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Pockelé, J.S.; Merino Martinez, R.

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Influence of Ambient Noise in Sound Quality Assessment of Auralised Wind Turbine Noise

Josephine Siebert Pockelé[1] and Roberto Merino-Martinez
Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, 2629HS Delft, the Netherlands

Summary

The influence of ambient noise in the perception of wind turbine noise is evaluated in this exploratory study. For this purpose, experimental field measurements of an NTK wind turbine at different wind speeds and background noise levels are considered. Synthetic wind turbine noise auralizations are then computed to replicate the weather and operational conditions during the experiments. Different background noise recordings were then synthetically added to the simulated auralizations to investigate the effect in sound quality metrics, such as loudness, roughness, or the psychoacoustic annoyance model by Zwicker. A least-squares analysis was applied to the resulting sound signals. It was found that adding background noise to the auralisations notably reduced the differences in metrics between simulations and experiments. However, the behaviour with respect to the A-weighted signal-to-noise ratio then becomes background-noise dependent and, hence, more challenging to predict. Therefore, for perceptual studies, it is recommended to use experimental recordings with low background noise as a ground truth.

1. Introduction

In the onshore wind energy sector, noise remains a prevalent issue for the social acceptance of new installations [1]. Whereas offshore wind is on the rise, the majority of current new installations are still onshore [2], [3]. Since current research on noise annoyance due to wind turbines is mostly limited to surveys of inhabitants around existing installations [4], [5], it is important to bridge the knowledge gap between human noise perception and wind turbine design.

For human perception research, sound signals are required [6], [7], which are normally not available during the early design stages of wind turbines. Merino-Martinez *et al.* [8] proposed one method involving auralisation (i.e. the creation of sound files from simulated data) to integrate noise annoyance within the design loop [8]. Auralisation using simulated data has recently shown promising results in research about human perception [9]–[11].

One issue highlighted by Pockelé [10] in the validation of fully synthetic auralisations is quantifying the influence of ambient or background noise (BGN) in the perception of the evaluated sounds. At the time of writing, the only established methods for dealing with ambient noise in the analysis of wind turbine noise consist simply of its subtraction (in the frequency domain) from experimental recordings aiming to isolate the wind turbine noise contribution. None of these methods are based on the exact ambient noise during the

[1]Corresponding author - Email: j.s.pockele@tudelft.nl

measurements of the turbine, which is a known limitation [12]. While acceptable for spectral analysis in research and permitting, wind turbine noise in the time domain (for human perception research) can only be isolated in sound signals if the exact background noise during the recording is known. This is, however, very challenging to achieve in practice.

This exploratory study proposes two different methods for dealing with background noise in human perception research of auralised wind turbine noise: (1) accounting for background noise by adding representative sample signals to the auralisations, or (2) not adding background noise and considering recordings with low ambient noise levels as a ground truth. A preliminary analysis comparing both methods is therefore presented to explore the establishment of a best practice for future research. The sound analysis in this study is conducted using sound quality metrics (SQMs) from the field of psychoacoustics, which are expected to represent human perception more accurately than conventional sound metrics [13].

The experimental measurements of wind turbine noise considered for this study are described in section 2. Section 3 introduces the employed auralisation methodology, as well as the wind turbine model and operating conditions. The descriptions of the SQMs considered for the acoustic analysis of the wind turbine sounds are briefly explained in section 4, as well as the main results per metric. Lastly, concluding remarks are given in section 5.

2. Experimental Noise Measurements

Noise measurements of a *Nordtank NTK 500/41* wind turbine, conducted at the Technical University of Denmark (DTU) Risø campus are used. The dataset [14] contains simultaneous noise, met mast, and SCADA (Supervisory Control And Data Acquisition) data of the turbine. These measurements span 15, 16, and 23 October 2015, with varied wind and climatic conditions, and multiple background noise levels [15].

