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Creating sound immission mimicking real-life characteristics from a single wind turbine

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ABSTRACT

This paper describes a method to synthesise wind turbine sounds to be used in sleep studies using a parameter-based synthesis. The parameter values were determined using recordings of several types of operating wind turbines, thorough investigations of the recorded sounds, previous reports on wind turbine sound characteristics, and acoustic knowledge on how sound properties change from source to an outdoor receiver. The different wind turbine types are shown in the paper to have characteristic amplitude modulation (AM) spectra, with different AM strengths in different 1/3 octave bands. The statistical levels of the AM are evaluated and the correlation between A-weighted AM and AM in individual 1/3 octave bands is evaluated using linear regression. Method tests of the proposed synthesis technique show that it performs well and that wind turbine sound signals that include arbitrary AM spectra can be created. The work was part of the research project WiTNES (Wind Turbine Noise Effects on Sleep).

1. Introduction

Noise from wind turbines can lead to self-reported sleep problems and annoyance among people living in the vicinity of the turbines [1,2]. Compared to annoyance we know rather little on how sleep is affected by wind turbine noise and studies enabling objective measures of sleep in controlled exposure conditions are urgently needed. This requires, however, the ability to play back a wind turbine sound that has a high similarity to what nearby residents could be exposed to, and at the same time has a clear temporal variation so that the sound properties can be linked to physiological response during sleep.

1.1. Sleep effects of community noise

Sleep is a vital biological process. Disturbed sleep is associated with adverse effects on memory and metabolic and endocrine function [3,4], increased risk for developing type 2 diabetes [5], and reduced daytime functioning [6]. Night-time exposure to environmental noise has the potential to contribute towards sleep disturbance, and accounts for the loss of almost 1 million healthy life years annually in Europe alone [7]. The most prevalent source of environmental noise is transport from road, rail and air, and the physiological effects of noise from these sources have previously been rather extensively investigated [7–9]. Noise level, noise rise time, and the number of discrete noise events have all been found to contribute to the degree of biological response during sleep.

Studies on possible physiological effects of wind turbine noise on sleep are scarce. A recent field study measuring sleep using actigraphy found no association between long-term (1 year) equivalent A-weighted noise level and negative sleep impacts [10]. However, acute effects on sleep, as may result from a small number of especially deleterious noise events, are unlikely to be captured in such a long-term average, although the consequence of such acute effects on health in the long term is still unclear. The short-term impact of wind turbine noise on sleep should preferably be investigated using polysomnography, a technique considered the 'gold standard' of sleep research, which involves electrophysiological measurements of brain activity. Due to the methodological expense of polysomnography (the requirement for the equipment and attendance of specialist technicians) and the need to exclude exposure from other noise sources such studies are usually performed in laboratory environments.

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As the noise immission levels of wind turbines are in the range of $L_{eq} < 45$ dBA, the dose–response relationship between sound pressure levels and annoyance for wind turbines among people exposed in their homes cannot directly be compared to most other community sources such as transportation noise [11–13]. The context is also different; wind turbines are typically placed in rural areas with low ambient noise levels. Nevertheless, attempts to compare responses show that the frequency of respondents reporting annoyance due to wind turbine noise is similar to that of annoyance due to air traffic, while the frequency of highly annoyed can exceed that of other noise sources (i.e. air, rail and road traffic, or industry) [14]. The unexpectedly high proportion of highly annoyed has been associated with the distinctive character of wind turbine sound. The sound is described by lay people as lapping, swishing/lashing, whistling, pulsating/throbbing, rustling, and resounding [11,13,15], indicating that amplitude modulations and dominance of low frequency sound pressure levels are audible parts of the sound and also possible triggers of psychological responses.

1.2. Amplitude modulation in wind turbine sounds

Amplitude modulations are an easily perceivable sound characteristic [16] associated with a higher risk of unpleasantness [17] and annoyance [18,19]. Laboratory listening tests showed that different wind turbine sounds played back at the same A-weighted equivalent sound pressure level are rated differently with regard to annoyance and awareness [20,21]. When subjects were asked to interactively adjust the most and least unpleasant characteristics in frequency and temporal domain while keeping the A-weighted sound pressure level the same, subjects decreased the frequency component above about 1600 Hz, and made temporal adjustments resulting in a reduction of loudness over time [15]. Recent studies point in the same direction; amplitude modulation strength influences the evaluation of wind turbine sound [22] though absolute sound pressure levels also need to be considered [23].

Aerodynamic sound is generated when the rotor blades of a wind turbine move through the air, producing a broad band rhythmic, i.e. amplitude modulated, sound. The frequency of the modulations correspond to the revolution and modern wind turbines with three rotor blades usually generate amplitude modulations in the range of 0.5 to 2 Hz. The amplitude modulation is stronger in the rotor plane than in a downwind position when measured at a close distance from a wind turbine; however the absolute sound pressure level is higher in the downwind position [22]. Epidemiological studies show that the downwind situation is the most critical for the perception of the noise among people living in wind turbine areas [13]. Recent reports distinguish between 'normal' and 'other' or 'extraordinary' amplitude modulation [24,25]. In [24] the characteristics of extraordinary amplitude modulation were shown to be stronger and more low-frequency in character. Larsson noted that extraordinary amplitude modulation could be detected in his long-term measurements in 19% of the evaluated periods at 1 km distance and 33% at 400 m distance, but he made no attempt to define its characteristics [25].

