Auralization of Wind Turbine Noise: Emission 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 synthesis of wind turbine sounds, considering spectral content and frequency dependent amplitude modulation (AM). The generated sound pressure signal is composed of discrete tonal components and amplitude modulated broadband noise, whereas the latter is processed in 1/3 octave bands. For each band, level fluctuations are synthesized as the superposition of a random process and a periodic function with the blade passing frequency. The model uses around 120 low-precision input parameters which are obtained by signal analysis of audio recordings. The separation of the stochastic and the periodic part of the level fluctuations is performed by using the autocorrelation function. The stochastic level fluctuations are further investigated by making use of the cross-correlation function. In this article the signal analysis algorithms and the synthesis model are exemplarily applied to recordings from two modern 2MW turbines. The original and the synthesized sounds are provided. The quite complex wind turbine sound can be decomposed into only a few components that can be described by few parameters. As demonstrated by a listening test, the reconstruction of the wind turbine audio signal can be easily confused with the original sound.

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1. Introduction
Auralization has quite a long tradition in room acoustics [1] but has been discovered only recently for applications in environmental noise [2, 3, 4, 5, 6]. 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 1/3 octave band equalizer according to damping values obtained with a spectral propagation model [4, 6]. The approach chosen here is based on a purely synthetic emission audio signal and a subsequent filtering [7] 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 [8, 9, 10] that will study the landscape impact assessment of wind farms considering linked visual and acoustical stimuli.

Sounds from modern wind turbines generally consist of broadband noise and possible discrete tonal components [11, 12]. An often reported phenomenon related to wind turbine noise is the periodic amplitude modulation (AM) of the sound pressure level, which is related to the blade passing frequency of the turbine. Often found terms describing the hearing sensations of AM are "swishing", "thumping" or "beating" which are likely to be caused by different physical mechanisms [13, 14, 15]. A good overview of the sound generation mechanisms of wind turbines can be found in the book by Wagner et al. [16].

In this article a pure synthesis model for wind turbine emission sounds is presented in section 2. The input parameters of the model are obtained by elaborate signal analysis algorithms described in section 3 which are exemplarily applied to emission recordings of two modern wind turbines in section 4.

2. Synthesis Model
2.1. General assumptions and model structure
It is assumed that the wind turbine emission signal has a stationary character in terms of an invariant short-term spectrum where 'short' means about 5 seconds. The signal is supposed to be comprised of possible tonal components and broadband noise with frequency dependent amplitude modulation (AM). The AM functions consist of periodic and stochastic parts. Discrete impulsive sounds are not taken into account. With these preconditions follows the flow chart in Figure 1, describing the synthesis
The spectral shaping of the broadband noise component is performed in 1/3 octave bands. For each 1/3 octave band \( i \), white noise is generated and filtered with a digital pink filter. The pink filter is realized by a cascaded series of three IIR second-order sections, i.e. three digital biquad filters. The output of the pink filter is bandpass filtered by a 8th order Butterworth filter and normalized to unit signal power to obtain the signal \( n_{i}(t) \). The broadband component is given by

\[
p_{\text{noise}}(t) = \sum_{i=1}^{N_{b}} p_{0} 10^{L_{i}(t)/20} \cdot n_{i}(t),
\]

with \( N_{b} \) being the number of considered 1/3 octave bands and \( L_{i}(t) \) being the sound pressure level of band \( i \).

### 2.4. Amplitude modulation

The amplitude modulation (AM) is implemented in equation (3) by the use of 1/3 octave band levels \( L_{i}(t) \) being a function of time \( t \). The level curves \( L_{i}(t) \) are assumed to consist of three additive parts

\[
L_{i}(t) = \overline{L}_{i} + F_{\text{periodic},i}(t) + F_{\text{stochastic},i}(t),
\]

where \( \overline{L}_{i} \) denotes the arithmetic mean sound pressure level, \( F_{\text{periodic},i}(t) \) is a periodic level fluctuation function representing the periodic AM and \( F_{\text{stochastic},i}(t) \) is a stochastic process representing the stochastic AM. \( L_{i}(t) \) is synthesized at a sampling frequency \( f_{s} = 30 \text{ Hz} \) and up-sampled to the audio sampling frequency \( f_{s} = 44.1 \text{ kHz} \) before being applied as amplitude modulation in equation (3).

