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Perception of Noise from Large Wind Turbines

Authors: S v Hünerbein[1], A King[1], J Hargreaves[1], A Moorhouse[1], C Plack[2], T H Pedersen[3]

[1]University of Salford, Salford, UK

s.vonhunerbein@salford.ac.uk

a.king@edu.salford.ac.uk

j.a.hargreaves@pgr.salford.ac.uk

A.T.Moorhouse@salford.ac.uk

[2]University of Manchester, Manchester, UK

Chris.Plack@manchester.ac.uk

[3]Delta, Copenhagen, DK

THP@delta.dk

Abstract

To determine whether noise annoyance from large wind turbines is generally different from that of small turbines listening tests were carried out. The question arose in the context of concerns of the Danish population over the widespread replacement of small turbines with large turbines.

Audibility thresholds and equal annoyance contours were established for idealised wind turbine sounds containing low frequency tones with focus on the question whether annoyance changes with the frequency of the tone. The test sounds consisted of a specific low frequency tone embedded in a broadband spectrum. The participants were asked to imagine being in an indoor scenario and an outdoor scenario with and without masking garden noise.

In a second part of the study wind turbine recordings from a large and a small wind turbine were compared in annoyance with steady traffic noise.

Results are presented on the appropriateness of current standards to establish masking thresholds and on the frequency dependence of annoyance as well as the significance of spectral content on annoyance.

Introduction

The presented work is part of the EFP-06 project “Low Frequency Noise from Large Wind Turbines”. The project was designed out of the concern about the

sound characteristics of modern, large wind turbines at a time when in Denmark small turbines started to be replaced by larger ones [1]. The question arose whether Danish regulations would be sufficient to protect neighbouring residents from excessively annoying noise. Particular concerns were raised about the low frequency content of sound from large wind turbines.

In a first part of the project, characteristic properties of small and large wind turbine sound were measured and analysed. The main findings published in the summary report [2] were that the broadband characteristics of small and large wind turbines where very similar. A small average difference in low frequency content of up to 3 dB was attributed to the presence of low frequency tones between 20 and 200 Hz in sound from large turbines. It was concluded however that spectral characteristics often vary more strongly between turbine models of similar size than between different turbine sizes.

There is contradictory evidence in the literature such as [3] and [4] on how annoyance is related to the low frequency content of sound. Therefore the objective characterisation of the sounds needed to be supplemented by listening tests. And because the low frequency tonal content had been identified as the characteristic difference between small and large turbines, idealised stimuli were designed to systematically investigate the frequency dependence of annoyance.

While annoyance scales such as categorical and numerical scales are commonly used in survey studies [5], the laboratory environment offers the opportunity of using comparative methods such as the paired comparison where a test stimulus is adjusted to match the annoyance of a reference stimulus. The relative measure is more meaningful because absolute scales that are established in a laboratory environment do usually not apply to the context that the sounds are naturally perceived in.

Amplitude modulation, which naturally occurs in wind turbine sound, was excluded from the idealised stimuli because of the general lack of knowledge on this phenomenon [6] and because of its huge variability which would have made the scope of the listening tests unfeasible. However, recordings were used in a second part of the test to realistically compare the annoyance between a large and a small wind turbine.

The perception of noise does not only depend on the characteristics of the sound but also on the listening context such as busy or leisure times, time of the day [7] and sense of ownership and personal space [8]. It was therefore regarded as important to enable the comparison of different listening scenarios with respect to annoyance.

In summary, listening tests were performed at the University of Salford with the following main objectives:

- To establish audibility thresholds and relative annoyance contours for low frequency tones in the presence of broadband masking noise

- To establish relative wind turbine levels that produce equal annoyance for two sizes of turbines taking into account the effect of masking noise on these estimates.
- To answer the question whether noise from large wind turbines is more annoying than noise from small wind turbines

Study design

The tests were conducted in the listening room conforming to ITU-R BS 1116-1 (Figure 1). The room contains extensive passive absorption, resonant absorption and diffusion, giving it a low reverberation time (RT) and eliminating false spatial cues. Precise sound reproduction was required to ensure accurate reproduction of each scenario, particularly at low frequencies. A planar ambisonic reproduction system was chosen for its well-defined source-direction-rendering properties, supplemented by a low-frequency reinforcement system. The system was calibrated using a custom measurement system and modification of the stimuli signals sent to each loudspeaker. The performance of this approach was evaluated using a 01 dB Symphony PC measurement system and DELTA's NoiseLab software.

