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Abstract: To increase the understanding of wind turbine noise on sleep, human physiological reactions need to be studied in a controlled laboratory setting. The paper presents an outdoor–indoor noise level difference as a function of frequency, applicable to creating wind turbine indoor sounds with the outdoor sounds as input. For this, a combination of measurement data and modeling results has been used. The suggested data are provided in a table.

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1. Introduction

According to the International Energy Agency, the recent growth in wind power is forecast to continue globally.[1] Wind turbines are therefore likely to become increasingly commonplace, and hence a growing number of people are going to live close to them in the future. Despite public complaints, the effects of wind turbine noise (WTN) on nearby residents are not well understood. Although there are indications for self-reported disturbance,[2] a recent study found no associations between one-year averages of WTN and objective measures of sleep obtained via actigraphy.[3] These long-term measures do not account for acute sleep disruption following isolated periods of deleterious noise. Disturbed sleep in the long term may, even without being consciously perceived, contribute toward negative health outcomes. It is therefore of interest to further objectively identify the effects of WTN on sleep. This requires increased knowledge on sound immission from wind turbines, resulting in low-frequency noise exposure in the home environment. The current paper describes a model spectrum for creating indoor wind turbine sound with the outdoor sound as input, described as an outdoor–indoor noise level difference as a function of frequency. Within the project, called Wind Turbine Noise Effects on Sleep (WiTNES),[4] the model is used to investigate human physiological reactions in controlled laboratory settings.

In regions where the effects of WTN on populations exposed in their homes is of concern, much of the noise from wind turbines is in the low-frequency region, i.e., between 20 and 200 Hz.[5,6] Sound transmitted from the outside of a building to the inside will be changed in overall sound pressure level as well as spectrally.[7,8] At outdoor WTN levels of 44 dB(A), noise at frequencies upwards of around 40 Hz begin to exceed hearing thresholds indoors,[7] and at the same time the outdoor-to-indoor sound insulation of residential buildings typically increases with frequency. Indoor WTN levels can therefore be dominated by low frequencies, which may further be compounded by the presence of room modes.[9] Spectral information down to low frequencies, of

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both the source and sound propagation attenuation, is thus necessary for modeling indoor WTN.

2. Method and result

Whereas the outdoor–indoor noise level difference spectrum varies between individual buildings, enhanced by low-frequency room resonances, the approach of the current work has been to define and use a single, smoothed, generic spectrum rather than a larger number of different case based spectra. Using a single spectrum allows a wider test range of amplitude modulation effects in laboratory tests, which is a planned application of the result. The modeling of the outdoor–indoor noise level difference spectrum is further described below.

Typically the noise environment in bedrooms is of interest when considering possible effects of noise-induced sleep disturbance. The sound enters the bedroom via the walls, windows, doors, ceiling, and ventilation openings. Given proper sound insulation data, i.e., reduction index and reverberation time, in relevant frequency bands, it is possible to estimate the total apparent sound pressure level difference between the outside and inside.[10] What building element is the main contributor to the sound level inside is not possible to estimate *a priori*, since practically used constructions differ acoustically on a very wide scale. However, slightly open windows or open fresh air ventilation ducts are often responsible for high sound levels in the mid and high frequency range. In the low frequency range they are usually of less importance because of their relatively small size.

Sound insulation data for building elements, normally provided in third-octave bands, are often only available in the 50–5000 Hz frequency range, whereas here we aim for data down to 20 Hz. Since the measurement uncertainty, using standardised laboratory methods, is largely increasing at low frequencies (e.g., Ref. 11), case-based field measurement data are considered more representative for actual living conditions.[7,8] On the other hand, with the limitations of the current project to use only one sound insulation spectrum, there is a risk in picking one of the field spectra, due to the large variation in strength as a function of frequency caused by the room resonances of the different dwellings. Also dips in reduction index due to the facade construction can play a role. Therefore, we have chosen to use a smooth sound insulation spectrum.