### 2.5. Periodic amplitude modulation

The periodic level fluctuation \( F_{\text{periodic},i}(t) \) is a periodic function with zero mean and period \( T_{BP} = 1/f_{BP} \). \( f_{BP} \) denotes the blade passing frequency (BPF) of the turbine given in Hz and can be calculated from the rotational speed \( f_{rot} \) [rpm] of the turbine by \( f_{BP} = f_{rot} \cdot N_{\text{blades}} / 60 \) with the number of blades \( N_{\text{blades}} \) being typically \( 3 \). With the periodic level fluctuations the well-known “swishing” and “thumping” sounds are implemented. Regarding phase it is assumed that the maximum level of those sounds occurs at the downstroke when the blades pass the horizontal position \([17, 15]\). From the initial position \( \phi_{0} \) of the down stroking blade, defined as the angle between the blade and the vertical axis in degrees \( \circ \) (up = 0\( \circ \)), the time shift

\[
T_{h} = \frac{90^\circ - \phi_{0}}{360^\circ} \cdot \frac{N_{\text{blades}}}{f_{BP}}
\]

is calculated. The periodic level fluctuation is a periodic function with a defined amplitude and can be expressed as

\[
F_{\text{periodic},i}(t) = s_{\text{periodic},i} \cdot G(t - T_{h}),
\]

with the standard deviation \( s_{\text{periodic},i} \) of the periodic level fluctuations in \( \text{dB} \) and the periodic function \( G \) having zero mean, period \( T_{BP} \), its maximum at \( t = 0 \) and unit signal power. Motivated by measured sound pressure level curves (see Figure 4 or [18]) and hence based on listening tests where measured signals were compared to synthetic signals, it was decided to use a triangle wave form for \( G \). In order to satisfy the unit signal power condition, the triangle wave has to be scaled to have minimum and maximum values \( \pm \sqrt{3} \), respectively.

### 2.6. Stochastic amplitude modulation

The stochastic level fluctuations \( F_{\text{stochastic},i}(t) \) are generated by random processes. As especially at high frequencies the stochastic level fluctuations between 1/3 octave bands are highly correlated, groups of 1/3 octave bands steered by the same fluctuation function \( n_{i}(t) \) are used. For every group \( j \) an ARMA model generates a stochastic fluctuation function which is then normalized to unit signal power.
power to obtain the fluctuation signal $\eta_i(t)$. The stochastic level fluctuations are then given by

$$F_{\text{stochastic},i}(t) = s_{\text{stochastic},i} \cdot \eta_i(t), \quad (7)$$

where $s_{\text{stochastic},i}$ is the standard deviation of the stochastic level fluctuations in dB. It has been shown that in all cases studied so far, the level fluctuations could be well modeled by a white Gaussian process filtered by a 1st order Butterworth low-pass filter. From about 20 measurements at different wind conditions and different turbine types by means of least squares fits the following approximation formula for the cutoff frequency $f_{\text{ARMA},j}$ of the low-pass filter was derived,

$$f_{\text{ARMA},j} = \frac{1}{N_{m,j}} \sum_{i \in j} \left\{ \begin{array}{l}
10^{0.7 \log(f_{c,i}) - 1.5} \text{ Hz}, \\
5 \text{ Hz}, \\
10^{0.7 \log(f_{c,i}) + 1.5} \text{ Hz},
\end{array} \right. \quad (8)$$

with $N_{m,j}$ being the number of 1/3 octave bands in group $j$.

3. Signal Analysis

The basis for the signal analysis is a measured sound pressure signal, $p(t)$, (see section 4) with sampling frequency $f_s = 44.1 \text{ kHz}$. On one hand it should be guaranteed that the signal to be analyzed is short enough in terms of constant signal characteristics, e.g. no impulsive sounds, constant blade passing frequency, etc. On the other hand the signal should be long enough to ensure stable statistics. A signal length of around 20 seconds seems to be an appropriate compromise. The signal analysis is structured into four steps: 1) tonality analysis, 2) spectral analysis, 3) periodic AM and 4) stochastic AM.

