filtering of an audio signal, according to the effects of sound propagation from a wind turbine to a receiver. The model is based on FIR filters that are applied consecutively, each representing a specific propagation phenomenon. It has been shown, that a relative small number of filter taps is sufficient, thus allowing the model to run in realtime. However in a future step it will be investigated to what extent the computational effort may be lowered by combining the different propagation effects and representation by a single filter.

Initial measurements have revealed that wind turbines have to be viewed as largely extended sources. This leads to considerable smoothing of the ground effect dip and level variations due to turbulence. The assumption so far, that the source is extended over the whole rotor diameter, has to be refined in future investigations.

The auditory scenery in the vicinity of a wind turbine is complemented by a vegetation noise synthesizer. The synthesizer generates a noise-like signal with an appropriate spectral shape and temporal variation according to a randomly varying wind speed. In a future step the wind noise audio signal will be refined by adding transient leaves effects.

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References

Heutschi et al.: Auralization of wind turbine noise