Whereas the above-mentioned field data from Lindkvist[8] and Møller and Pedersen,[7] which we use here as a basis, cover frequency ranges of 20–200 and 8–200 Hz, respectively, the identified needs of our laboratory studies involves a frequency span of 20–800 Hz. (The noise above 800 Hz will not be influential indoors due to the low levels, which is usually not the case for outdoor WTN.) The reduction spectrum for frequencies between 250 and 800 Hz (here denoted as the mid-frequency WiTNES curve) is calculated for a hypothetical room with the size $4.0 \times 4.0 \times 2.5$ m on the upper floor of a house on the Swedish countryside, i.e., a typical location for installing wind turbines. Sound from the wind turbine is transmitted into the room via the outer wall (10 m^2), the window (1.8 m^2), and the roof (16 m^2). The representative wall is chosen from common construction found on the Swedish countryside, i.e., a wooden timber wall with thickness 120–150 mm. A typical window is chosen, with double glazing, each pane 3 mm thick, separated by a 40 mm air gap. To include the additional transmission through the roof, a typical wooden roof with brick tiles and insulation between rafters was chosen. A composite spectrum for the roof and wall with window was constructed from their respective sizes and reduction index spectra obtained from measured data going down to 50 Hz.[12] The input data used can be found in Table 1. In Ref. 14, the reported values were validated by comparing with reduction indices from using the software Insul and adjusting to empirical measurement values. A high internal damping of the construction was assumed in order to provide a smooth spectrum. Since an acoustically good, *noise proof*, air inlet gives negligible detriment to the facade insulation, the combination of the roof, timber façade, and the window is chosen to determine the total sound insulation, assuming no leakage or other faults in the building construction. Assuming a reverberation time of 0.5 s, the frequency dependent difference, ΔL_p, between the outdoor free field level (i.e., without facade reflection) and the indoor level, is calculated as $\Delta L_p = R - 10\log(S/A) - 3$ (dB), where R is the frequency dependent reduction index, S is the area of the transmission surface, and A is the absorption area of the room, determined from the volume and the reverberation time.[13] From 200 Hz and below, the ΔL_p spectrum is extended following a smooth version of the Swedish data from Lindkvist, which is for a similar case.[8] The smoothing was made visually with the objective to construct a monotonically increasing sound pressure level difference with frequency, i.e., a sound pressure level difference without resonances. Both curves are plotted in Fig. 1, denoted "Lindkvist" and

Table 1. Reduction indices for wall (22 mm wood panel, 150 mm timber, 19 mm wood panel), roof (brick tiles, wood support, waterproofing, 19 mm wood panel, 175 mm insulation between rafters, 25 mm wood panel), and window (3 mm glass, 40 mm air gap, 3 mm glass; coupled sashes).

Frequency (Hz)	R_{wall} (dB)	R_{roof} (dB)	R_{window} (dB)
50	17	22	17
63	18	23	16
80	19	24	15
100	14	25	14
125	16	26	12
160	19	28	10
200	20	30	20
250	22	32	26
315	24	35	29
400	25	38	32
500	27	41	35
630	27	44	37
800	30	45	39
1000	31	46	41
1250	32	45	43
1600	32	43	45
2000	33	41	47
2500	36	42	47
3150	39	43	45
4000	42	43	42
5000	45	43	41
Area (m^2)	10	16	1.8

"Lindkvist–smooth," respectively. The Danish data by Møller and Pedersen, encompassing ten different facades,[7] denoted "Moller 1–10," are plotted for comparison, showing a general overall agreement with the Lindkvist curve. It should be noted that there is not much data available that covers the frequency range of interest, going down to 20 Hz.