3.1. Tonality analysis

In order to detect possible tonal components a narrow-band frequency analysis is performed. The power spectral density (PSD) of $p(t)$ is estimated by using Welch’s method (Hanning window, 50 % overlap, 16 k FFT, $\Delta f = 2.7 \text{ Hz}$). In the PSD all local maxima inside a defined band (typically 100 Hz to 5 kHz) are searched. Each local maximum exceeding the arithmetic mean level inside the critical band centered around the detected frequency by more than 4 dB is considered a tone. For each tone the tone level is evaluated by integrating the PSD over a range of 10 Hz around the tone frequency.

In order to suppress the detected tones for the following analysis, a notch filter bank is created. For each tone a 4th order Butterworth band-stop filter at the tone frequency is designed. For frequencies below 1 kHz a relative bandwidth of 5 % of the center frequency is applied, whereas for frequencies above 1 kHz a fixed bandwidth of 50 Hz is used. The notch filter bank is then applied to $p(t)$ resulting in signal $\tilde{p}(t)$.

3.2. Spectral analysis

Following the concept of sub-band coding, the signal $\tilde{p}(t)$ is decomposed into 1/3 octave bands by applying a 8th order Butterworth bandpass filter bank with center frequencies, $f_{c,i}$, from 20 Hz to 10 kHz. Together with the mean levels, the presented synthesis model relies on detailed information about the level fluctuations per 1/3 octave band.

Therefore for every 1/3 octave band signal, $\tilde{p}_i(t)$, the time-weighted sound pressure level

$$L_i(t) = 10 \log \left( \frac{1}{\tau_i} \int_{t-\infty}^{t} \frac{\tilde{p}_i^2(t')}{p_0^2} e^{(t'-t)/\tau_i} dt' \right) + C_{\text{notch},i} \text{ dB}, \quad (9)$$

with frequency depending time constant

$$\tau_i = \frac{a}{f_{c,i}} \text{ [s]} \quad (10)$$

is calculated. Based on listening tests of resynthesized wind turbine sounds, the smoothing parameter $a$ is chosen as 20. This choice of $a$ yields a time constant of 20 ms at 1 kHz. The correction term $C_{\text{notch},i}$ compensates for the influence of the notch filter bank on the broadband noise part of $p(t)$. $C_{\text{notch},i}$ is determined by evaluating the 1/3 octave band level attenuation of the notch filter bank applied to pink noise. The resulting 1/3 octave band level curves are then downsampled to a sampling frequency $f_{sL} = 30 \text{ Hz}$ which was again validated by subjective assessments of resynthesized signals. The arithmetic mean noise level per 1/3 octave band is given by

$$\overline{L_i} = \frac{1}{T - T_0} \int_{T_0}^{T} L_i(t) \, dt, \quad (11)$$

where the integration time offset $T_0$ is set to 2 seconds in order to avoid edge effects at low frequencies.

3.3. Level fluctuations

Generally, the level fluctuations are obtained by subtracting the DC offset $\overline{L_i}$ from $L_i(t)$. However, together with perceptible level variations, wind turbine sounds also exhibit imperceptible slow level variations which are not intended to be covered by the synthesis model. Therefore after removal of the DC offset, the signals are high pass filtered with a cutoff frequency of 0.1 Hz to obtain the level fluctuations $F_i(t)$.

Sections 2.4 and 2.5 suggest that the level fluctuations are composed of two independent additive terms

$$F_i(t) = F_{p,i}(t) + F_{s,i}(t), \quad (12)$$

namely a periodic function $F_{p,i}(t)$ with period $T_{\text{BP}} = 1/f_{\text{BP}}$ and the blade passing frequency $f_{\text{BP}}$, and a stochastic term $F_{s,i}(t)$. Both functions are assumed to have zero mean.
3.4. Estimation of the blade passing frequency

