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Wind Turbine Noise Propagation over Flat Ground: Measurements and Predictions

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Summary
Noise from wind turbines is of concern in the planning process of new wind farms, and accurate estimations of immission noise levels at residents nearby are required. Sound propagation from wind turbine to receiver could be modelled by a simplified standard model assuming constant meteorological conditions, by an engineering method taking atmospheric and ground propagation conditions into account, or by a more exact model. Epidemiological studies have found a higher frequency of annoyance due to wind turbine noise than to other community noise sources at equal noise levels, indicating that the often used simplified model is not sufficient. This paper evaluates the variation of immission sound levels under the influence of meteorological variation and explores if the prediction of levels could be improved by taking the effect of wind speed on sound propagation into account. Long-term sound recordings and measurements at a distance of 530 m from a wind turbine show that the simplified standard model predicts the average sound pressure levels satisfactorily under downwind conditions, and that a more complex propagation model might not be needed for wind turbine noise at a relatively short distance. Large variations of sound immission levels at the same wind speed were however present. Statistical analysis revealed that these variations were influenced by meteorological parameters, such as temperature, static pressure and deviation from ideal downwind direction. The overall results indicate that meteorological factors influence the noise generated by the wind turbine rather than the sound propagation.

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1. Introduction

Developments of large wind farms are often opposed by the public. Wind turbine noise became an issue with the erection of wind turbines with down-wind rotors. These down-wind turbines generated a “thumping noise” with a considerable proportion of low frequencies [1]. With the next generation of wind turbines and with the rotor placed up-wind, the problem of low frequency noise was solved; however, mechanical noise from the gearbox, often comprising tones, became a new source of disturbance [2]. The main issue of modern wind turbines is the aerodynamic noise produced by the airflow around the rotor blades. The noise is amplitude modulated with a frequency corresponding to the time period of each rotor blade passing the tower – for large turbines typically in the range of 1 to 1.5 Hz. Most people describe the noise as swishing and pulsating [3].

The regulation for the planning process of wind turbines requires an estimation of the noise that will be received by people living nearby, i.e. the immission sound level. As field measurements of immission levels are difficult and time consuming, the need for good propagation models was early recognized. Large efforts have been made to ensure that the models predict the immission levels at nearby residents with an acceptable accuracy. In the work by Bass *et al.* [4], different engineering prediction tools for wind turbine noise were surveyed and evaluated in comparison with measurements. The method that was concluded to be the most preferable, called the IEA model, is quite similar to the one of the Swedish standard [5]. The uncertainty due to the sound propagation is estimated to be about 2 dB(A) (stated to not be exceeded 85% of the time) for typical wind turbine noise propagation conditions at wind speeds of about 8 m/s and propagation ranges of about 1000 m [4]. However, as also stated, the variability of the source output power adds to the uncertainty.

The method according to Swedish standard for wind turbine noise propagation over land models the effect of

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Figure 1. Measurement wagon and wind turbines.

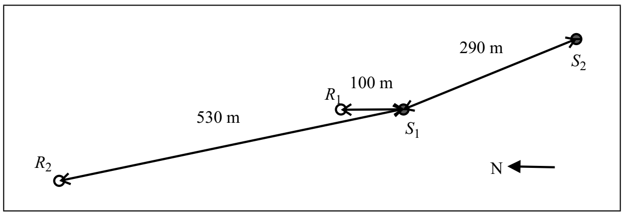

Figure 2. Measurement site; S_1 = measured wind turbine, S_2 = additional wind turbine, R_1 = location of emission measurements; R_2 = location of immission measurements.

air attenuation assuming constant meteorological conditions and the ground effect as a simplified ground-type independent addition to the sound level. Furthermore, the method does not model any variation of refraction, i.e. curved sound paths due to wind speed profile or temperature gradient. However, for long distance and strong wind, refraction in downwind sound propagation situations is expected to lead to strong focussing and increased sound levels near to the ground. More recent engineering methods for community noise, like Nord2000 [6] and Harmonoise [7], model atmospheric and ground propagation conditions in more detail. For instance, refraction effects are modelled using a linear approximation of the sound speed profile. For more exact modelling of e.g. a logarithmic wind speed profile, the parabolic equation (PE) method or the fast field program (FFP) is applicable (e.g. [8]). For further complicated propagation conditions, e.g. with complex terrain variations, finite-difference time-domain methods (FDTD) could be used (e.g. [9]), at an additionally increased computational cost. In this paper we have used the PE method in addition to the one of the Swedish standard, as an example of a simplified method, and the Nord2000, as an example of an engineering method.