Meteorological conditions at the source, i.e. the wind turbine, will influence the character of the emitted sound. Wind shear can create substantial differences in wind speed over the rotor area resulting in unstable operating conditions [26]. In certain meteorological conditions, this will lead to local stall in the outer parts of the rotor area, inducing strong amplitude modulation and significantly higher sound pressure levels in the low frequency region. Previous studies show large differences in sound between wind turbine types [27], indicating that there are large differences in acoustic behaviour between wind turbine models, meteorologically induced and/or modulated by high local wind speeds, high turbulence or large wind shear.

1.3. Sound propagation effects

Concerning sound propagation, the wave reflection from the ground surface will affect the spectral shape at the receiver, and the total distance of propagation will affect the overall amplitude reduction due to spherical spreading and the attenuation at higher frequencies due to air absorption. Height variations in temperature and wind speed cause refraction, i.e. a curving of the sound paths, which may lead to sound focussing and slight change of ground reflection. For operating wind turbines and receivers in downwind direction, the focussing is mainly due to the wind speed profile. However, for usual propagation distances to the closest dwelling, e g about 500–600 m, and corresponding hub heights of > 65 m, the mean refraction effect is expected to be small. This can be substantiated by the conclusions of a previous wind turbine noise study based on measurements and calculations. In that work, propagation calculations to a receiver at 530 m distance from the wind turbine, for wind speed variations of 5 to 12 m/s, showed negligible influence using the Nord2000 model and about 1 dBA variation using a wave-based numerical prediction method [28]. The influence of ground type variation was predicted to be slightly larger, up to about 2 dBA. In addition to the mean meteorological effects, there are random fluctuations in the sound pressure level due to wind and temperature turbulence, affecting both the sound emission and the propagation.

1.4. Summary

To summarise, a sound representative of what people living in the vicinity of wind turbines could be exposed to in their bedrooms should:

- be based on downwind conditions
- be valid for more than one type of wind turbine
- comprise amplitude modulations corresponding to a variety of real wind turbine noise conditions
- represent the sound at distances relevant for residents in the neighbourhood

In the following, sound recordings representative for dwellings are acoustically evaluated in detail to find their key parameters. The parameters are then used in a method that can synthesise 8 h sound files (the duration of the sleep period time in the laboratory studies) of sufficiently high quality for the sleep study. The main focus of this paper is to describe this method to synthesise wind turbine sound files that are on the high end of the annoyance scale. These sound files will then be used in the WiTNES project to study if wind turbine noise at the Swedish requirement limit, $L_{eq} = 40$ dBA, can influence sleep. The sleep study, including descriptions of the chosen noise exposures, the reproduction system and sleep disturbance evaluation methods, will be presented in future papers.

2. Recording sites

There are reports in the literature of detailed semi-empiric modelling of noise radiation from wind turbines (see e g [29,30]) with good or at least reasonable fit to experimental data. However, these prediction schemes require detailed information on blade aerofoil shape and attack angles in the real situation. In the general case, this information is not publicly available. This in combination

Table 1
Brief description of the immission recording sites used in the paper.

Location	Power (MW)	Turbine diameter (m)	Hub height (m)	Distance (m)	Number of recordings	Total recording length	Calendar time
1	1.8	70	65	550	7005	∼117 h	∼1 month
2	2.0	90	80	580	2	3.5 h	4 h
3	2.0	90	105	500	850	∼7 h	∼1 month
4	2.4	110	95	650	30	30 min	∼8 h

with the large observed differences in radiated sound power from wind turbines reported in e.g. [27] makes it unlikely that there exists a general set of any physical parameters that can be used to predict the sound from all wind turbine models.

The WiTNES project has collected four datasets of short- and long-term recordings at dwellings near single wind turbines, from four different locations in Sweden. All recordings were made with equipment fulfilling the requirements for a Type 1 sound level meter. All wind turbines included here have been verified in measurements regarding their sound power level, i.e. they fulfil the manufacturer's specifications. The locations are briefly described in Table 1. The wind turbines at locations 1 and 2 are from the same manufacturer, but of a different type and age. The wind turbines at locations 3 and 4 are of a different manufacturer to one another, in turn different from those at locations 1 and 2. The locations in the table could thus be argued to possess a large acoustic variation, even though it does not represent all available wind turbine types or manufacturers. To make a complete overview of the acoustic characteristics of all installed wind turbine types today is outside the scope of the WiTNES project. The recordings at locations 2 and 4 are made only in downwind conditions, for around 8 m/s wind speed at 10 m height. For locations 1 and 3 the wind speed and direction varied, but the recording positions were chosen to be downwind from the wind turbine in the dominant wind direction. The temporal influence of meteorological variation on wind turbine sounds is implicitly included in this study since recordings over long time are used.

