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Auralization and Assessments of Annoyance from Wind Turbines

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Abstract
Noise from wind turbines is of great concern for the neighbours. Both the sound level and other characteristics of the wind turbine noise are of significance for the annoyance. By applying a model for sound propagation, it is possible to auralize the sound from the wind turbine at the neighbouring residents. This approach potentially gives a more realistic presentation of the actual wind turbine noise as input to the decision-making process. In the present work, five different wind turbines were recorded and auralized at two distances using the Nord2000 propagation model. 20 subjects rated the processed recordings on overall annoyance both with and without additional natural background noise. Relevant sound attributes like loudness, pace, tonality and swishing sound were also rated by the subjects and compared with physical metrics. As a result, a metric for swishing sound is proposed. Finally, a model based on the results from this study on annoyance of sound from wind turbines is presented.

Introduction
The development of wind turbines moves towards maximizing the produced power by increasing size. In general larger often means louder and that gives rise to concern for people living near places for new wind turbine projects. Therefore focus also is kept on minimizing the emitted sound to make wind turbines more acceptable for the people living near them. A measure for the emitted sound is the A-weighted sound pressure level. This quantity is also referred to in legal requirements. However, this value is not the only parameter of relevance for the annoyance. Also other sound characteristics, the context and personal variables play a role. The annoyance should be the key parameter when deciding where to build any new wind turbine park. Earlier studies have addressed this issue and identified perceptive attributes of the wind turbine sound that contributes to the overall annoyance. But how does outdoor sound propagation and natural background noise influence on these quantities?

In the present study five different wind turbines were auralized at the distances of closest allowed residence according to Danish legislation (6 hub heights) and twice that distance. Perceptive attributes were evaluated for the auralized sounds by a group of 20 selected subjects and the evaluations were attempted linked to physical metrics. The effect on annoyance when adding recorded natural background noise was also addressed.

This project was part of a larger investigation financed by the Danish Ministry of Science, Technology and Innovation on noise annoyance of different outdoor sound sources [11].

Stimuli

Recordings of Wind Turbines

Five different wind turbines ranging in power from 225 kW to 2 MW were recorded at wind speeds around 5 m/s and at distances of 1.5 and 3 hub heights (HH) according to the procedures described in DS/EN 61400-11. Specifications on the recorded wind turbines are found in Figure 1.

Wind turbine	**1**	**2**	**3**	**4**	**5**
Power	600 kW	1 MW	2 MW	225 kW	850 kW
Hub height (HH)	35 m	45 m	60 m	30 m	54 m
Rotor diameter	39 m	71 m	80 m	27 m	52 m

Figure 1 - Specifications on the five recorded wind turbines. The recordings were made at distances of 1.5 and 3 hub heights from the wind turbines.

The wind turbines were placed in the western part of Denmark and away from major roads and other disturbing sound sources. Some of the turbines were placed in groups of 2-5 but during the recordings, the nearest wind turbine was shut down, so only one turbine was recorded at a time. The recording system consisted of a Brüel & Kjær Head and Torso Simulator (HATS) type 4100 and a laptop based recording software which stored the sound files on a hard disk. The recording height (at the ears of the HATS) was 1.7 m above ground. To eliminate wind noise in the microphones, the HATS was equipped with a special designed Rycote fur wind cap.

The recordings of the wind turbines did not contain significant natural background noise from wind in trees or bushes. However, since the influence of background noise on the overall annoyance was a parameter for the listening test, recordings of natural background noise was made in the early autumn in a soundscape close to trees and bushes representative for a typical Danish garden in the countryside. No traffic noise or other unnatural sounds were present in recording and birds singing were also avoided.

Auralization

It was decided to auralize the wind turbines at a fictive distance of 6 and 12 HH. The reason for choosing these distances was that according to Danish legislation wind turbines have to be more than 6 HH away from the nearest residence. The Nordic sound propagation model called Nord2000 was employed for the spectral manipulation of the recorded sounds [5]. The model accounts for wind speed, -direction, -gradient, temperature, relative humidity, and terrain properties and calculates the attenuation in 1/3-octave bands. Nord2000 is implemented in an easy to use software version called SPL2000 developed by Birger Plovsing, DELTA. This software was used for calculation of the sound propagation attenuation. By defining the source and receiver position besides parameters for ground and air absorption, sound pressure levels in 1/3-octave bands at the receiver point can be exported to a spreadsheet file for further use implementation in sound editing tools like Adobe Audition.