Figure 1 - Listening room setup. Detail on sound reproduction is available in [1]

The loudspeakers and acoustic room treatment were hidden to the participants by a white curtain to make it visually neutral. The comfortable, non-vibrating chair, screen and low table are objects that could be found in a typical living room or outdoor leisure environment.

The participants were asked to imagine being in different scenarios which were indoor and outdoor scenarios with and without 'garden noise' from wind in vegetation. The outdoor scenario presented tones embedded in broadband sounds largely representative of a wind turbine at three A-weighted sound pressure levels, each with and without garden noise, whereas the indoor scenario omitted the garden noise since the facade attenuation rendered it inaudible.

The tone frequencies consisted of four low frequency test tones at 32, 44, 72 and 115 Hz, a reference tone at 180 Hz and a mid-frequency tone for comparison at 400 Hz.

The wind turbine masking spectra were derived from third-octave sound power measurements of 45 wind turbines, each attenuated to simulate propagation to the minimum distance permitted to a dwelling by Danish regulations (4 total heights), scaled to the target A-weighted SPL, and finally averaged. Propagation

attenuation was predicted in third octave bands by the Nord2000 model for a receiver 1.5 m above flat grassy terrain with a wind speed of 8m/s in the downwind direction.

The local garden noise was created to match a noise spectrum of 8 m/s wind through deciduous foliage. A similar process was followed for the stimuli for the indoor scenario, except that a third octave façade attenuation spectrum was applied to all spectra, and the propagation attenuation for the wind turbine was averaged over three heights (0.5 m, 1.5 m, 2.5 m) to account for excitation over the full height of the façade. The façade attenuation was chosen from the values presented in [9].

First, tone audibility thresholds were established for each participant using a two-Alternative-Forced Choice (2AFC) method to test their hearing and allow comparison with the annoyance values.

In a second step, a comparative adaptive method was used to establish relative equal annoyance levels in the form of equal annoyance contours. The stimulus containing the 180 Hz tone was used as the reference stimulus as that was considered similar enough to the low and high frequency stimuli to make the adaption procedure possible. The test tones combined with the masking noises were played and compared to a reference tone at 180 Hz at a fixed tone level above masking [3]. The participant adjusted the test tone level until they considered it as annoying as the reference stimulus (**Error! Reference source not found.**).

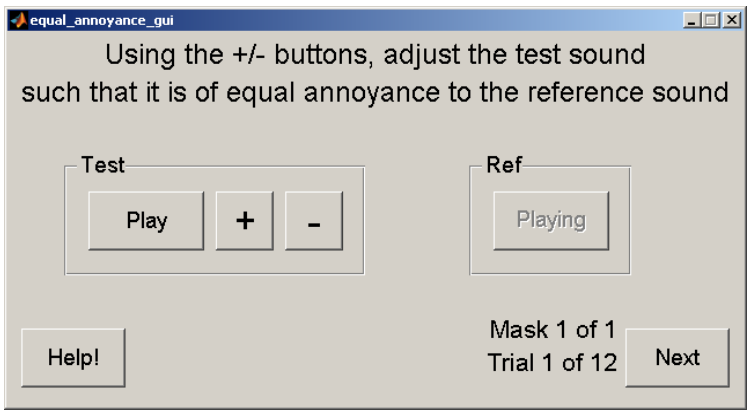

Figure 2 – Graphical user interface to measure equal annoyance.

The tests were designed to enable comparisons between different scenarios, broadband levels, tone frequencies, masked and unmasked ‘wind turbine’ sound, and two different prominence levels for the reference tone at 180 Hz.

In a second part of the study wind turbine recordings from a large and a small wind turbine were compared in annoyance with steady traffic noise using a similar user interface to Figure 2. The recordings were manipulated to include the effect of sound propagation and façade attenuation. They were also normalised to equal A-weighted levels.

20 listeners, 10 male and 10 female of normal hearing participated in the tests. Their age ranged from 19 to 65 years. All participants either lived or wanted to live in the countryside. This was important because the results of a Zimmer-Ellermeier noise sensitivity questionnaire study used for screening participants

suggested higher noise sensitivity in volunteers with countryside preference. More detail on the study design can be found in [10].

Results on audibility and masking thresholds

Results on tone audibility in quiet, that is in the room without artificial noise played back, are shown in Figure 3. The measured audibility threshold (blue line) is seen to be in good agreement with the published hearing threshold (black line) according to [11]. The red and green curves in Figure 3 are equal annoyance contours and will be explained in the following section. As the broadband noise level increases the tones are heard at levels that are determined by the masking level as shown in Figure 4 (blue line).