3. Outdoor sound characterisation

A few sound clips (each ∼30 s long) for each location in Table 1 were subjectively chosen by the authors, based on the following criteria. The clip should.

1. Have an equivalent level close to the highest measured sound level for that location
2. Include a perceptually strong amplitude modulation
3. Subjectively be judged as representative and with as little background disturbance as possible.

These sound clips were analysed in both the time and frequency domain with the aim to find important acoustic parameters that afterwards have been evaluated for the full recording length for each location.

3.1. Equivalent sound level spectra

In the present context it is not the absolute equivalent sound level spectrum that is of main interest; the equivalent level spectrum shape is more important. Therefore, the equivalent sound level in each 1/3 octave band was normalised with L_{eq} (the total equivalent sound level, unweighted with respect to frequency) to get the partial level of each 1/3 octave band through

$$L_{eq,partial,i} = L_{eq,i} - L_{eq} \quad (1)$$

for each 1/3 octave band i between 20 and 5000 Hz. The resulting partial spectra for locations 1–4 are shown in Fig. 1. For the frequency range up to 1 kHz, differences up to 8 dB in single 1/3 octave bands can be seen, but all locations follow a similar spectrum shape, albeit with spectrum variations. The differences are larger at higher frequencies but those differences are related to background sounds such as wind hiss, birdsong and other disturbances. Note that the spectra shown in Fig. 1 are not mean values for various meteorological situations or over different time periods for the same turbine. They describe a sort of worst-case scenario, chosen for their subjectively strong level and distinct amplitude modulation. The recordings evaluated in Fig. 1 sound subjectively different despite the similar equivalent spectra, and it is thus necessary to analyse the recordings in the time domain to find their amplitude modulation (AM) characteristics.

3.2. Amplitude modulation parameters

The time domain information is important since our focus is to synthesise wind turbine sound in a way that is relevant for sleep disturbance tests. Suggestions on signal analysis methods that can be used to track amplitude modulation in a noisy signal can be found in e.g. [31].

The amplitude modulation is commonly described using the A-weighted signal. The focus now is to study amplitude modulation characteristics for different wind turbines, and for this the amplitude modulation is studied in the 1/3 octave bands between 20 and 5000 Hz. The ear's critical bands correspond well to the 1/3 octave bands for most of the important frequency range [16], and most wind turbine manufacturers provide sound power levels in 1/3 octave bands. The 1/3 octave bands are also used in environmental guidelines for indoor sound pressure levels.

A few examples of individual 1/3 octave bands for location 3 are shown in Fig. 2 to demonstrate the main aspects. However, evaluations were done for all 1/3 octave bands. In the graphs a 'Fast' time weighting was added to the signal for visibility. The A-weighted total sound level using the same time weighting is also shown for reference. In the figure, individual blade pass-bys are seen as peaks. The peaks in the A-weighted level as well as in

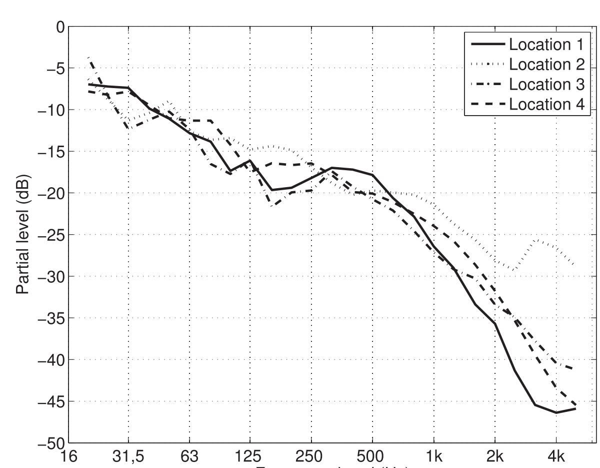

Fig. 1. Evaluated partial sound pressure levels in 1/3 octave bands for all locations.

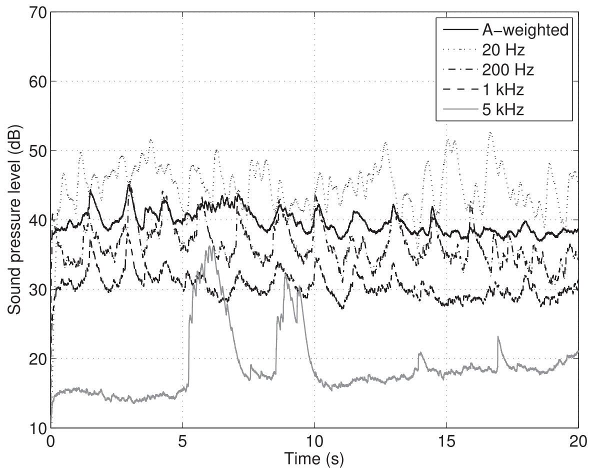

Fig. 2. Time sequences for the A-weighted total level for location 3 together with selected 1/3 octave bands.