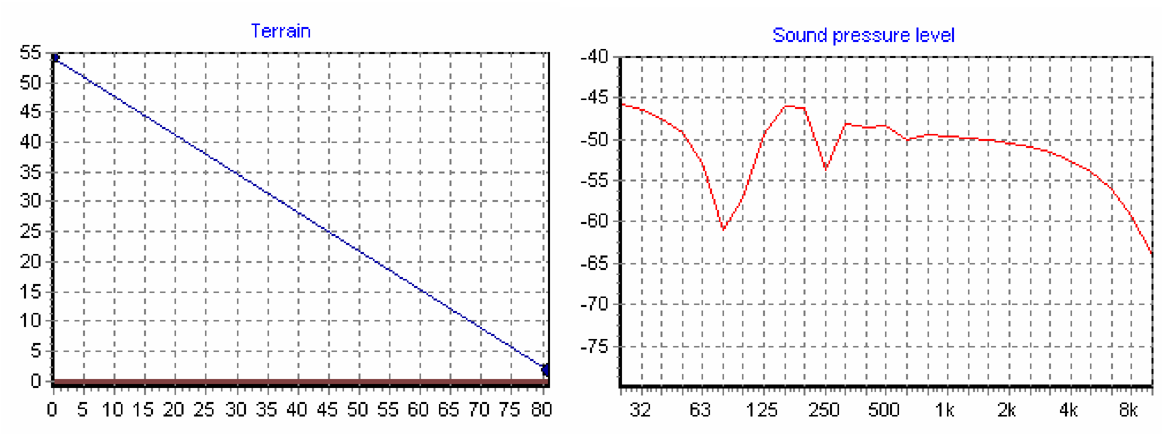

Figure 2 - Example of calculation made with SPL2000 for the sound propagation from a 55 m tall (HH) wind turbine measured at a receiver point 82 m away and at 1.7 m height above ground.

Stimuli for Listening Tests

The sound samples for the listening tests were constructed from 3 elements: a) wind turbine recordings, b) auralizations at 6 and 12 HH, and c) wind generated vegetation noise, see Figure 3. The HATS recordings made at 1.5 HH were auralized to a distance of 6 HH and the recordings at 3 HH were auralized to 12 HH. The recordings were as a first step band pass filtered to 20 Hz - 20 kHz (to avoid low frequency components to "occupy" part of the dynamic range). Next step was to apply the 1/3-octave band attenuations calculated with SPL2000. The values were found as the sound pressure attenuation difference $\Delta L_{p(Hr1-Hr2)}$ between the propagation path from the hub centre of the wind turbine to receiver positions at 1.5 HH and at 6 HH (and also at 3 HH and 12 HH). The third and final step of the signal processing was necessary because the inevitable wind generated noise in the microphone on the recordings sounded very unnatural after the spectral shaping in step 2. It was important to eliminate the low frequency rumble leftovers to keep focus on the wind turbine sound in the listening test. Therefore a high pass filter was applied to filter out frequency content below 150 Hz (for the 6 HH auralization) and 200 Hz (for the 12 HH auralization). The main components of the wind turbine noise are above these frequencies.

The recording of natural background noise from vegetation was band pass filtered (50 Hz-20 kHz) and adjusted -6 dB in level to avoid complete masking of some of the wind turbines.

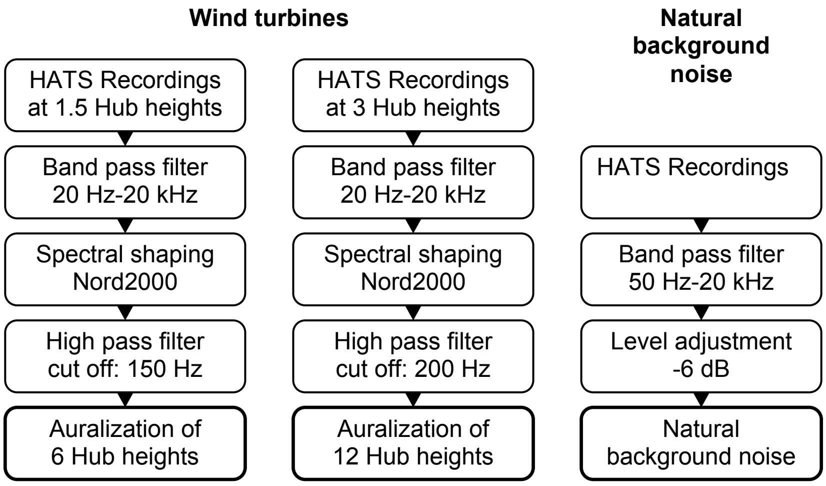

Figure 3 - Illustration of the performed editing path of the HATS recordings.

Three groups of stimuli were prepared for the listening tests. The first and second group of stimuli was intended for assessments of annoyance according to the questions in ISO 15666 [3] and therefore relatively long 90-second excerpts of the auralized sounds were selected. The first group of stimuli contained only the 'clean' wind turbine sound at the auralized distances. The second group used the same stimuli as group one, but had a 90-second excerpts of the natural background noise mixed together with it.