2.1 Measurement Setup

The wind turbine noise is measured using eight microphones, evenly distributed along a circle of 45-m radius centered at the turbine tower. The microphones are manufactured by *BSWA Technology Co.* (ref. MPA 261 combining a 1/2” microphone and a pre-amplifier) and are configured according to the IEC 61400-11:2012 measurement standard [16], without a secondary windshield [15]. Their respective positions are shown in Figure 1. The sampling frequencies employed for the acoustic recordings were 50 kHz on 15 October and 25 kHz on 16 and 23 October.

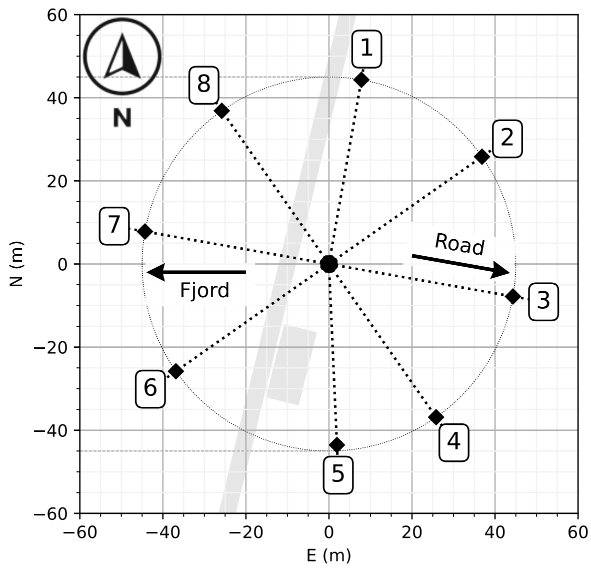

Figure 1 Microphone positions in the noise measurement dataset. Adapted from Pockelé, Figure 8.2 [10].

The SCADA data of the turbine covers the rotor RPM, power output, yaw, and other operational parameters, as well as wind speed and direction measured by the nacelle's anemometers. The met mast data contains wind measurements at different heights and measurements of air temperature and pressure at sea level. All these data are recorded at 35 Hz on a 16-bit data acquisition system [15].

2.2 Wind Turbine Noise Measurement Selection

The data from 15 October is used to represent high-level, road-related background noise, whereas the data from 23 October is used to represent low-level background noise from the fjord. Henceforth, the 15 October data is referred to as "*road*", while the 23 October data is referred to as "*fjord*".

For both dates, a selection of 30 second measurement segments is made. To limit the scope of this work, the selection is limited to the four microphones that most closely represent the IEC 61400-11:2012 standardised measurement positions [16], considering the mean wind direction on each date. The selected microphone numbers are given in Table 1:

Table 1 Microphones used to represent the positions from the IEC 61400:11-2012 standard [16]. The microphone numbers refer to Figure 1.

IEC position	1	2	3	4
15 October	6	7	2	5
23 October	3	4	7	2

Firstly, an initial selection is made using the local minimum wind speed fluctuations, based on the 30-second moving standard deviation. These segments are sorted into 1 m/s mean wind speed bins. Since the noise measurements are to be used for listening experiments, clipping beyond a 1.0 Pa amplitude should be accounted for, as clipping results in audible disturbing artefacts. Since no intervals are found with no clipping, a selection criterion is set up, which combines the deviation of the mean wind speed from the bin wind speed and the amount of clipping. This criterion is defined in Equation 1, where the second term is the integral of all sound signal peaks where the pressure magnitude goes beyond 1.0 Pa (representing the amount of clipping).

$$\text{criterion} = \left|U_{\infty,\text{bin}} - U_{\infty,\text{mean}}\right| + \int_0^{30} \left(|p(t)|_{|p(t)|>1} - 1 \right) dt \tag{1}$$

After this selection, one 30-second segment remains per wind speed, per measurement data. To limit the scope of this work to steady background noise conditions, the sound files are manually inspected for audible disturbances such as aircraft flyovers, bird noises, and other impulsive noises. If such a disturbance is found, the segment is excluded, and the above selection process is repeated. A short summary of the final selection is provided in Table 2. The $L_{A,eq}$ of the selected 30-second wind turbine noise measurements ranges from 55 dBA to 60 dBA.