The acoustical estimation of the blade passing frequency \( f_{BP} \) from level fluctuations can be understood as a pitch detection task which can generally be performed in either the time or the frequency domain. Following other authors [19, 20, 18, 21] initial attempts were made to use the periodic and stochastic parts is critical, particularly as the method was found by using the ACF well, results also at low frequencies, \( s_{periodic,i} \) of an noise signal is maximum at \( \kappa = 0 \) and steadily declines to both sides. The ACF of \( x(t) \) is defined as

\[
R_x(\kappa) \equiv x(t)x(t + \kappa)
\] (13)

with the time lag \( \kappa \). The application of the ACF to a periodic function preserves its periodicity, whereas the ACF of a noise signal is maximum at \( \kappa = 0 \) and steadily declines to both sides. The ACF of \( F_i(t) \) therefore shows local maxima at \( \kappa = nT_{BP} \) with \( n \) an integer. This property is now used to estimate the blade passing frequency from the level fluctuations \( F_i(t) \). For this, by using a priori knowledge, a search range for the blade passing frequency is defined, i.e. \( f_{BP} \in [b \ldots c] \) with e.g. \( b = 0.5 \) Hz and \( c = 1.5 \) Hz. Then the 1/3 octave band, \( i' \), with the largest local maximum of the unbiased ACF within the search range \( 1/c < \kappa < 1/b \) is selected and used to estimate the blade passing frequency \( f_{BP} = 1/T_{BP} \), where \( T_{BP} \) is the time lag of the largest local maximum within the search range.

3.5. Standard deviation of the periodic AM

The standard deviation, \( s \), of a zero mean signal, \( x(t) \), is related to the signal power \( P_x \) by

\[
s^2 = P_x \equiv \left< x^2(t) \right> = R_x(0). \] (14)

In order to determine the standard deviation, \( s_{periodic,i} \), of the periodic AM, initial attempts were made by using the PSD. However, it appeared that the spectral separation of periodic and stochastic parts is critical, particularly as harmonics of the periodic part are present and in some cases the stochastic component dominates. A more robust method was found by using the ACF as well,

\[
s_{periodic,i}^2 = F_{i,t}^2(t) = R_{F_i,nT_{BP}}. \] (15)

with \( n \) being an integer except 0. In the implementation the unbiased ACF is used and, in order to obtain reliable results also at low frequencies, \( s_{periodic,i} \) is evaluated as an average for \( n = 1, 2 \) and 3.

3.6. Stochastic AM

The standard deviation, \( s_{stochastic,i} \), of the stochastic AM is calculated by

\[
s_{stochastic,i}^2 = s_{tot,i}^2 - s_{periodic,i}^2 = s_{pinknoise,i}^2, \] (16)

where \( s_{tot,i} \) denotes the total standard deviation of \( F_i \) and \( s_{pinknoise,i} \) is the standard deviation of level fluctuations of a reference pink noise signal which is processed in the same manner as the wind turbine signal.

By looking at measured level fluctuations it is apparent that there exists a coherence of the stochastic AM between 1/3 octave bands, especially between high frequency bands. Experiments with synthesized sounds have revealed that the implementation of this finding is very important for a realistic synthesis. The coherence of the stochastic AM between frequency bands can objectively be investigated by using the cross-correlation function (CCF) which for two continuous functions \( x(t) \) and \( y(t) \) is defined as

\[
R_{xy}(\kappa) \equiv \left< x(t)y(t + \kappa) \right>. \] (17)

As a measure of the coherence between the stochastic AM of two 1/3 octave bands \( i \) and \( j \), the following expression for the correlation coefficient was deduced,

\[
\rho_{ij} = \frac{\text{Cov}(F_{i,t}, F_{j,t})}{\sqrt{\text{Var}(F_{i,t})}\sqrt{\text{Var}(F_{j,t})}} = \frac{R_{F_i,F_j}(0)}{\sqrt{R_{F_i}(0)R_{F_j}(0)}} = \frac{R_{F_i,F_j}(0) - R_{F_i,F_j}(T_{BP})}{\sqrt{|s_{tot,i}^2 - s_{periodic,i}^2|} \cdot |s_{tot,j}^2 - s_{periodic,j}^2|}. \] (18)

Now for every 1/3 octave band \( i \) the number \( N_{a,i} \) of adjacent 1/3 bands with \( \rho_{ij} > 0.5 \) are counted. The vector \( N_{a,i} \) is then used to build groups of 1/3 octave bands being modulated by the same stochastic AM function.

The spectral content of the level fluctuations is investigated by applying a 1/3 octave band filter bank to \( F_i(t) \) prior to the calculation of the standard deviations by (16). Modulation frequency spectra of the stochastic component are evaluated for a typical range of the modulation 1/3 octave band center frequencies from \( m = 0.1 \) to 10 Hz and with \( s_{periodic,i,m} \) being the modulation frequency spectra of \( F_{i,t} \) estimated by \( s_{periodic,i,m}G(t) \).