The interest for sound propagation of wind turbine noise has been revived with the results of epidemiological studies suggesting that annoyance from wind turbine noise may be higher than noise annoyance reported from other community noise sources at equal noise levels [3, 10, 11]. Factors not related to the noise such as the visibility of the turbines (increasing annoyance) [12] and economical benefits (reducing annoyance) [11] have been found to influence the response. However, it could not be excluded that the comparatively high annoyance could be due to a poor correlation between the calculated immission sound levels and the actual sound level or sound characteristics reaching the respondents. Some support for these statements can be found from the results of long term measurements carried out at a distance of 400 m and 1500 m from a wind turbine park in Germany [13]. That study showed that the hub height wind speed at night deviated considerably from what could be expected from the wind profile valid during daytime, resulting in comparatively higher noise levels than were expected, which was also linked with changes in temperature gradient. Furthermore, the high rotational speed at night time generated a "thumping" impulsive noise that increased the annoyance. These findings are of special concern as the height of wind turbine towers currently erected commonly exceeds 90 m.

Taken together, more knowledge is needed on immission levels of wind turbine sound, especially taking meteorological variance into account. The aim of the study presented here was to evaluate the variation of equivalent immission sound levels over time and to see if the variation could be explained by meteorological influences. A further aim was to explore if the prediction of the sound immission level was improved by taking the influence of wind speed on sound propagation into account.

2. Method

Measurements of noise from a wind turbine were undertaken 530 m from the turbine to resemble the situation of a resident living nearby (Figure 1). The measured results were compared with calculated immission levels. For these calculations, emission measurements of the wind turbine sound were carried out, as well as meteorological measurements. The measured immission levels were furthermore related to simultaneously obtained meteorological data in order to evaluate the impact of meteorological variations.

2.1. Measurement site

The measurements were carried out in the south of Sweden. The measurement site was a typical agricultural area with very few obstacles (trees, bushes, building). It comprised two identical three-bladed wind turbines: Enercon E66, with a rotor diameter of 70 m and a hub height of 65 m. These wind turbines have a nominal power of 1.8 MW, but are at this measurement site reduced to 1.5 MW to secure that the noise limit required by the authorities at nearby residents is not exceeded. The wind turbines were standing 290 m apart (Figure 2). The topography of the terrain for the nearest 2–3 km was flat. The ground was cultivated during the first days of immission measurements.

2.2. Emission measurements. Determining the acoustic power radiated by the source

Emission measurements were performed following as closely as possible the procedures in IEC 61400-11 [14], which defines a methodology for determining the A-weighted sound power level of a turbine as a function of wind speed. By this methodology, measurements are made at locations close to the machine to minimize the influence of propagation factors, while far enough away to allow for the finite size of the turbine. Following the standard, A-weighted and 1/3-octave band acoustic measurements of the source power were performed at ground level using a hard microphone board ($1.12 \times 1.25\,\mathrm{m}^2$) with the microphone off centre, at a location 100 m downwind of the turbine tower (Figure 2). Wind speed and direction were simultaneously measured at a standard height of 10 m at a location outside of the wake of the wind turbine. Acoustic and wind measurements were each averaged over synchronous one- minute periods, during both turbine-on and turbine-off conditions. The measurements were carried out at several occasions. The ranges of collected wind speeds were in total: 2–4, 7–8, and 10–15 m/s, of which the data for the mid-range wind speeds (7–8 m/s) were given from a previous measurement campaign. Because of the presence of a second wind turbine at the site, measurements were not performed when winds prevailed from the north (from the subject turbine towards the second turbine), in order to avoid acoustic measurement locations heavily influenced by noise from the second turbine. During the ambient (turbine-off) measurement periods required by the standard, both turbines were stopped.

Acoustic measurements were performed using a Brüel & Kjær type 2260 sound level meter located remotely from the measurement microphone using an extension cable. Calibration for the system was checked before and after each measurement session. In accordance with the standard, a 90 mm diameter hemispherical foam windscreen was applied to the microphone on the hard microphone board, and a secondary 400 mm diameter hemispherical windscreen (knit fabric on a wire frame) covered the foam windscreen and microphone [14]. The insertion loss of this dual-windscreen configuration was determined for random sound incidence in a reverberant chamber, and a corresponding correction was made to the measured data (around 1 dB(A) influence on wind turbine noise). Meteorological measurements were conducted using a Davis Weather Monitor II weather station with logging capability. For each 1-minute period, average wind speed, average wind direction, and peak wind speed were collected from the anemometer at 10 m height. Other meteorological conditions were measured at 1 m height (temperature, relative humidity and atmospheric pressure).