Table 2 Summary of the final selection of noise recording segments.

BGN condition	Road	Road	Road	Road	Road	Road	Fjord	Fjord	Fjord	Fjord
$U_{\infty,\text{bin}}$, [m/s]	5	6	7	8	9	10	6	7	8	9
$U_{\infty,\text{mean}}$, [m/s]	4.51	6.32	6.97	7.90	9.02	10.10	6.41	7.01	7.83	8.62
σ_{U_∞}, [m/s]	0.54	0.73	0.79	0.88	0.90	0.98	0.21	0.29	0.35	0.35
Criterion	0.56	0.33	0.03	0.18	0.12	0.20	0.41	0.01	0.17	0.45

2.3 Background Noise Selection

For the first proposed method (adding representative ambient noise to auralised signals), a selection is made of the background noise (BGN) recordings in the NTK turbine measurements. For each operational interval, per microphone position, a 30-second background noise sample is selected from the background recordings before the turbine was started. The selection is based on a manual inspection to eliminate audible disturbances, such as aircraft flyovers, birds, or other impulsive sounds. These are excluded for the same reason as for the case of the wind turbine noise measurements.

3. Setup of Wind Turbine Auralisations

3.1 Auralisation Methodology

A simplified version of the method presented by Pockelé [10] is used. In the current work, the Gaussian beam tracing is replaced with a simpler image-source model.

The aeroelastic-aeroacoustic simulations are handled with the HAWC2 code developed by DTU, and the attached aeroacoustics module [17]. These simulations model the wind turbine dynamics and the following noise sources: (1) leading-edge turbulent inflow noise, (2) turbulent boundary layer trailing-edge noise, and (3) flow separation/stall noise [15].

Ground reflections are calculated using the model by Embleton et al. [18] and Delany and Bazley [19]. Atmospheric absorption losses are determined using the model in ISO standard 9613-1 by Bass et al. [20], [21]. To use the latter two models, the HAWC2 noise results per blade are used and are assumed to propagate from three moving monopole sources at 85% of the blade span.

The result of the above method is six spectrograms (for each blade: one for the direct and on for the reflected sound signal). These spectrograms are individually reconstructed into sound signals, using the Inverse Short-Time Fourier Transform (ISTFT). In order to meet the requirement for STFT sample points in time and frequency, the HAWC2 spectrogram outputs are interpolated using a piecewise-linear method in the frequency axis. Before the ISTFT, a randomised phase is added to the spectrogram. The direct and reflected signals are assigned the same random phase. The six resulting sound signals are summed to obtain the final auralised wind turbine noise signal.

3.2 Wind Turbine Model Description

The above auralisation method is applied to the validated simulation model of the *Nordtank NTK 500/41 wind turbine* developed by DTU [14], [22], [23]. In the available model, the XFoil boundary layer data, with a critical amplification parameter $N_{crit} = 3$ is used to represent a workflow with low computational cost. The properties of the NTK turbine are summarised in Table 3:

Table 3 Relevant specifications of the NTK 500/41 wind turbine [23].

Power Rating	0.5 MW
Rotor Diameter	41.1 m
Hub Height	36 m
Control	Passive
Mechanism	Aerodynamic Stall
Rotor Speed	Constant (27.1 RPM)

3.3 Simulation Input Conditions

The simulated operational conditions are obtained from the above-described measurements to match the conditions during the selected recording intervals. The simulations span the full intervals in the measurements where the turbine is operating to avoid any transient effects of the simulation start-up. From the resulting sound signals, the selected intervals are extracted for the analysis.