3.7. Compensation of sound propagation

As the above extracted levels are immission levels, they have to be corrected for sound propagation effects in order to ensure a proper interface to the sound propagation simulation [7]. Thus, the tone levels and the mean noise levels are converted to a reference distance \( r_0 = 1 \) m. The propagation effects geometrical divergence, ground effect and atmospheric absorption are taken into account:

\[
L_{1m} = L_{im} + 20 \log \left( \frac{R_1}{r_0} \right) + A_{gr} + A_{atm}. \] (19)

with \( L_{im} \) being the extracted sound pressure immission levels, with the distance \( R_1 \) between microphone and the source, the ground effect \( A_{gr} \) and the atmospheric attenuation \( A_{atm} \). \( R_1 \) is approximated by

\[
R_1 \approx \sqrt{R_0^2 + H^2}, \] (20)
with the hub height $H$ and the horizontal distance $R_0$ between microphone and the wind turbine tower. The measurements were performed on a hard plate according to [11] which means that the ground effect $A_{gm} = -6$ dB. $A_{gm}$ is calculated according to the standard ISO 9613-1 [22] with measured temperature and humidity for the tone frequencies and the center frequencies of the 1/3 octave bands, respectively.

4. Evaluation

In this section the proposed signal processing algorithms are exemplarily illustrated by applying them to two recordings from two different 2 MW wind turbines WT1 and WT2 (see Table I). On September 7, 2011 at 12h the recording of WT1 was taken at the wind turbine site on Mont Crosin, Switzerland, with temperature 9 $^\circ$C and relative humidity 94%. The recording of WT2 was performed at the wind turbine site in Saint-Brais, Switzerland, on July 23, 2012 at 21h with temperature 10 $^\circ$C and relative humidity 80%. Both recordings were taken at strong wind conditions with the turbines operating at nominal power. The sound propagation occurred over flat grassy ground and the microphones were placed on a hard plate of diameter 0.6 m at horizontal distance $R_0$ (given in Table I) to the turbines. For WT1 the microphone was mounted in downwind direction (position no. 1 according to [11]) and for WT2 in upwind direction (position no. 3 according to [11]). The equipment used consisted of a Sound Devices Two-Track Audio Recorder 702T and a B&K omnidirectional microphone 4006. Weather information was obtained from a nearby ground-based automatic weather stations operated by MeteoSwiss. The recorded audio files are provided at http://www.visasim.ethz.ch/auralization[10].

4.1. Spectra

Figure 2 shows power spectral densities of sound pressure immersion signals of two wind turbines at strong wind conditions. In contrast to WT2, for WT1 three tones have been detected. The corresponding extracted tone levels are indicated by circles. For WT1 also the power spectral density after applying the notch filter bank is drawn in grey.

4.2. Level fluctuations

Figure 4 shows level fluctuations of WT2 for five 1/3 octave bands. In all plotted bands clearly the periodic AM can be observed. In each band the differences of the maximum and minimum level amount to about 10 dB. The sound subjectively exhibits high frequent swishing as well as thumping sound.

4.3. Blade passing frequency

The proposed algorithm to estimate the blade passing frequency was applied to measured signals and compared to visually determined values. The algorithm proofed to be able to estimate the blade passing frequency within the range of uncertainty even in cases where it could not be subjectively detected by listening to the sounds.

Figure 5 shows the autocorrelation functions of the level fluctuations for the 1/3 octave band which was selected by the proposed algorithm to thereof estimate the blade passing frequency. Both curves clearly feature the periodical character of the level fluctuations. In case a) the 8 kHz 1/3 octave band, containing audible swishing...
Table I. Data of the investigated wind turbines.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>WT1</th>
<th>WT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Vestas V90-2.0 MW</td>
<td>Enercon E82-2.0 MW</td>
</tr>
<tr>
<td>Year of completion</td>
<td>2010</td>
<td>2009</td>
</tr>
<tr>
<td>Location</td>
<td>Mont Crosin (CH)</td>
<td>Saint-Brais (CH)</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Hub height [m]</td>
<td>95</td>
<td>78</td>
</tr>
<tr>
<td>Rotor diameter [m]</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>Measurement distance $R_0$ [m]</td>
<td>140</td>
<td>119</td>
</tr>
<tr>
<td>Nominal revolutions [rpm]</td>
<td>14.9</td>
<td>variable</td>
</tr>
<tr>
<td>Cut-in wind speed [m/s]</td>
<td>4</td>
<td>none</td>
</tr>
</tbody>
</table>