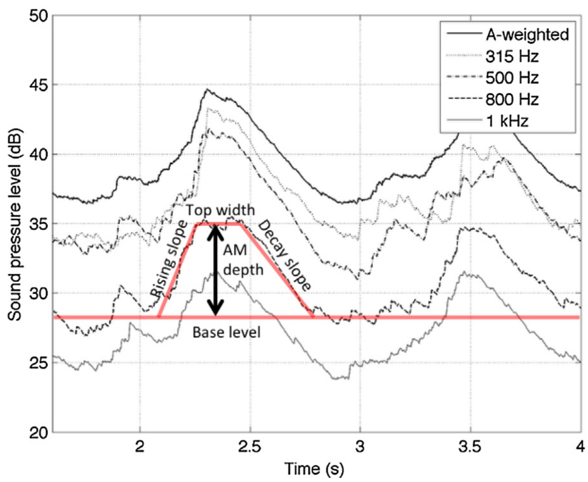

Fig. 3. Time sequences for individual blade pass-by for location 1 in selected 1/3 octave bands.

the 200 Hz and the 1 kHz band occur synchronously between 0 and 10 s. However, the pass-bys are not visible in the 5 kHz band. There are clear events in the 5 kHz band, but they are not simultaneous with the events in the 200 Hz band or in the A-weighted level, and are instead disturbances in the background. After making similar graphs for the other locations in Table 1 we concluded that the amplitude modulation in individual frequency bands is dependent on turbine type. This will be further described later in this paper. From the figure it is also clear that each blade pass-by is more or less individual, i.e. two subsequent pass-bys will not necessarily have the same amplitude modulation strength in all 1/3 octave bands. This can be seen in Fig. 2 after 11 s, where the amplitude modulation disappears in the 1 kHz band while maintaining the same strength in the 200 Hz band.

Looking into the shape of the individual blade pass-bys gives more information on important aspects. Again, only examples are shown in Fig. 3. In the figure a generalised time modulation shape is included. This generalised shape is deduced after visually evaluating over 100 individual pass-bys for the different locations and frequency bands, and it uses three parameters (as visualised in Fig. 3):

1. Modulation strength
2. Top width
3. Rising slope of the modulation peak

Interestingly the decay slope of the modulation peak seems constant for the different wind turbine types included here. The evaluated value is close to 20 dB/s for individual 1/3 octave bands that includes amplitude modulation. This is a significantly slower decay rate than for a 'Fast' time weighting, which has a decay rate of 35 dB/s. The three amplitude modulation parameters shown in Fig. 3 vary over time in a seemingly random way. Meteorological effects between wind turbine and dwelling probably partly cause this, since the propagation distance is 500 m or longer.

Evaluation algorithms for the top width and the rising slope have not been developed for this paper. Visual evaluations of the chosen sound clips have been used for these parameters. Limited listening tests held with a few experienced listeners showed that the rising slope and the top width has less influence on the subjectively perceived sound; the modulation strength has a much larger influence. This corresponds well with findings in other listening tests [23]. Therefore we focus our attention mainly on determining the statistics for the modulation strength.

3.3. Evaluation of amplitude modulation strength

Currently there is no generally accepted method for amplitude modulation strength evaluation. In this paper we adopt the formulation used in [22]:

$$\Delta L = 20\log\left(\frac{p_0 + p_f}{p_0 - p_f}\right) \tag{2}$$

where p_0 is the steady root mean square (RMS) value of the signal, corresponding to the equivalent level, and p_f is the RMS value of the signal at the blade pass-by frequency.

The method used in this paper is similar to the Reference Method proposed by the Institute of Acoustics [32] in the overall approach, but there are significant differences in the method details. The IoA Reference Method uses three distinct frequency bands (50–200, 100–400 and 200–800 Hz), while the method presented here uses 1/3 octave bands. Both methods use Fourier Transform of the signal magnitude to find the blade pass-by frequency. Our formulation of the AM strength (above) is evaluated in the frequency domain while the IoA Reference Method is evaluated after an inverse Fourier transform.

The first problem is to find the blade pass-by frequency from the recording. The wind turbine rotation changes with the wind speed, so the evaluation must be based on short-term data. Standard production data from wind turbines are most often mean values over 10 min periods. This is too long a period compared to the real-life variation of the acoustic parameters, i.e. too long to characterise the subjective acoustic parameters of interest. Additionally, since the sound at the dwelling is the main focus of the present paper it is advantageous if all evaluations can be based on recordings at the dwelling alone, without the need for production data from the wind turbine.