The wind measurements from the met mast, at multiple heights, were input in HAWC2, using the *met_mast_wind* input parameter. The necessary wind time series file is built from the measurements of the south-facing cup anemometers as they are the least disturbed by the met mast structure. The turbulence intensity for the noise calculations is derived from the sonic anemometer at 34.5 m height. The air temperature and pressure are set as the mean of the respective operational intervals. Since the humidity is not available in the dataset, it is derived from the Danish Meteorological Institute's open data [24] based on the date and time of the noise measurements.

4. Sound Quality Metric Results

4.1 Sound Quality Metrics

Sound Quality Metrics (SQMs) describe the subjective perception of sound by human hearing, unlike the sound pressure level L_p metric, which quantifies the purely physical magnitude of sound based on pressure fluctuations. Previous studies [8], [13] showed that these metrics better capture the auditory behavior of the human ear compared to conventional sound metrics typically employed in noise evaluations. The four most commonly used SQMs [6] are:

- Loudness (N): Subjective perception of sound magnitude corresponding to the overall sound intensity [25]. The loudness results in this paper are expressed in loudness levels L_N in phon.
- Sharpness (S): Representation of the high-frequency sound content [26].
- Roughness (R): Hearing sensation caused by sounds with modulation frequencies between 15 Hz and 300 Hz [27].
- Fluctuation strength (FS): Assessment of slow fluctuations in loudness with modulation frequencies up to 20 Hz, with maximum sensitivity for modulation frequencies around 4 Hz [28].

These SQMs were calculated for each wind turbine noise sample. The 5% percentile values of each metric (i.e., the value of each SQM exceeded 5% of the total recording time) were combined into a global psychoacoustic annoyance (PA) metric following the model outlined by Zwicker [29]. All SQMs and the PA metric were calculated using the open-source MATLAB Sound Quality Analysis Toolbox (SQAT) v1.2 [6], [7], which is available on GitHub[1].

4.2 Analysis Method

The differences between the measured wind turbine noise recordings and the auralised sound samples are quantified in terms of the differences of the analysed metric under consideration. These differences are analysed against the estimated A-weighted signal to noise ratio SNR_A. The SNR_A for each sample is estimated with the synthetic wind turbine noise auralisations and the corresponding background noise sample. In general, the cases with road background noise present relatively low (and even negative) SNR_A, whereas the cases with fjord background noise, the SNR_A is generally higher than 10 dBA.

The difference, per metric, between simulation and recording are quantified with and without background noise added to the synthetic wind turbine noise signals. For each case, both least-squares models in Equation 2 and Equation 3 are fitted to the data:

[1]Available online: `https://github.com/ggrecow/sqat`

$$\Delta\text{metric} = \begin{cases} \left(x_{1,\text{fjord}} + \Delta x_1\right) \cdot \text{SNR}_\text{A} + x_{2,\text{fjord}} + \Delta x_2 & \text{if road} \\ x_{1,\text{fjord}} \cdot \text{SNR}_\text{A} + x_{2,\text{fjord}} & \text{if fjord} \end{cases} \tag{2}$$

$$\Delta\text{metric} = \begin{cases} x_{1,\text{road}} \cdot \text{SNR}_\text{A} + x_{2,\text{road}} & \text{if road} \\ \left(x_{1,\text{road}} - \Delta x_1\right) \cdot \text{SNR}_\text{A} + x_{2,\text{road}} - \Delta x_2 & \text{if fjord} \end{cases} \tag{3}$$

While both models give identical results, they are fitted to determine the p-values and confidence intervals of the slopes and intercepts for the road and fjord BGN separately.

4.3 Psychoacoustic Annoyance

The differences in the mean psychoacoustic annoyance between the measurements and simulations are analysed in terms of $\Delta 10 \cdot \log_{10}(10 \cdot \text{PA}_\text{mean})$. The base 10 logarithm of the PA metric is used, as it typically shows a better fit with listening experiment data [13], [30]. Figure 2 shows that the auralisations without added background noise have a similar slope with respect to the SNR_A for both the road and fjord background cases. The samples with added BGN show a significantly different trend between the two BGN conditions. It is expected that differences in annoyance get masked by the ambient noise at lower SNR_A values, which is reflected by the insignificant slope for the road BGN case for low SNR_A.