The third group of stimuli was intended for assessments of perceptive attributes and hence 20 second excerpts of the stimuli in group one were selected for this listening test. The reason for shortening the stimuli was that the method used for these assessments was based on comparison of stimuli rather than absolute ratings which meant that the listeners most likely would listen to short parts of the sound stimuli due to our short acoustic memory. The total A-weighted sound pressure levels of the final stimuli for the listening test are given in Table 1.

Wind turbine	**Distance**	**L_{Aeq} [dB re 20 μPa]**	**L_{Aeq} [dB re 20 μPa]**
		Wind turbine alone	With background noise
1	6 HH	39.5	43.8
	12 HH	33.4	41.8
2	6 HH	35.8	42.4
	12 HH	30.0	41.5
3	6 HH	39.3	43.6
	12 HH	34.2	42.1
4	6 HH	31.8	41.7
	12 HH	29.1	41.4
5	6 HH	41.3	44.5
	12 HH	35.3	42.3

Table 1 - Equivalent A-weighted sound pressure levels of the stimuli used in the listening tests.

Listening Experiments

The listening test was divided in two parts. In the first part assessments of annoyance of the sound from the wind turbines according to the questions in ISO 15666 using an 11-point category scale (0-10) with verbal labels were made. The second part of the test addressed the characteristics of the sound from the wind turbines using a method that combined semantic differential and paired comparison methods.

Test Subjects
20 Danish naive test subjects participated in the test. All test subjects reported normal hearing for their age but no audiograms were measured. The subjects were 24 to 63 years old, with an average of 46.6 years.

Subjects qualified for participation if they either lived in the country side or declared that they had a wish to live in the countryside. This screening criterion was included in order to get a representative group of people with a preference for more quiet surroundings.

Scenario
For the assessments of annoyance the scenario that the subject was instructed to imagine was: sitting at home in their own garden in the countryside drinking a cup of coffee or tea and maybe reading the newspaper or a book.

To help visualize the context for the subjects a picture of a wind turbine was projected on a large screen in front of them in the standardized listening room. The pictures supported the presented stimuli by bringing the wind turbine closer (enlarging) for the stimuli at 6 HH than the ones at 12 HH. The visual angle of the turbines at the screen was approximately as they would be when seen at these distances.

Attributes
For the assessments of perceptive attributes in the second part of the listening test, a list of four attributes was defined. The attributes were: Loudness, Swishing sound, Tonality and Pace. Besides these a repeated question for the annoyance under these circumstances was included.

For each attribute, a written definition was provided for the subjects to minimize the effect of divergent concepts of the attributes. Also an acoustical example on Swishing sound and Tonality was presented for the subjects before the test to ensure their understanding of these terms.

Answering Scales
Different scales were used for the two listening tests. The answering scale used for the assessments of annoyance according to ISO 15666 was an 11-point category scale with five verbal labels added for clearer definition of the scale across subjects. The scale is shown in Figure 4.

Not at all		Slightly		Moderately			Very			Extremely
0	1	2	3	4	5	6	7	8	9	10

Figure 4 - Rating scale used for assessments of annoyance according to ISO 15666.

Danish translations of the words on the scale shown were used [6]. Ratings on the different perceptual attributes were given on continuous scales on a computer screen via a mouse. The screen layout is shown in Figure 5.