1/3-octave band sound pressure level spectra were energy-averaged from at least three measurement spectra at each integer wind speed. Figure 3 shows the averaged source spectrum at around 12 m/s wind speed (12–15 m/s). The total acoustic power of the source, in dB(A), is estimated from the measurements after correcting for the background noise. The background noise level is shown together with the source data in Figure 4, as function of wind speed. Source data at wind speed 7.7 m/s, which is a single point from a 30-minute average, are those given from a previous measurement campaign, also following the standard. (For the regression, this data point is given 30 times heavier weight than the remaining 1-minute measurements; see plot legend.) The A-weighted sound power was determined at each integer wind speed from a second-order polynomial curve fit to the sound pressure level versus wind speed data in accordance with the standard, of which data for the wind speed range 5–12 m/s are used in the predictions (Figure 5).

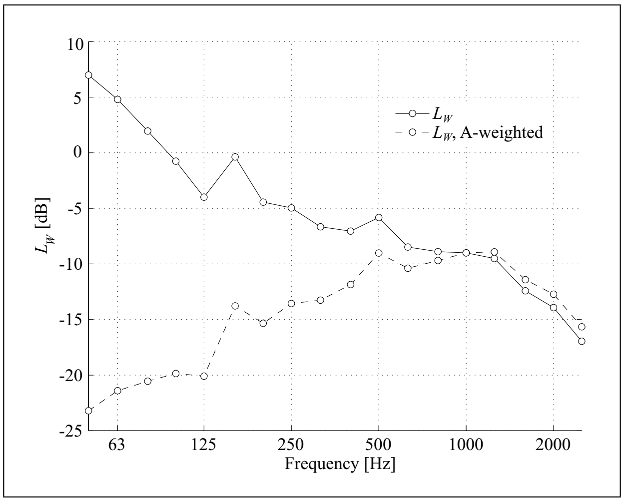

Figure 3. Source spectrum from emission measurement at wind speeds around 12 m/s (at 10 m height), shown both as A-weighted and unweighted level, normalized to 0 dB(A).

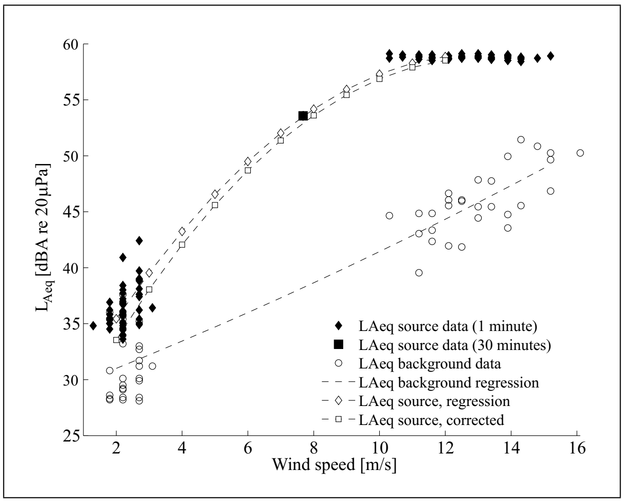

Figure 4. Measured source data and background as function of wind speed, shown together with their regression curves and the source data regression curve corrected for the background.

2.3. Immission measurement

The measurement set-up was situated on soft ground, at a distance of 530 m, north of the wind turbines (direction 345 degrees) (Figure 2). Immission measurements were

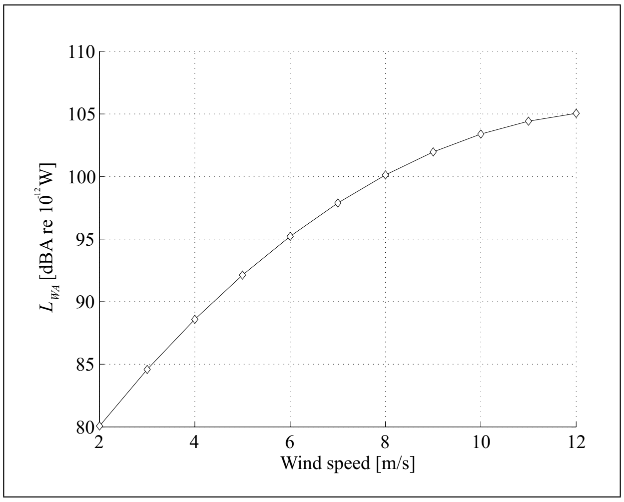

Figure 5. Measured wind turbine output power level as function of wind speed.