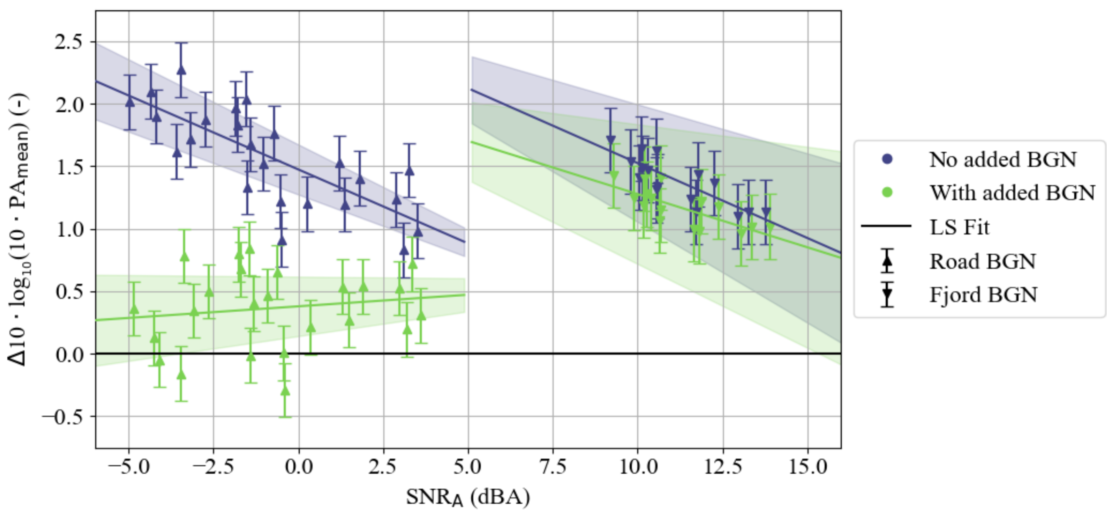

Figure 2 Difference in the mean PA metric between the experimental recording and synthetic auralisation, with and without added background noise, as a function of the A-weighted signal-to-noise ratio (SNR_A). Mean difference values and their least-squares estimated standard errors are shown per measurement sample.

For the road case, adding BGN to the auralized sounds make their differences with respect to the experimental data considerably smaller (closer to the $y = 0$ line). However, for the evaluation of auralised wind turbine noise, the behaviour observed for the cases without added background noise is more desirable, since a constant relation with SNR_A in different BGN conditions can be more easily compensated for than a background-noise-dependent relation with SNR_A. The coefficients of the least-squares model are shown in Table 4. Without added background noise, the slope of the difference with SNR is essentially constant, with only an offset in the intercept between the two BGN conditions. For the cases with added BGN, on the other hand, the intercept offset remains similar, while the slope with SNR_A becomes significantly different between the road and fjord ambient noise.

Table 4 Least-squares regression coefficients of Equation 2 and Equation 3 for the differences in the PA metric between recording and simulation. All p-values are ≪ 0.05, except for the underlined coefficients.

BGN Condition	Slope (x_1) Road	Slope (x_1) Fjord	Slope (x_1) Δ	Intercept (x_2) Road	Intercept (x_2) Fjord	Intercept (x_2) Δ	Adjusted R^2
No added BGN	−0.118	−0.120	<u>0.002</u>	0.880	2.120	1.240	0.570
With added BGN	<u>0.019</u>	−0.085	0.104	0.472	1.702	1.230	0.692

4.4 Loudness Level

The difference in mean loudness levels $L_{N,mean}$ between the recorded and synthesised noise in Figure 3 shows a similar behavior as the PA metric. Previous findings with this dataset [10], [31] showed that the loudness results of the NTK wind turbine noise had a dominant influence on the PA metric.