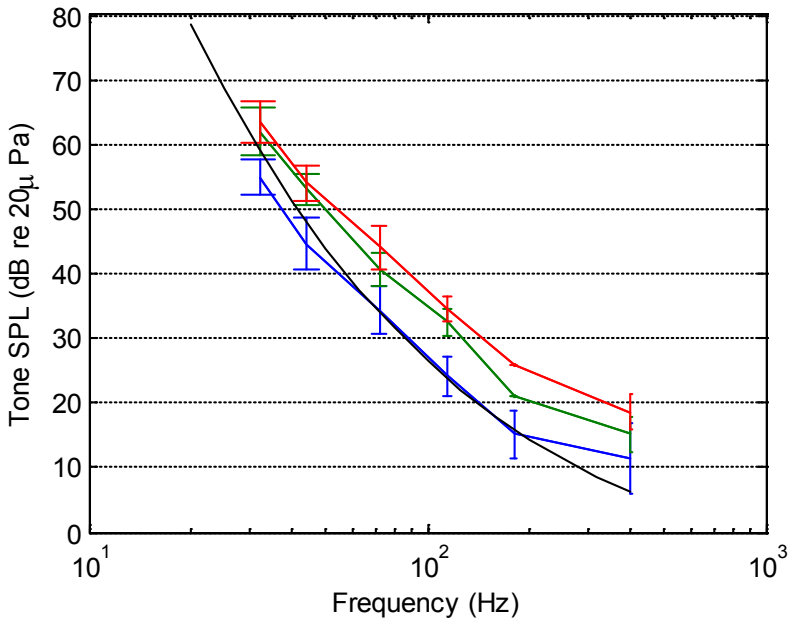

Figure 3 - Room background without masking noise - Audibility threshold (blue), equal annoyance to 180 Hz tone at 5 dB audibility (green) and 10 dB audibility (red) of low frequency tones. Black solid line: Hearing threshold according to [11]. Error bars denote 95 % confidence intervals.

Masking thresholds predicted by [12] (black dashed line in Figure 4) agree well with the measured tonal audibility thresholds as long as the masking noise clearly exceeds the hearing threshold of the tones. As low levels can frequently occur indoors in the neighbourhood of wind turbines when the Danish noise regulations are observed it would be useful to extend the standard to include a method to evaluate the hearing threshold.

Results on the annoyance of tones in background

Low frequency tones were adjusted to higher tone levels above the masking threshold to be equally annoying as higher frequency tones. Examples of the

measured equal annoyance contours in quiet are shown by the red and green lines in Figure 3 and for equal annoyance contours in the outdoor scenario in Figure 4. In both figures the equal annoyance contours are almost parallel to the masking threshold thereby demonstrating that annoyance is dominated by the frequency dependence of the hearing threshold. This is also demonstrated by the fact that the equal annoyance levels increase as the masking noise levels increase.

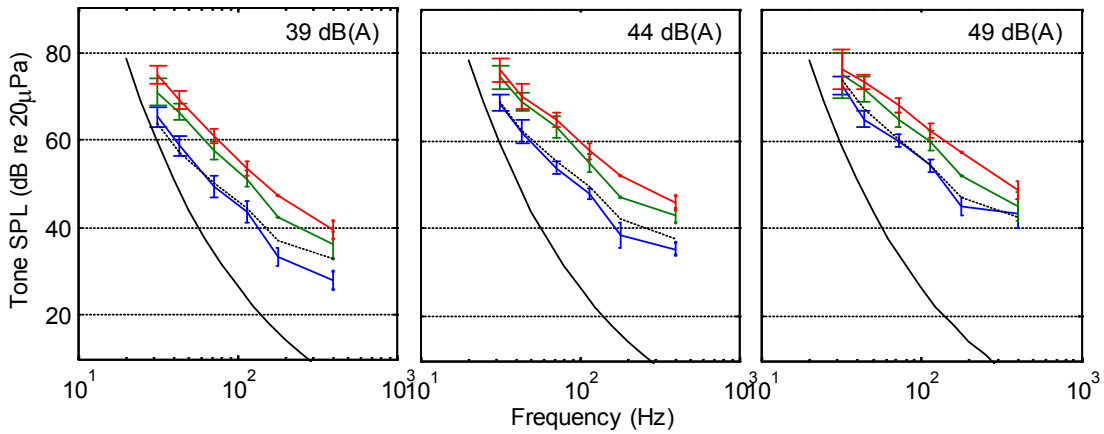

Figure 4 - Outdoor scenario – Masking thresholds (blue), equal annoyance to 180 Hz tone at 5 dB audibility (green) and 10 dB audibility (red) of low frequency tones within broadband masking noises at A-weighted levels as labelled. Black solid line: Hearing threshold according to [11]. Dashed black line: Masking threshold according to [12]. Error bars denote 95 % confidence intervals.

