Applied Acoustics 143 (2019) 66–73

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

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

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ARTICLE INFO

Article history:
Received 29 December 2017
Received in revised form 14 August 2018
Accepted 14 August 2018

Keywords:
Wind turbine noise
Amplitude modulation
Sleep study

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).

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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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https://doi.org/10.1016/j.apacoust.2018.08.015
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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

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