The smoothed Lindkvist data are lowered by 5 dB before it is combined with the above described mid-frequency WiTNES curve, motivated by the interest here in a slightly more severe case, as described below, as well as that the receiver position is assumed to be representative for a sleeping person's head position close to a corner of the room. The resulting curve, after implementation as a filter, with additional smoothing applied to avoid ringing, is plotted in Fig. 2. It could be pointed out that half of the Møller curves display, in relation to the WiTNES curve, a lower ΔL_p value in at least one-third octave band, thus further indicating that the level of the WiTNES curve is appropriate. To conclude, the here suggested outdoor–indoor level difference is a

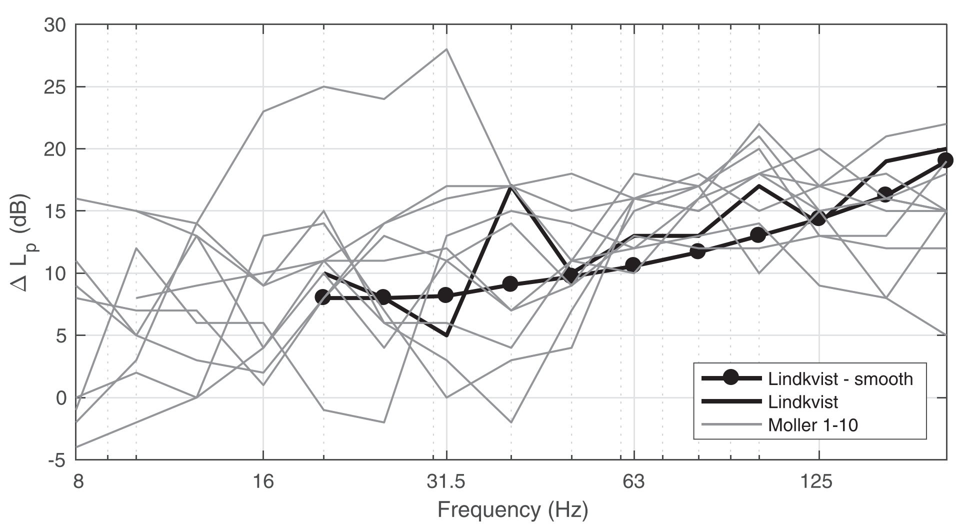

Fig. 1. Plotted difference between free field and indoor sound pressure levels; measured data and the smoothed Lindkvist curve.

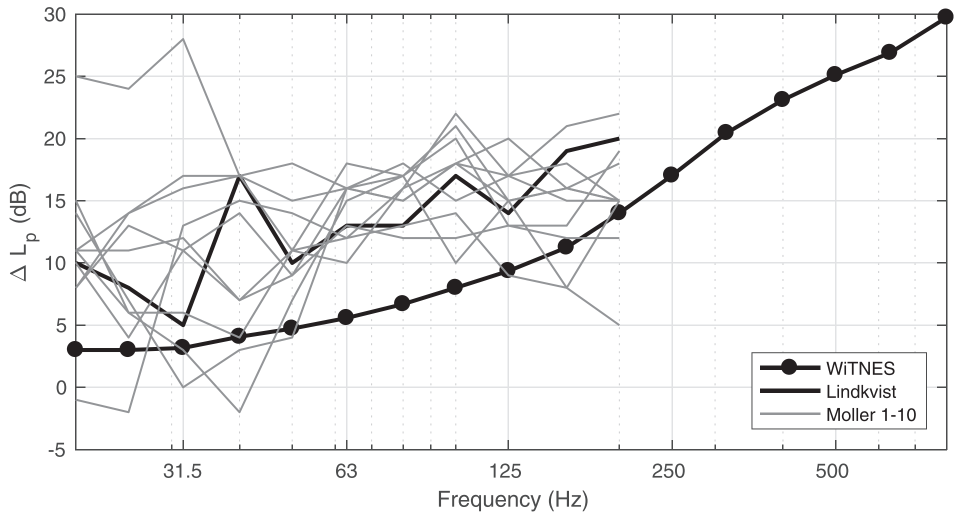

Fig. 2. Plotted difference between free field and indoor sound pressure levels, including the final WiTNES curve.

smooth curve, with general applicability to housing focusing on wooden constructions, exemplified to be compatible with Swedish and Danish data. The final WiTNES insertion loss data are listed in Table 2 together with data for a slightly open window (denoted *Open window*); the latter being based on laboratory measurements for acoustic gaps typical for slightly open windows, exhibiting a cut-on frequency of 200 Hz, above which the facade insulation is deteriorated compared with closed window.[14] Both facade insulation curves are to be used in the laboratory sleep studies.