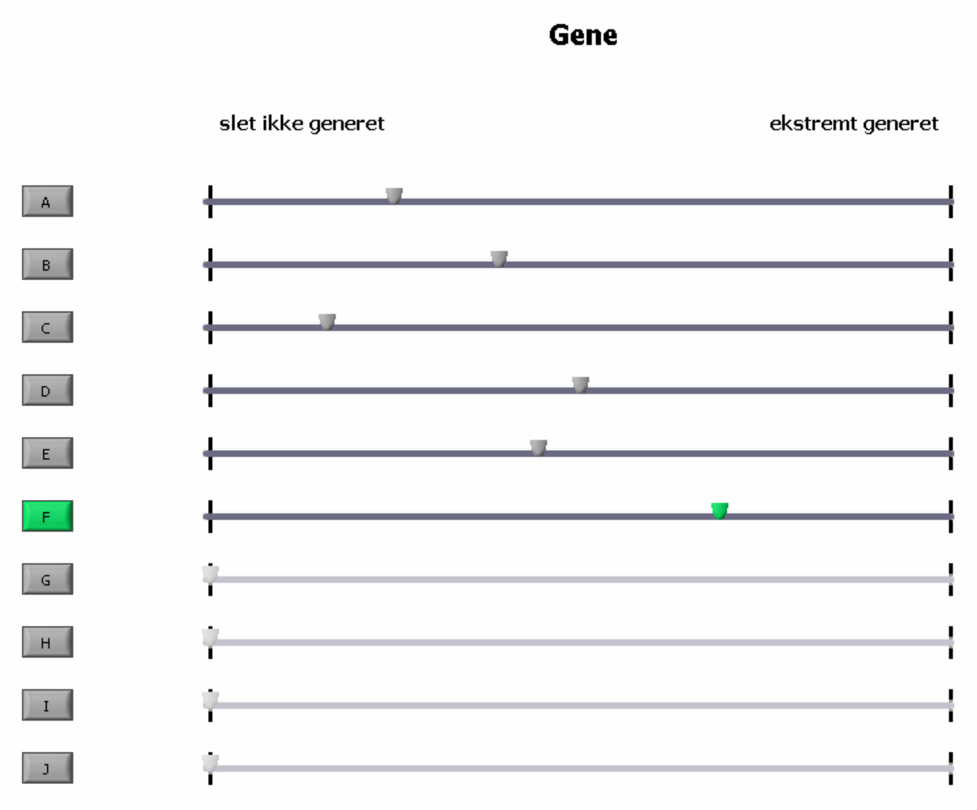

Figure 5 - Screen layout for presentation and assessment of the stimuli.

The slider's positions were read by the software on a continuous scale from 0 to 15. The 15 units correspond to the length of the scale in centimetres when displayed on the screen.

Test Procedure

The listening tests were conducted in an EBU 3276 standard listening room at DELTA. The stimuli were presented via headphones. A photo of the setup is shown in Figure 6.

Figure 6 - The setup in the listening room at DELTA.

The sound pressure levels of the system were calibrated each day by measuring the acoustical output of the headphones placed on a HATS. Groups of up to four subjects performed the listening test simultaneously.

For the assessments of annoyance according to the question and scales of ISO 15666 all subjects in the group were presented with the same stimulus via headphones and they were instructed to wait until the completion of each stimulus before placing their individual final mark on the printed rating scale. The rating was given on the basis of the following question: ‘If you imagine this is the sound in your garden, how disturbed or annoyed would you feel of the sound from the wind turbine?’ The subjects were not allowed to talk to each other during the listening test. The stimuli for the ISO 15666 assessments were divided into two groups: at 6 HH and at 12 HH distance. Each of the stimuli groups was subdivided into groups with and without natural background noise. A stimulus with only the sound of natural background noise was added to each of the groups containing stimuli with natural background noise. The stimuli were randomized within groups and for group presentation order across subject groups to eliminate order effects.

In the second part of the listening test concerning assessments of perceptive attributes, the subjects were conducting the test individually. For each attribute, the subject could shuffle between all 10 stimuli and make ratings at own will until they felt confident about the assessments. The order of the attributes was fixed for the first two attributes to be ‘Annoyance’ and ‘Loudness’. The remaining attributes were randomized between subjects. The answers from the test subject were automatically stored.

On completion of the listening tests, each subject completed a 9-item noise sensitivity questionnaire developed by Karin Zimmer and Wolfgang Ellermeier translated into Danish (to be found in [11] in English and Danish).

The total time of the listening tests was about 1 hour 30 min including break.

Instrumental Analysis

In the search for objective psychoacoustic metrics to describe relevant perceptive attributes of the sound from the wind turbines, all stimuli used in the listening test were analyzed using Brüel & Kjær PULSE Sound Quality software. Calculations on loudness, sharpness, roughness and fluctuation strength were made. To measure tonality in the stimuli the noise analysis software "noiseLAB" developed by DELTA was used [7]. In noiseLAB tonality is measured according to the international standard ISO 1996-2 Annex C.

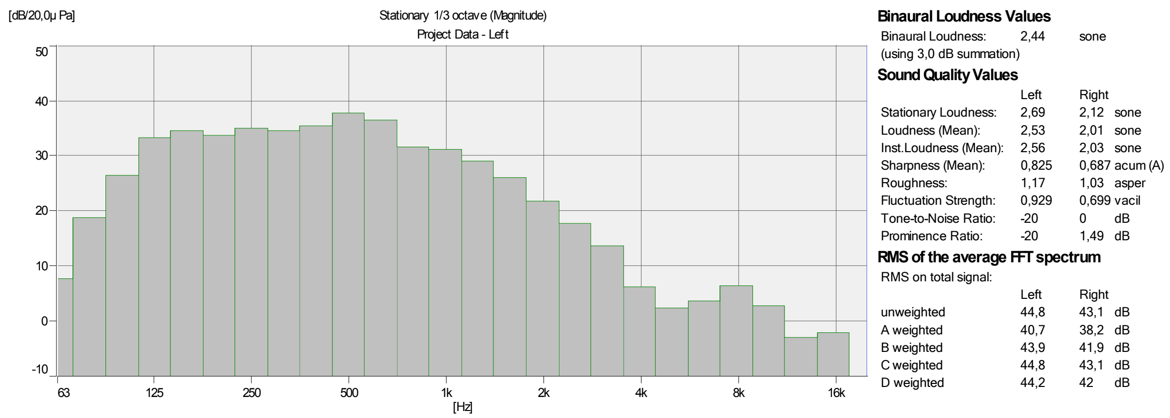

Figure 7 - Output from Brüel & Kjær PULSE Sound Quality software for 1/3-octave average spectrum with sound quality metrics.