The Fast Fourier Transform (FFT) is commonly used for identification of frequencies of tones, but its drawback is the rather coarse frequency resolution when working with short signal lengths. A 10 s sound clip, as used in [32], gives a frequency resolution of 0.1 Hz, which in turn leads to a rotations per minute (RPM) resolution of 2 RPM. This is insufficient accuracy for our purposes; we need a resolution of 0.1 RPM, which corresponds to a frequency resolution of 0.005 Hz. To obtain this we use a combination of the Discrete Fourier Transform (DFT) and direct calculation of the Fourier coefficients, a technique usually called Zoom-FFT [33]. The main steps of the algorithm used here is as follows:

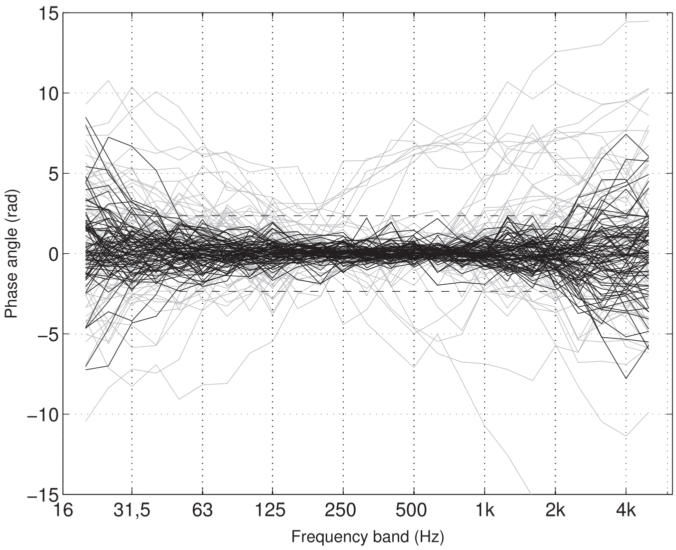

Fig. 4. Phase angles over frequency bands for all sound clips at location 4. The dashed black lines show the coherency limits, the black lines are the recordings that are assessed to be coherent, and the grey lines the recordings that are not coherent.

1. Find the peak in the DFT of the squared amplitude of the A-weighted signal, in a modulation frequency range relevant for the turbine
2. Calculate the Fourier coefficients for a finer frequency resolution close to the peak found in step 1. The resolution can be chosen arbitrarily, and the blade passing frequency is found through the maximum absolute value of the coefficients

The AM in each 1/3 octave band at the blade pass-by frequency can then be evaluated by a single-frequency DFT. A Hamming window together with 50% signal overlap has been used for all signal evaluations in this paper.

The phase of the amplitude modulation can be used to determine which 1/3 octave band amplitude modulations are coherent, i.e. the modulations that happen at the same time. A significantly different phase angle corresponds to AM that is not coherent, e.g. from background disturbances such as birdsong or randomly modulated wind noise in trees. Fig. 4 shows an example evaluation for location 4 where a coherency limit $\pm 3\pi/4$ rad in the 50–2000 Hz frequency range is set for the phase difference between the A-weighted AM and the AM in each 1/3 octave band respectively. In the figure it can be noted that the phase spread is largest in the low and high frequency end. The large spread means that the amplitude modulations at very low and very high frequencies are more commonly disturbed by events in the background. This AM is thus not related to the wind turbine rotation.

3.4. Evaluation for the test locations

The method presented in Section 3.3 was applied to all locations in Table 1. Fig. 5 shows a histogram of the evaluated A-weighted AM for all locations. In the figure only sound clips that have passed the coherency limits in Fig. 4 and that show a rotation speed relevant for the turbine are included. The histogram uses proportional occurence instead of absolute values in order to facilitate comparisons between the locations since they have very different overall recording times (see Table 1). It could be pointed out that location 3 shows a slightly higher A-weighted AM than the other locations. In the WiTNES project we have decided that the modulation strength that is apparent at the 90% occurrence level is our parameter choice for creating the sound exposures, i.e. 10% of the events

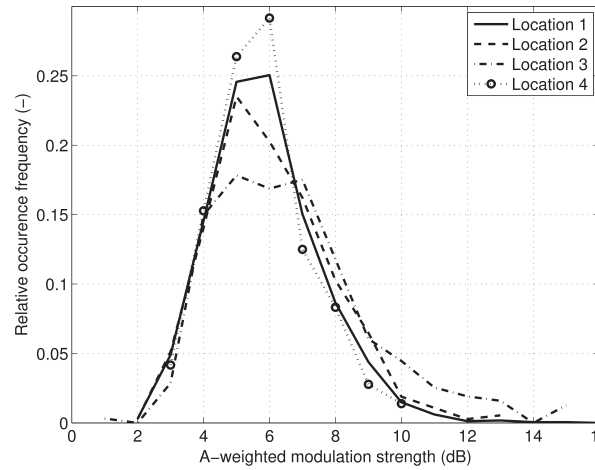

Fig. 5. Relative occurence frequency of A-weighted AM strength for the locations.

in the recordings have stronger amplitude modulation. The 90% occurence level of the A-weighted AM strength in Fig. 5 was between 8 and 10 dBA for the different locations.