sound, was selected. From this curve the blade passing frequency $0.75 \text{ Hz}$, corresponding to $15 \text{ rpm}$, was estimated. In case b) the $315 \text{ Hz}$ band, containing the typical thumping sound, was selected and revealed a blade passing frequency of $0.81 \text{ Hz}$, corresponding to $16 \text{ rpm}$.

Figure 4. Level fluctuations of five 1/3 octave bands for WT1 a) and WT2 b) at strong wind conditions.

Figure 5. Autocorrelation function of level fluctuations with thereof estimated blade passing frequency (vertical black line) and its search range (dashed lines) of WT1 a) and WT2 b) at strong wind conditions.

4.4. Amplitude modulation

Based on the estimated blade passing frequency, the separation of periodic and stochastic AM is performed with help of the proposed algorithm. The standard deviations of the level fluctuations are shown in Figure 6. In both cases at frequencies below $125 \text{ Hz}$ no significant level fluctuations occur. At higher frequencies the stochastic AM rises up to $\approx 1.5 \text{ dB}$. For WT1 the stochastic AM dominates over the whole frequency range. But it has to be mentioned that a high frequent swishing sound is perceived clearly which corresponds to the fact that the periodic AM has its maximum standard deviation of $1 \text{ dB}$ at $6.3 \text{ kHz}$. Compared to WT1, WT2 shows considerably higher values of...
the periodic AM. Around 250–500 Hz the periodic AM even dominates and reaches standard deviations > 1.5 dB, which by assuming a triangle waveform of the periodic level fluctuations amounts to differences of maximum and minimum levels > 1.5 \cdot 2 \cdot \sqrt{3} \text{ dB} = 5.2 \text{ dB}. This part of the AM corresponds to the thumping sound and is perceived also at greater distances (e.g. at 500 m). In [4] the maximum fluctuation strength of five 0.6 to 2 MW turbines was measured in the frequency range 350–700 Hz which confirms our findings related to WT2.

As an indicator for the coherence of the stochastic AM between frequency bands, the number \( N_n \) of adjacent 1/3 octave bands are counted as described in section 3.6. Figure 7 exhibits that the stochastic AM for frequency bands below 1 kHz can be modeled independently for each 1/3 octave band. However, above 1 kHz large groups of approximately 5 bands with simultaneous stochastic AM occur. The ten third octave bands above 1 kHz can thus be modeled by just two frequency groups.

Figure 8 shows modulation frequency 1/3 octave band spectra of stochastic AM for 1kHz and 4kHz. The maxima of all curves are located around 4 Hz. This coincides with the frequency for which the auditory system is most sensitive to level fluctuations [23]. Lower 1/3 octave bands exhibit a decreasing tendency of the maximum modulation frequency band.

5. Discussion

5.1. Quality of the synthesized sound

The quality of the proposed wind turbine emission synthesis model was evaluated by a test with 12 experienced listeners (11 male, 1 female, age between 25 and 55). For that purpose, four audio files of 8 seconds length were prepared. Two files were the recorded sounds of WT1 and WT2.
WT2 which were analyzed in section 4 and two files were the corresponding synthesized sounds created by the proposed model. In order to remove a high frequency hiss sound caused by the recording equipment, 10 kHz low-pass filtering was applied to the recorded sounds. The files were presented by a mono loudspeaker in an anechoic environment at a listening level of 55 dB(A). This corresponds to a realistic sound pressure level in a distance of approximately 150 m from the turbine.

The course of the listening test was controlled exclusively by the listener. At the beginning, the test person had the choice to listen to the recordings of WT1 and WT2 as many times as desired. After feeling familiar with the sounds, the listener could initiate the real test. Hereby each of the four files (2 recordings, 2 synthesized sounds) was played twice in a random sequence. Immediately after the presentation of a file, the listener had to identify the sound as “original recording” or “synthesized sound”. As a third option “I don’t know” could be selected.