It is shown that increasing the tone level by 5 dB (at 180 Hz: red line level – green line level) increases the equal annoyance level by a smaller value both for tone frequencies lower than 180 Hz and at 400 Hz. This casts doubt on the appropriateness of the adjustment used in [12] which adds penalty adjustments which increase linearly with sound pressure level above masking.

Relative sensation levels are calculated from equal annoyance contours to determine whether low frequency tones are relatively more annoying than high frequency tones. This is done by subtracting the measured audibility level from the annoyance level for both the test tone and the reference tone. Then that level difference at the test tone was subtracted from the difference at the reference tone. The results for all scenarios are very similar and an average relative sensation level is shown in Figure 5. When accounting for a familiarisation effect at 180 Hz the frequency dependence is not shown to be significant. The main influence on these levels is the tone level above masking level: Tones at higher levels are more annoying than tones at lower levels above masking. Both findings are common for the indoor and outdoor scenarios.

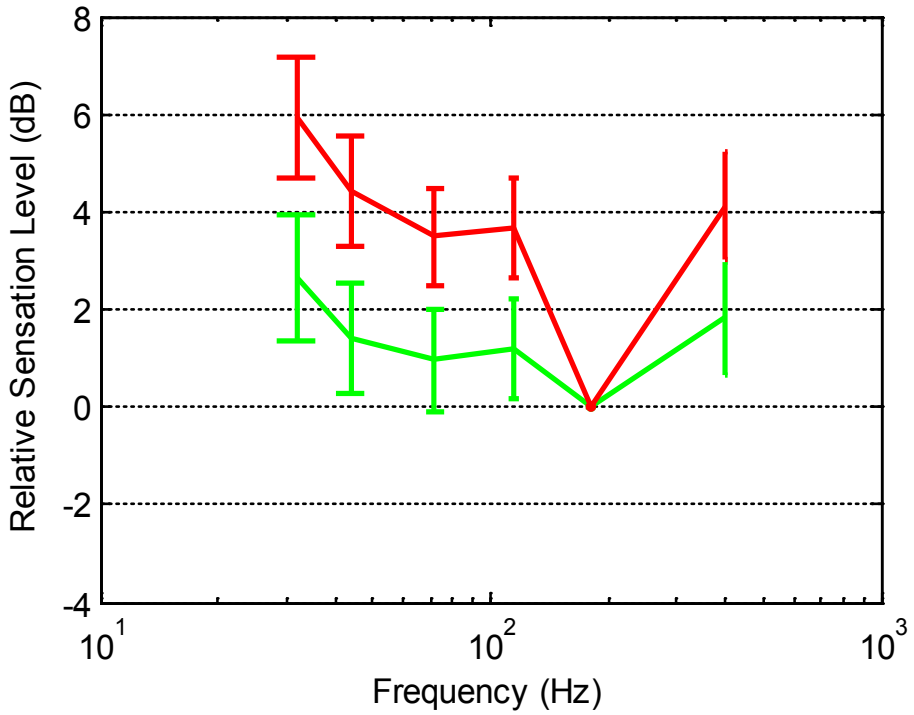

Figure 5 - Relative sensation level for equal annoyance averaged over all masking noise types and scenarios at reference tone prominence levels of 5 dB (green) and 10 dB (red). Error bars show 95 % confidence intervals.

Results on annoyance when comparing recordings of a small and a large wind turbine

To compare real recordings of a large and a small wind turbine a test protocol was developed. An example of outdoor results is seen in Figure 6.

The comparison between normalized recordings show the spectral characteristics of the small turbine to be more annoying outdoors than those of the large turbine recording. This is attributed to the different spectral and temporal characteristics of the two turbines. These differences are effectively masked by garden noise and the equal annoyance ratings change accordingly.