Fig. 6 shows the evaluated modulation strengths in 1/3 octave bands for the four locations, and the figure shows that different

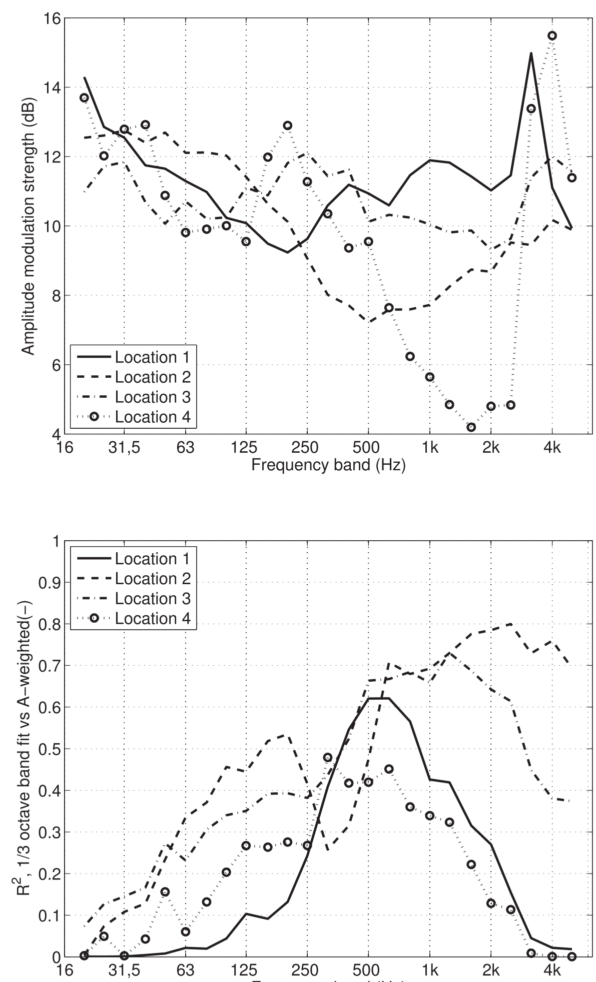

Fig. 6. Amplitude modulation strengths at 90% occurrence levels for the four locations (above). Linear regression R^2 values between 1/3 octave bands and the A-weighted AM (below).

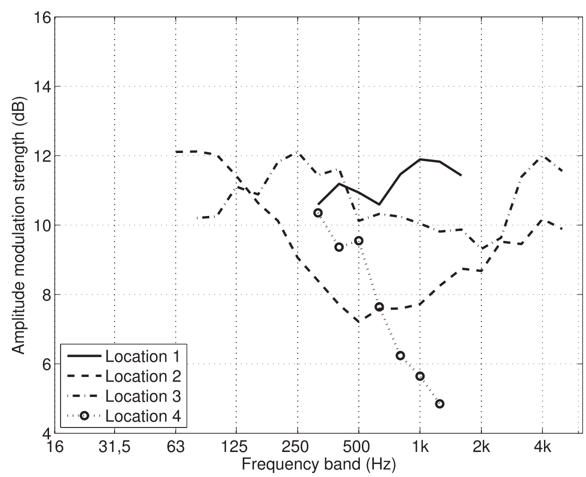

Fig. 7. Amplitude modulation strengths at 90% occurrence levels for the four locations, only for 1/3 octave bands with $R^2 \geqslant 0.3$.

wind turbine types have quantitative differences in AM strengths over frequency. However, it was suspected that the high AM strengths at low frequencies could be caused by background noise. Therefore a linear regression was made between individual 1/3 octave band AM and the A-weighted AM using a first-order polynomial. A higher-order polynomial was not motivated judged from the appearance of the data. The lower graph in Fig. 6 shows the resulting R^2 model fit. The choice of A-weighted AM strength may seem as an implicit importance reduction of low frequency AM. However, in this context this choice represents the existence of audible AM inside a 10 s period. The regression shows to what degree the AM in any 1/3 octave band is simultaneous with the A-weighted AM, thus showing the existence of audible AM in that particular 1/3 octave band. The model fit in Fig. 6 can be seen to be limited in all locations, probably due to natural variations of meteorology and the sound generation at the blades, a character which was shown in Fig. 2. In this paper we set an arbitrary limit of $R^2 \geqslant 0.3$ to indicate wind turbine AM. Fig. 7 show the AM strengths only for the 1/3 octave bands where $R^2 \geqslant 0.3$, and we consequently use this AM data as representative for wind turbines. Note that this choice only applies to the existence of AM, not to the absolute equivalent sound level.

Some turbine types show strong amplitude modulation in the low frequency region (below 200 Hz), while other types do not. This is something that must be considered when designing the sounds that should be used in the sleep tests. Different amplitude modulation spectra, here exemplified in Fig. 7, are probably linked to the subjectively qualitative differences that exist between sounds from different wind turbine types [21]. The chosen methodology focuses on the ’worst case’ situations for amplitude modulation strength, and which frequency bands that are modulated. There will certainly be periods of time at any dwelling where the wind turbine sound will be less pronounced, less loud and thus less annoying. However, little is known of which time base or statistical percentage level should be used to assess annoyance or sleep disturbance at dwellings. This is also noted by the Institute of Acoustics in their report [32].