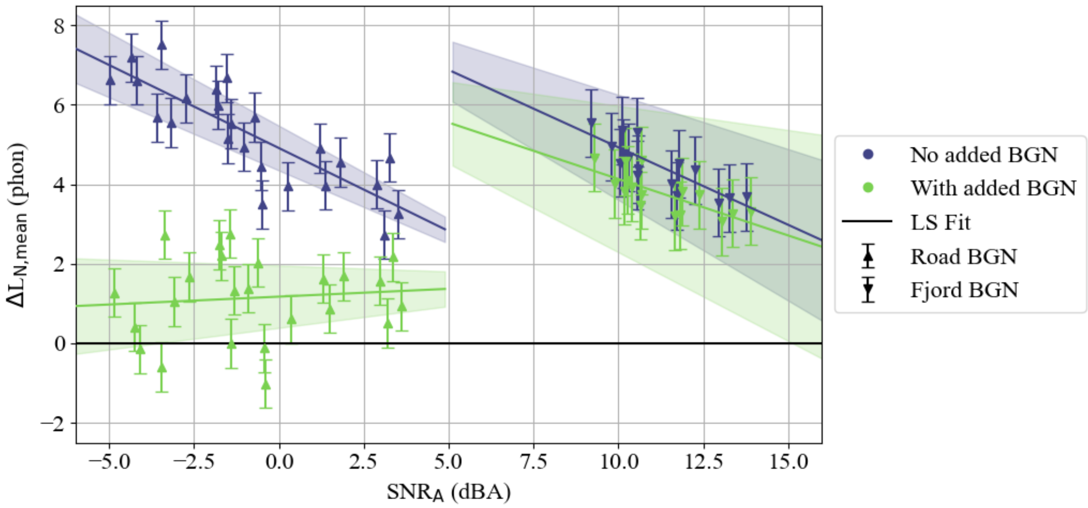

Figure 3 Difference in the mean loudness level $L_{N,mean}$ between the experimental recording and synthetic auralisation, with and without added background noise, as a function of the A-weighted signal-to-noise ratio (SNR_A). Mean difference values and their least-squares estimated standard errors are shown per measurement sample.

The coefficients in Table 5 confirm the observations from Figure 3. Once more, the slope with respect to SNR_A is similar between the road and fjord BGN when no ambient noise is added to the simulations. The slope is significantly different between these two BGN conditions when the background noise is added to the simulations. The change in intercept between these two cases is again similar and independent of adding ambient noise to the simulated noise sample.

Table 5 Least-squares regression coefficients of Equation 2 and Equation 3, for the differences in the loudness level $L_{N,mean}$ between recording and simulation. All p-values are ≪ 0.05, except for the underlined coefficients.

BGN Condition	Slope (x_1) Road	Slope (x_1) Fjord	Slope (x_1) Δ	Intercept (x_2) Road	Intercept (x_2) Fjord	Intercept (x_2) Δ	Adjusted R^2
No added BGN	−0.418	−0.390	<u>0.028</u>	2.821	6.874	4.054	0.689
With added BGN	<u>0.040</u>	−0.284	0.323	1.369	5.550	4.180	0.687

4.5 Roughness

The differences in mean roughness between the measurements and auralisations are plotted in function of the signal-to-noise ratio in Figure 4. The mean roughness metric is converted to a log-scale as $10 \cdot \log_{10}(10 \cdot R_{mean})$ before taking the difference, as it was done for the PA metric. In the preliminary analysis, this logarithmic conversion resulted in better p-values and adjusted R^2 values.