Each of the 12 listeners generated 8 answers, summing up to a total of 96 responses. 8 out of the 96 were “I don’t know”. In case of the recording of WT1, 18 out of 24 answers were correct, in case of the synthesized sound of WT1, 8 out of 24 answers were correct. The recording of WT2 was correctly identified 13 times, the synthesized sound of WT2 was correctly identified 17 times. On the other hand, wrong answers were obtained: 4 in case of the recording of WT1, 14 for the synthesized sound of WT1, 9 for the recording of WT2 and 5 for the synthesized sound of WT2. In total, 54% correct answers were given for WT1 and 65% correct answers for WT2. On the other hand, 38% of the answers were wrong in case of WT1 and 29% in case of WT2. The somewhat higher percentage of correct identification in case of WT2 may be explained by the sound of some cow bells contained in the recording of WT2. This may have helped to discriminate between recording and synthesized sound.

Given the fact, that with 54% and 65% correct answers the percentage of proper discrimination between recorded and synthesized sound is only slightly above the result obtained by arbitrary response, and taking into account that at least a few correct decisions were based on the observation of background noise contained in the recording only, the quality of the synthesized sounds can be rated as very good. Indeed, all listeners assessed the synthesized sounds as very plausible. The interested reader is referred to the website http://www.visasim.ethz.ch/auralization [10] where the four audio files are provided for individual listening tests. Remark: The recorded sounds still contain the above mentioned high frequency hiss sound caused by the recording equipment.

5.2. Variation of sounds and model parameters

In section 4 the signal analysis described in section 3 is exemplarily applied to two recordings in order to obtain the input parameters of the emission model. However, it turned out to be difficult to obtain representative model parameters to generally characterize the sound of the wind turbines. We observed that for identical conditions - from our limited perspective by observing 10 minute averages of horizontal wind speeds only - the emission sounds and thus the model parameters may differ significantly.

Figure 9 demonstrates that the sound pressure level considerably fluctuates on a short-term basis. Measurements of WT1 at strong wind conditions revealed standard deviations of the arithmetic mean 1/3 octave band levels, $T_{i}$, as well as of the tone levels, $L_{i,k}$, of 2–3 dB. At moderate wind speeds even larger variations for some tonal components were observed. However at steady rotational speed the tone frequencies stayed fairly constant.

The measurements confirmed that the amount of periodic AM typically varies a lot, which was already reported by some authors [13, 24, 19]. For WT1 the standard deviation, $\sigma_{periodic}$, of the periodic level fluctuations exhibited standard deviations of 0.2 dB at mid and 0.3 dB at high frequencies which is in the same order of magnitude as their mean values 0.2 and 0.4 dB, respectively. For WT2, where the thumping sound was present, even larger variations occurred. Within 10 minutes, standard deviations of 0.3 to 0.5 dB at mean values between 0.5 and 1.2 dB were measured. E.g. for the 500 Hz 1/3 octave band, compared to 1.7 dB as shown in Figure 6, within the same 10 minutes period also a value of only 0.6 dB was measured. This involves a variation of the difference between maximum and minimum level of the periodic AM of 2 to 6 dB within 10 minutes, which is a well audible change. However, at least the model parameters regarding the stochastic AM generally showed minor variations compared to their absolute values.

6. Conclusion

With the proposed signal analysis method, the quite complex wind turbine sound can be decomposed into only a few components that can be described by few parameters. As demonstrated by a test with experienced listeners, the model allows for a synthesis of an audio signal that can be easily confused with the original sound.
Depending on the tonal content of the sound, the synthesis model only uses about 120 low-precision figures. The model can for example be implemented in MATLAB with help of the Signal Processing Toolbox by less than 50 lines of code. On a contemporary PC the synthesis model runs in real time.

The model also showed to be applicable to other technical sounds consisting of broadband amplitude modulated noise plus discrete tonal components, such as noise generated by technical installations such as heating, water supplies, air conditioning or ventilation. Possible further applications may include emission sounds for road or air traffic.

The synthesis model together with a sound propagation filtering and a reproduction system is a reliable basis for psychoacoustic studies in which the effect of specific sound characteristics can be systematically modified and hence investigated.

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References