Physical Metric on Swishing sound

The perhaps most dominant characteristic in the emitted sound from large wind turbines is the swishing sound caused by the wings rotating in the air. This component is described in most studies on annoyance of wind turbines as being a significant contributor to the overall annoyance. An attempt was made to create a metric describing the swishing sound.

First step of the process was to find the frequency band where the swishing sound was most dominant for the auralized distances of 6 HH and 12 HH. A first suggestion for a pass band was made by applying different band pass filters to the stimuli and listen to the outcome. The target of a metric would be a measure for the amplitude and frequency modulation in the specified frequency band. The psychoacoustic metric called fluctuation strength already exists and measures both types of modulations in sounds [2]. Therefore by applying the fluctuation strength for the specified frequency band a first version of a psychoacoustic metric on swishing sound was formulated.

In Bruël & Kjær PULSE Sound Quality software the fluctuation strength was measured for the 350 Hz – 700 Hz band pass filtered stimuli. Different cutoff frequencies and band widths were tested to verify that the largest value on fluctuation strength was found at exactly the identified pass band. (In an earlier study [4] for smaller turbines the same effect was found to be most prominent in the 1 kHz range, but the 350-700 Hz range seems to be the optimum for large modern wind turbines).

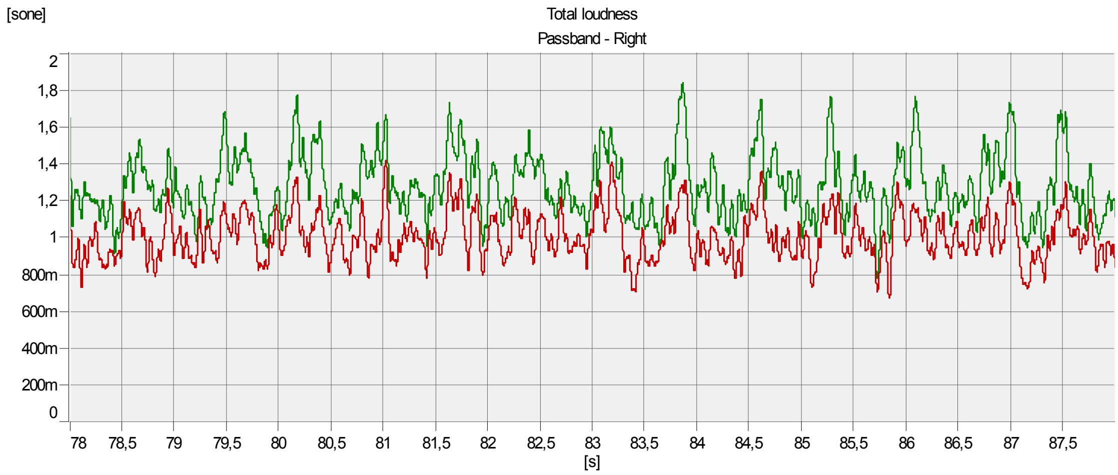

Figure 8 - Stationary Loudness vs. time in the pass band 350 Hz – 700 Hz for a selected sequence of 10 seconds to illustrate the metric on swishing sound. (Green: left ear, Red: right ear channel).

Results

The results from the ISO 15666 scales annoyance ratings on the 90-second stimuli with and without natural background noise (BN) are given below:

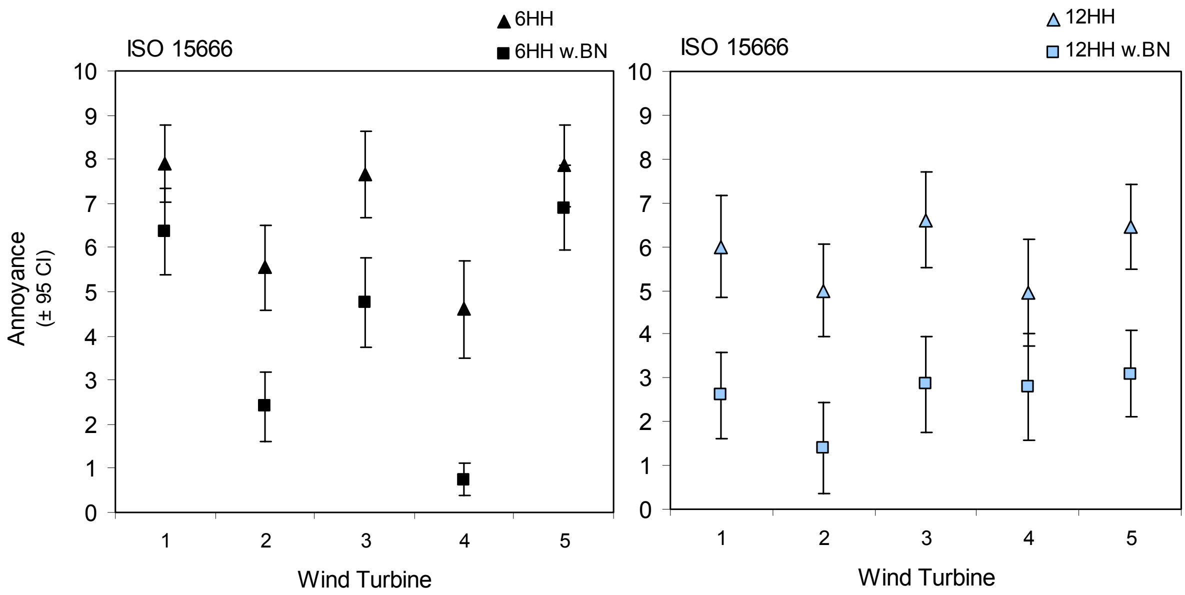

Figure 9 - Assessments of annoyance according to the scales of ISO 15666 on 90-second stimuli at auralized distances of 6 HH and 12 HH from the wind turbines with and without natural background noise.

The influence of natural background noise on the annoyance of sound from the wind turbines is significant. The annoyance decreases from 6 HH to 12 HH except for wind turbine 4. However, this can be explained by the presence of a clearly audible tone placed in a frequency band of which the sound propagation induces less attenuation at 12 HH than for 6 HH.

The results from the assessments of perceptive attributes for 20-second stimuli of wind turbines at auralized distances of 6 HH and 12 HH are presented as a function of the corresponding calculated physical metric.

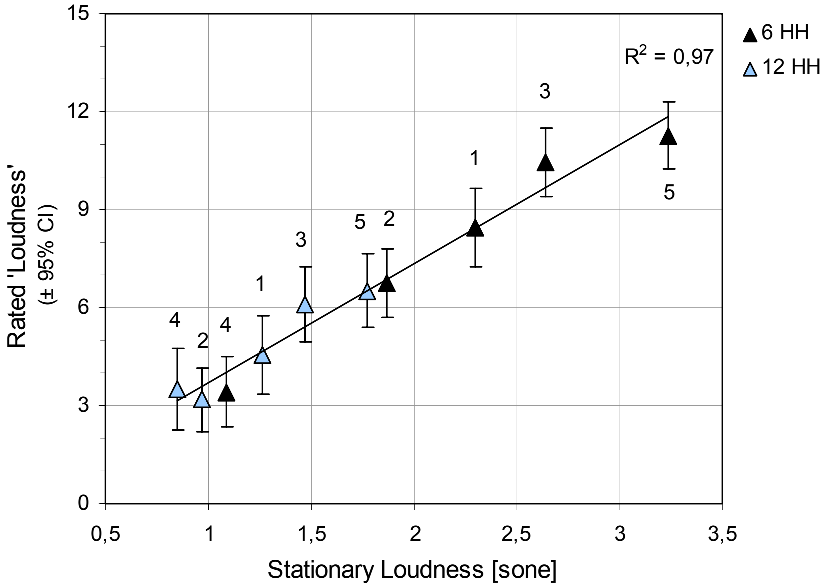

Figure 10 - Rated 'Loudness' versus calculated Stationary loudness.

There was a high correlation (R^2 = 0.97) between the perceptive rated 'Loudness' and the metic for stationary loudness of the stimuli. The correlation between rated loudness and A-weighted sound pressure levels of the stimuli was R^2 = 0.94.

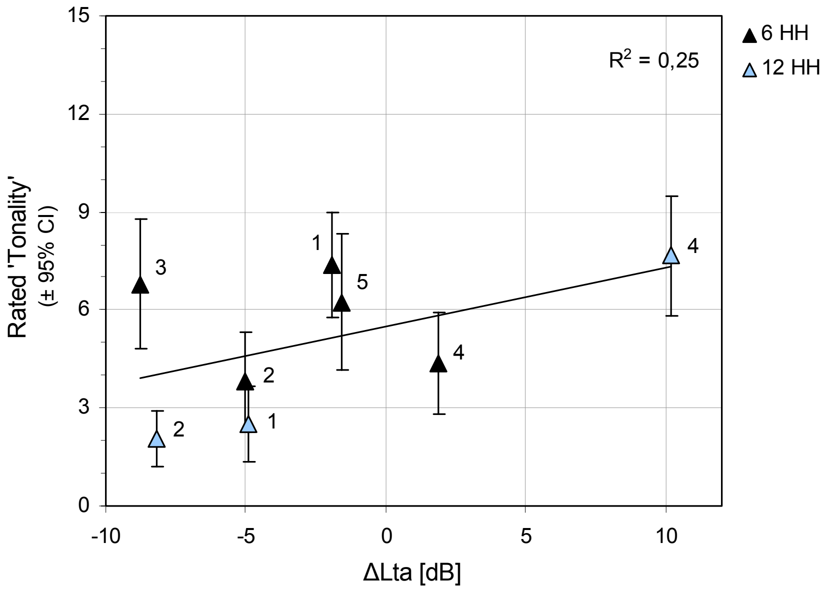

Figure 11 - Rated 'Tonality' versus calculated prominence of tones ΔL_{ta} according to ISO 1996-2.