4. Creation of laboratory exposures

Early in the project it was concluded that it is unlikely that we can find sufficiently long recordings that can be used directly in the sleep studies, especially since the recordings should not include strong wind noise, birdsong, rainfall, or other distinct background noise events. The use of short sound files, on the other hand, can lead to perceived periodicity by the subjects, and may thus affect the final results. Instead of using direct recordings, the project chose to find a method to synthesise wind turbine sounds from data representative to wind turbine type and meteorological situation. With synthesised files it is also possible to control exposure levels, frequency spectrum and various amplitude modulations.

4.1. Description of the synthesis

The sound file synthesis was designed to give representative sounds for an outdoor situation in free field, and it used the flow chart in Fig. 8. The input data used rotation frequency and number of blades for the turbine as global information to get blade pass-by frequency. Amplitude modulation data through modulation strength, top width and rising slope were given in each 1/3 octave band. Each band was adjusted to its target equivalent level after the modulated 1/3 octave band signal was constructed, i.e. the time-varying signal was evaluated for its equivalent level, and adjusted to its desired value. Realistic parameter values for the modulation strengths and equivalent levels were taken from the evaluations in Section 3.4.

To make the signals sound more realistic, the individual blade passages need to be non-identical. Looking at the amplitude modulation of real wind turbines (as in Fig. 2), each blade pass by has its individual shape. A two-step randomisation for the modulation strength was introduced to make the sounds more realistic:

1. A random amplification of the wide band amplitude strength that describes each individual blade pass-by strength. The amplification is given in dB, and follows a normal distribution with zero mean value and 1 dB standard deviation. Note that the amplification can be below zero, i.e. individual blade passes are damped.
2. The wide band random amplification in step 1 was scaled for each 1/3 octave band individually using 1/4 of the modulation strength as standard deviation for each 1/3 octave band respectively. The actual modulation strength for all 1/3 octave bands are thus correlated with each other. In other words, a strong blade pass by is strong in all 1/3 octave bands.

At a real wind turbine site the transmission path from source to receiver is never constant. A random time delay (normally distributed with zero mean value and standard deviation 50 ms) was also added between the individual blade pass-bys to mimic variations in sound travel time between wind turbine and receiver.

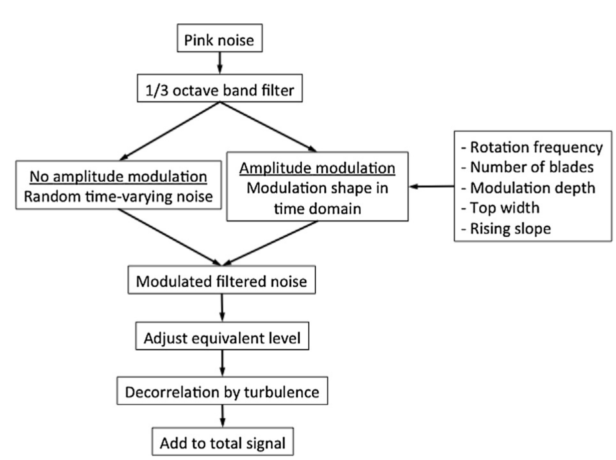

Fig. 8. Flow chart of the sound file synthesis.

A second normally distributed time delay with zero mean value and 20 ms standard deviation was furthermore added to each 1/3 octave band individually. This last random time delay was uncorrelated between the 1/3 octave bands.

Not all 1/3 octave bands show amplitude modulation for real wind turbines. For bands with no amplitude modulation a time-varying shape using one random number per minute and one uncorrelated random number per second was used. The time envelope was then linearly interpolated over time to avoid sudden sound strength changes. The equivalent level for each 1/3 octave band was then adjusted in the same way as for a 1/3 octave band with amplitude modulation.

The influence of turbulence along the transmission path was modelled similarly to the method used in [34]. The turbulence fluctuations result in amplitude variations also on a shorter time scale than that of a blade passage. Air absorption along the propagation path was also introduced using the method described in the standard ISO 9613-1.

Experienced listeners who are used to wind turbine sounds have been used in the development of the synthesis method to evaluate the subjective quality of the resulting wind turbine sounds. The final method, which has been described here, have been found to produce sounds that subjectively sound like wind turbines. Listening tests to corroborate this statement will be performed in another project.

Other noise sources, such as background noise caused by wind in nearby vegetation or distant road traffic, can be added to make the sound more realistic. Hovever, any such addition would have an impact on the total level and the AM of the final sound clip, and have not been studied further here.

4.2. Example evaluations of synthesised sounds

Three test cases were designed to validate that the synthesis method actually can produce sound files with arbitrary AM:

1. A frequency independent AM, i.e. a modulation that is equally strong in all 1/3 octave bands
2. AM exists in the 1/3 octave bands between 160 and 500 Hz
3. AM in the 500 Hz 1/3 octave band

The AM strength was varied between zero (no AM) and the maximum value found from the real life recordings as described in Section 3.4. All test cases used 8 sound files of 5 min length with AM nominal range from 0 dB up to 14 dB with 2 dB step. The equivalent level spectrum of the signals was set to a spectrum similar to the spectra shown in Fig. 1.