Since the final importance lies with the indoor noise level, the spectrum of the outdoor noise as well as the outdoor–indoor noise level difference spectrum are of importance. Here we assume a single outdoor spectrum, motivated by the relatively high spectral similarity in the source sound of different wind turbine types.[7] The choice of overall level indoors uses the Swedish guideline value as a starting point, i.e., an outdoor equivalent level of 40 dB(A). However, due to the variability between different nights, it is of interest to study a slightly more severe case. Using a slightly more severe case is also motivated by our smoothing of room resonances. The more severe case is also of relevance in an international perspective since some countries use higher guideline values, e.g., an outdoor equivalent level of 44 dB(A) in Denmark.[7]

Table 2. Final WiTNES level difference data: Difference between outdoor free field and indoor sound pressure levels, ΔL_p, for closed window and window slightly open, for the frequency range 20–800 Hz.

Frequency (Hz)	Closed window ΔL_p (dB)	Open window ΔL_p (dB)
20	3.0	3.0
25	3.0	3.0
31.5	3.2	3.2
40	4.1	4.1
50	4.7	4.7
63	5.6	5.6
80	6.7	6.7
100	8.0	8.0
125	9.4	9.4
160	11.2	11.2
200	14.0	14.0
250	17.0	14.0
315	20.5	14.0
400	23.1	14.0
500	25.1	14.0
630	26.9	14.0
800	29.7	14.0

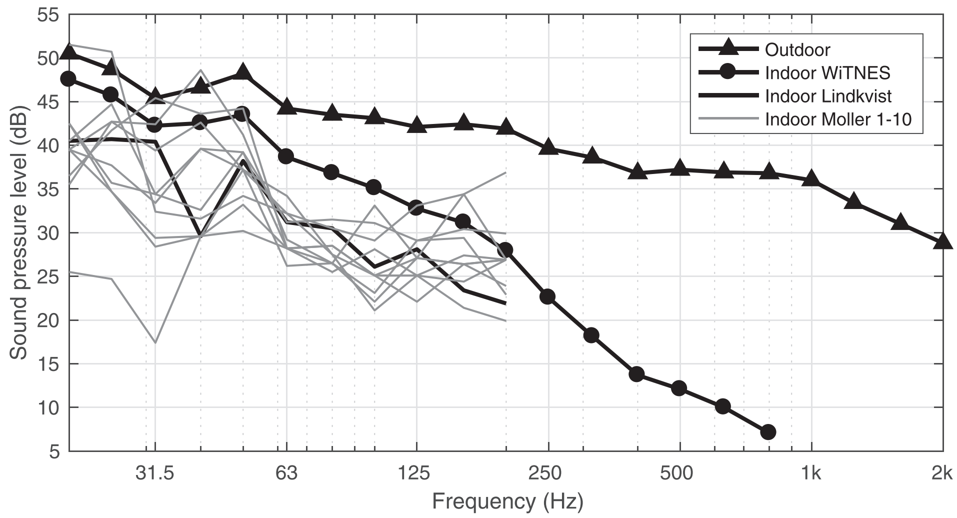

Fig. 3. Plotted indoor spectra together with the used outdoor spectrum. The finally used spectrum is the one called "Indoor WiTNES." Included in the graph are the corresponding indoor spectra when applying the Lindkvist and Møller data.

Figure 3 shows a typical outdoor spectrum (for use in the planned experimental work) and the resulting indoor spectrum from using the WiTNES sound pressure level difference displayed in Fig. 2. In Fig. 3 the results of applying the Lindkvist and Møller level difference curves to the same outdoor spectrum are shown. For the laboratory studies, the outdoor wind turbine sound is synthesised and mixed with recorded background wind noise before a filtering is applied to achieve the wanted indoor sound levels. The filtering is implemented using an 8192 tap linear-phase equalisation fast Fourier transform window finite impulse response filter in Audacity 2.0.1 using 48 kHz sampling frequency. No change of the time signal due to room reverberation is applied. (Further description of the sound synthesis is planned to be published elsewhere.)

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