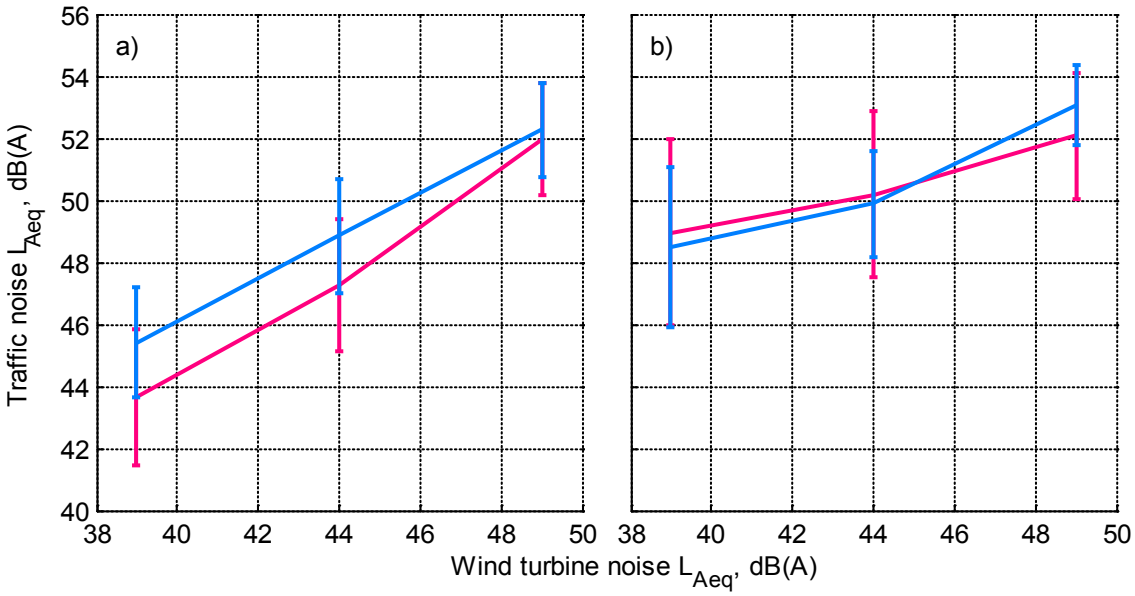

Figure 6 - Equal annoyance contours for recorded turbines small wind turbine (blue lines) and a large wind turbine (red lines) matched to a neutral noise source (traffic noise) a) Outdoor scenario without garden noise, b) Outdoor scenario with garden noise. Error bars are 95 % confidence intervals.

Also in the indoor scenario the turbines were not found to be differently annoying. If these results can be reproduced in other listening experiments then it follows that the specific differences in spectral content will determine the annoyance levels from a wind turbine more than whether it is a small or a large turbine. It would also mean that the differences in annoyance between wind turbines get smaller when sufficient masking noise is present. Presently, the finding that the small turbine is more annoying cannot be generalised to large and small wind turbines or to a wider range of wind and terrain conditions than were used in the test. The listener responses are however consistent and therefore demonstrate the potential of the comparison method.

In answer to the initial question whether large turbines are more annoying than small wind turbines, the results of this study find no evidence for a significant difference in annoyance between small and large wind turbines as long as total noise levels and tonal characteristics are taken into account in the assessment. Temporal variations of wind turbine noise such as the level of swishing might also have to be evaluated in the future.

Conclusions

Within the project on “Low Frequency Noise from Large Wind Turbines”, the perception of low frequency noise from wind turbines was studied. Listening tests were conducted using synthesised stimuli consisting of tones in broadband wind turbine noise in the first part and recorded stimuli for small and large wind turbines in comparison in the second part.

More specifically

- audibility thresholds and equal annoyance contours were established for idealised wind turbine sounds containing low frequency tones at frequencies between 32 Hz and 400 Hz. The listening test simulated an indoor scenario and an outdoor scenario with and without masking garden noise.
- For the perception of real wind turbines, samples from a large and a small wind turbine were compared with traffic noise in the same scenarios used in the first part of the listening tests.

Within the scope of the test stimuli, the listening tests find no evidence for a significant difference in annoyance between small and large wind turbines.

More specifically the results show that for the same tone prominence there is no evidence that tones at lower frequencies are more annoying than tones at higher frequencies.

It is also shown that frequency dependence of annoyance level is strongly related to hearing and masking thresholds and that increasing the level of a tone in noise makes the tone more annoying. Both of these effects are covered in current standards but some improvements are suggested: Where the masking thresholds are close to the hearing thresholds in quiet a standard method of calculating the audibility of broadband noise should be defined. For tone penalty regulations more work needs to be done to establish whether annoyance scales linearly with tone levels above masking thresholds.

The results of annoyance ratings when comparing two wind turbine recordings are explained by spectral and temporal characteristics of the chosen sound samples. The method gives consistent results within the range of stimuli evaluated in this study. The general applicability of the results beyond this scope is not validated.

In summary the study shows that listening tests can be successfully used to find answers to the perception of low frequency tonal wind turbine noise and to compare recordings of wind turbine sounds although. However, a large number of sound samples would be required to get representative and general results on a sufficient number of wind turbine models, sites and meteorological conditions, all of which will change the sound characteristics and therefore the annoyance. Further work should be done to investigate the role of temporal variation on annoyance and to relate the annoyance between different scenarios.

Acknowledgements

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