Fig. 9 shows the equivalent level spectra of the given input data and the evaluated synthesised signals. The equivalent level spectrum of the synthesised file is within 0.7 dB from the desired value for all 1/3 octave bands up to 2 kHz. The differences were larger at higher frequencies, which is probably linked to the air absorption. The low sound levels at high frequencies makes these differences unimportant in sleep tests.

Evaluated results from all test cases are shown in Fig. 10, where it can be seen that the AM evaluated from the synthesized sound files follow the used input data. The AM shown in the figure are for 90% occurrence levels. Variations of around 1–2 dB can be seen for test case 1 (AM independent of frequency), at the lowest frequencies somewhat more, but this variation is expected since the synthesis method includes randomisation of the blade pass-bys. For test cases 2 and 3 the AM strength is high in the intended 1/3 octave bands respectively. The method is thus shown to be capable of creating high AM in broad band, bandpass in two octave bands, and in one single 1/3 octave band. Note that the evaluated AM strength increases at frequencies below 200 Hz where no AM

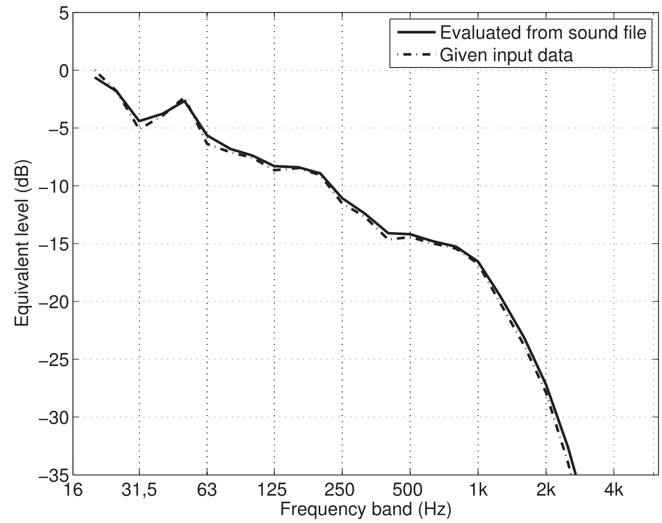

Fig. 9. Evaluated and desired equivalent level spectra.

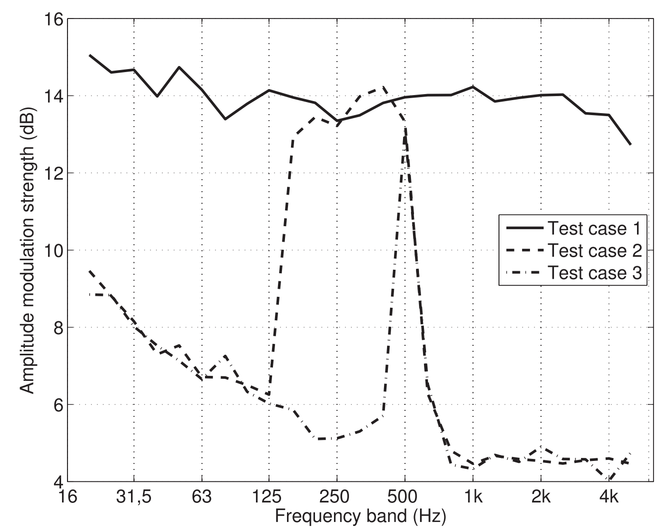

Fig. 10. Evaluated AM of synthesised wind turbine sounds according to test cases 1–3.

is intended. This is probably inherent in the pink noise that the synthesized signal is constructed from together with the fact that the AM evaluation uses 10 s clips. This conclusion is supported by linear regression evaluations that showed that the R^2 values were very low (<0.03) outside the frequency band with AM.

The data in Figs. 9,10 show that the presented synthesis method is capable of producing sound files with arbitrarily desired equivalent level spectrum *and* amplitude modulation spectrum simultaneously. This synthesis technique is an essential tool for creating realistic stimuli in the sleep studies.

5. Discussion and conclusions

A method to evaluate wind turbine amplitude modulation from sound recordings has been presented in this paper. The proposed method does not require additional information from the turbine, and is shown here to be applicable both on A-weighted signals as well as 1/3 octave band signals. Evaluations on sound recordings at dwellings from four wind turbine locations in Sweden showed that there are differences in both equivalent level spectra and amplitude modulation characteristics. The most important conclusion was that the four locations showed significantly different amplitude modulation strength spectra, which is probably linked to their subjectively perceived sounds.

The method to synthesise sounds that has been described in this paper is shown to be capable of producing sound files that have an equivalent level spectrum and amplitude modulation that correspond to wind turbine sounds that are recorded at dwellings in the field. Experienced listeners have stated that the synthesised sounds are subjectively close to real wind turbine sounds.

The synthesis method allows us to tailor both the equivalent level spectrum as well as the amplitude modulation strength spectrum of the sleep study exposures. This is a large advantage over using recordings.

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