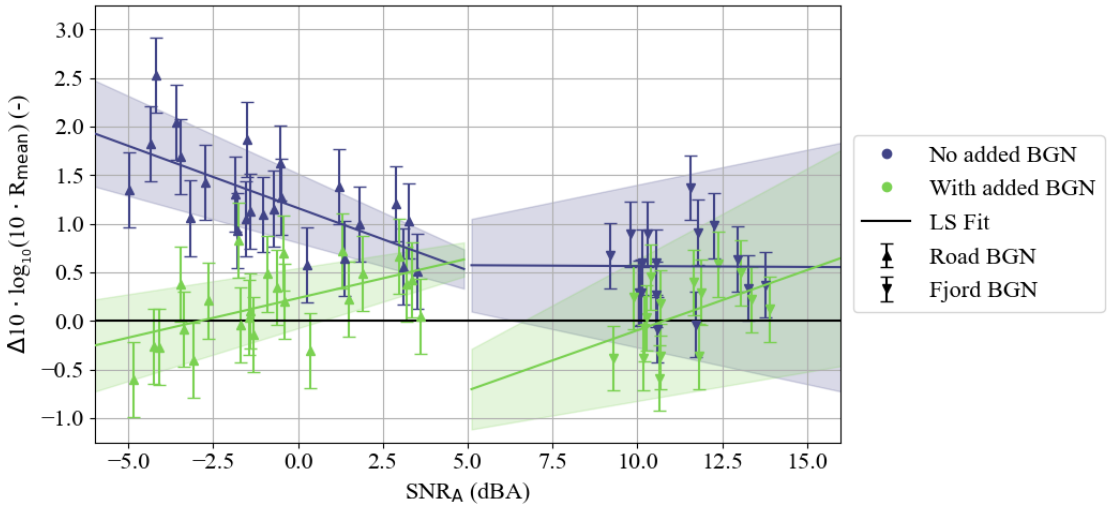

Figure 4 Difference in the mean roughness between the experimental recording and synthetic auralisation, with and without added background noise, as a function of the A-weighted signal-to-noise ratio (SNR_A). Mean difference values and their least-squares estimated standard errors are shown per measurement sample.

Roughness shows a very different behaviour to loudness and PA. In the roughness differences, the addition of background noise to the simulations results in a similar slope with respect to SNR_A between the two types of background noise, which the coefficients in Table 6 confirm. Adding no background noise, on the other hand, results in a different slope between the road and fjord noise. The analysis of the roughness differences should only be considered indicative since the adjusted coefficients of determination for the least-squares fits are very low. Especially for high SNR_A, the spread in the data points in Figure 4 is very large, which is reflected by the large confidence intervals of the least-squares functions.

Table 6 Least-squares regression coefficients of Equation 2 and Equation 3, for the differences in roughness R_{mean} between recording and simulation. All p-values are $\ll 0.05$, except for the underlined coefficients.

	Slope (x_1)			Intercept (x_2)			
BGN Condition	Road	Fjord	Δ	Road	Fjord	Δ	Adjusted R^2
No added BGN	−0.128	−0.002	0.126	0.520	0.573	0.053	0.507
With added BGN	0.081	0.124	0.043	0.641	−0.716	1.357	0.169

5. Conclusions

Ambient noise is an important factor in the investigation of the perceived annoyance due to wind turbine noise. This exploratory work presented acoustic measurements and auralised simulations to investigate two proposed methods for dealing with ambient noise in sound quality metric assessments. The first method involves adding representative background noise to the simulations, whereas the second method consists of using measurements with low BGN as ground truth instead of adding ambient noise to the simulations.

Based on the presented results, it can be recommended not to add background noise to auralised wind turbine noise signals and, instead, to use experimental recordings with high A-weighted signal-to-noise ratios (i.e. with low background noise) as a ground truth. When investigating loudness-based metrics and the overall PA metric, a consistent relation between the difference in metrics between simulated and recorded noise and the SNR_A is observed. At high SNR_A, the addition of background noise has little effect on the perceived differences.

For modulation-based metrics, such as roughness, the presented data gives no clear indication of which method for handling ambient noise results in the most desirable result. The results seem to indicate that the addition of ambient noise may be required to obtain consistent results for modulation-based metrics, such as roughness and fluctuation strength.

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