Perceptive rated tonality did in this case not correlate very well (R^2 = 0,25) with the metric for the prominence of tones. The combination of stimuli with tone levels below the average masking threshold (ΔL_{ta} = 0 dB) and the use of only slightly trained naive listeners may explain this. According to [8] naive listeners should be used for affective judgements (e.g. annoyance) while trained listeners or experts should be used for perceptive assessments.

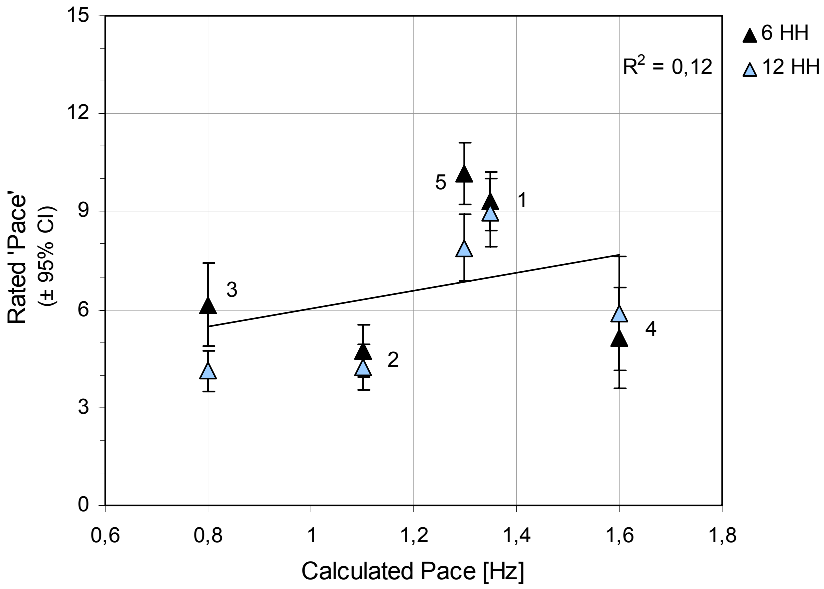

Figure 12 - Rated 'Pace' versus calculated 'Pace'.

It was surprisingly hard for the subjects to rate the pace of the wind turbines, even though the subjects were allowed to shuffle between all 10 stimuli before giving their final rating.

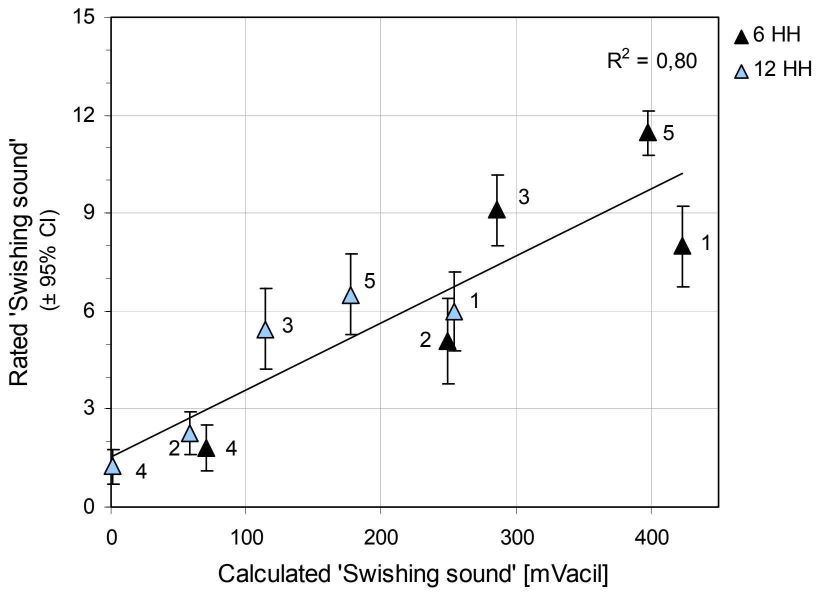

Figure 13 - Rated 'Swishing sound' versus calculated 'Swishing sound'.

The metric on swishing sound correlated well (R^2 = 0.80) with the perceptive ratings on 'Swishing sound'.

Results from the noise sensitivity test showed no correlation with age (R^2 = 0.04) or with the mean annoyance rating (R^2 = 0.01). The mean noise sensitivity of the subjects was 64 on a 0-100 scale, which is categorized as medium noise sensitive (33-66).

The results from the annoyance assessments of the 90-second stimuli can be described as a logistic function which is derived from logistic regression analysis [11]. Results from two international field studies are also modelled in [11] and shown in Figure 14.

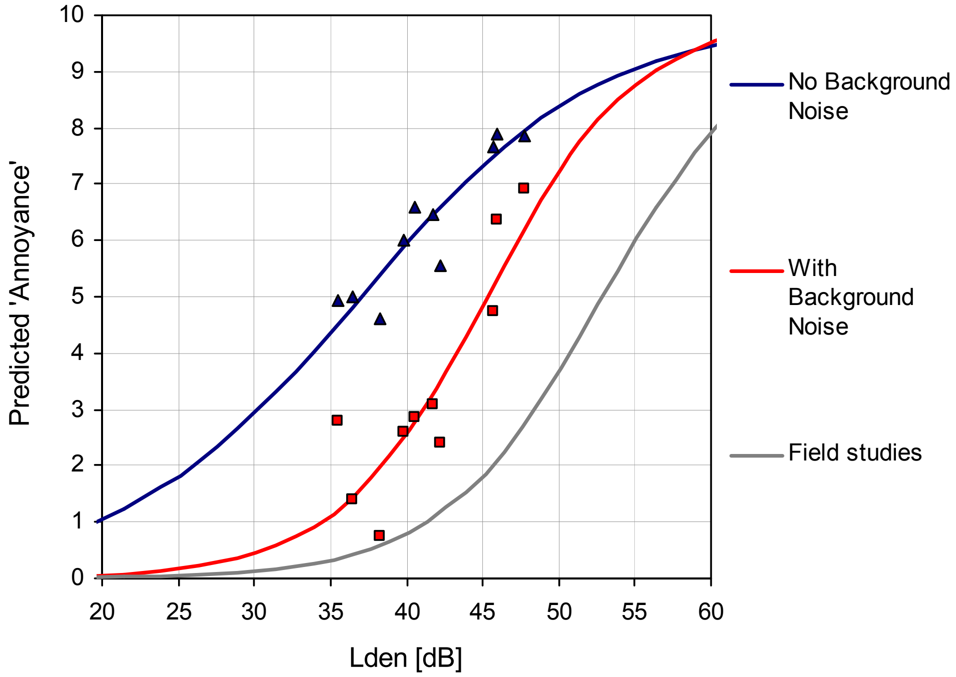

Figure 14 - Prediction model on annoyance for the 90-second wind turbines sounds with and without natural background noise. A common model for results from two field studies is also shown.

The prediction model is based on the day-evening-night level (L_{den}) of the wind turbines. The common curve for the two field studies is calculated in [11] from results in [9] and [10].

The effect of natural background noise is clear. By adding natural background noise, the wind turbine sound is masked at low levels and becomes less annoying. Other results, not presented in this paper, show that the model for annoyance can be improved by including the metrics for prominent tones and for the swishing noise.

By comparing the results from this laboratory study with the results from the two field studies, it is clear that many factors influence the result. The primary difference between the field studies and this laboratory study is the context. Even though great effort was made to create a relevant context in the listening room, it is not possible to make people feel at home. Another difference is that the subjects in this study were asked specifically about how annoyed they would be of the wind turbine sound if they were sitting in their garden in the countryside. In the field studies the questions were on a more overall level ("at home"). The use of different scales in the field studies and this laboratory study may also be a factor even though the scales have been normalised to the same range.

Conclusion

In the presented study wind turbines were recorded and auralized at distances relevant for the environmental aspects in the Danish legislation for protection of the people living next to them. Auralization was based on the sound propagation model Nord2000. The effect of natural background noise on the annoyance of sound from wind turbines was also investigated. Listening experiments were conducted using subjects who were representative for the group of people living in the countryside near wind turbines.

Natural background noise had a significant effect on the rated annoyance. By adding natural background noise to the wind turbine sounds, the rated annoyance decreased. This does not come as a surprise since the masking effect from wind generated noise in the vegetation is well known. One could then consider whether background noise should be a parameter in the Danish legislation when setting noise limits and assessing annoyance in the environment around new wind farms?

Perceptive attributes relevant for the annoyance of sound from wind turbines were also rated in the listening experiment and the results were linked to calculated physical metrics. The two primary attributes related to annoyance in wind turbine sounds are tonal components and the swishing sound from the rotating blades. The rated tonality of the stimuli did not correlate too well with the metric for prominence of tones ΔL_{ta} in this experiment. A metric for calculating swishing sound was developed and it correlated well with the ratings on 'Swishing sound' in the stimuli.

Finally, noise sensitivity measured on the participating subjects did not correlate with the mean annoyance score.

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