carried out by following as closely as possible the recommendations provided by the Expert IEA Group [15]. The acoustic data were recorded for 10 minutes every hour, 24 hours a day, for 30 days from November 16th to December15th 2005. A Matlab program started the recordings and saved the sound data as wave files. The wave files were acquired at a sampling frequency of 44.1 kHz.

The acoustical data were recorded using a microphone, mounted at the centre of a vertical wooden board of 1 m^2, which in turn was mounted on the side of a mobile measurement wagon (caravan). The microphone was positioned in a manner that the membrane plane was orthogonal to the board, 1.7 m above ground. It was equipped with a primary and secondary windscreen as for the emission measurements and the same insertion loss correction was made. The measured values of sound levels were in the analysis reduced by 6 dB due to pressure doubling.

The microphone used for the immission measurements was a Brüel & Kjær microphone 1/2-inch type 4165, coupled with a Brüel & Kjær preamplifier type 2669. Recordings were done for frequencies from 50 to 20000 Hz and the dynamic range was set to 6–96 dB. According to product data, the microphone has a flat response (variation less than 1 dB) for frequencies up to 10 kHz and the directivity amounts to less than 1.5 dB up to 6 kHz, for all angles of incidence, whereby no corrections were applied. Moreover, these effects were the same for all measurements. Before the measurements, the sensitivity at 1000 Hz was determined for the measurement chain set-up using a calibrator. The recorded signals were saved to give the calibration factor needed for post-processing the recorded data. The measurement chain was kept intact during the entire measurement series.

The ten, one minute long sound signal recordings during each ten-minute period were processed into A-weighted sound levels. The median value of the ten levels was used as an estimate of the equivalent A-weighted level for the ten-minute period. The measurements were corrected for the influence of the second plant, estimated to 1.5 dB(A). A background noise correction of the measured immission levels could not be made, because background levels were only obtained during the emission measurements, which turned out to be too high for a reasonable background noise correction of the measured immission levels. However, the immission measurements do likely contain much weaker background noise than the emission measurements. This is attributable to the measurement set-up with the vertical board on the caravan, which increases the signal-to-noise ratio by limiting the wind-induced noise while at the same time doubling the signal amplitude. By also listening through the signals, only keeping data where the wind turbine could be heard and discarding data where unwanted noise sources were identified, makes it reasonable to assume that the remaining background noise was sufficiently low to not corrupt the immission levels.

Data from the wind turbine (i.e. the wind speed at the hub height, the blades revolution per minute, rpm, and the output electric power) were made available by Vattenfall AB, and consisted of ten-minute averages. The start of the acoustic measurements was synchronized each hour with the hub meteorological data. In addition to those measurements, a measurement of temperature and relative humidity was made at the hub height and at the ground, using a Tinytag Plus RH.

For each ten-minute immission measurement, the wind speed at 10 m height was estimated from the measured wind speed at the hub (65 m height). The estimated relation between the wind speed at 10 m and at hub height was based on simultaneous data at the two heights from the emission measurements. Although the wind speed profile can change over time due to meteorological conditions, the estimated relation was used throughout the analysis as a reference situation. For the flat landscape of the measurement site and the daytime conditions of the emission measurements, it is reasonable to assume a set shape of the wind profile [13]. The resulting regression line and the data are shown in Figure 6.

2.4. Selection of data

Data for the analyses was chosen by listening to the one-minute sound signals. Data were included if (i) the wind turbine sound could be identified and if (ii) no contaminating sounds, i.e. sounds other than from the wind turbine or wind induced sounds, were heard. All data for wind speeds below 4.5 m/s were excluded since they generally showed a weak signal from the wind turbine in relation to other noises. For the immission measurements, the results for the downwind cases were investigated, with wind direction within 45° from the source-receiver line.

2.5. Calculations of immission levels

For many situations with sound propagation over long distances, there are significant effects of refraction, due to temperature variations with height or non-constant wind speed profiles. For downward refraction (for downwind sound propagation or positive temperature gradient), a significant focussing can occur near ground or water, which

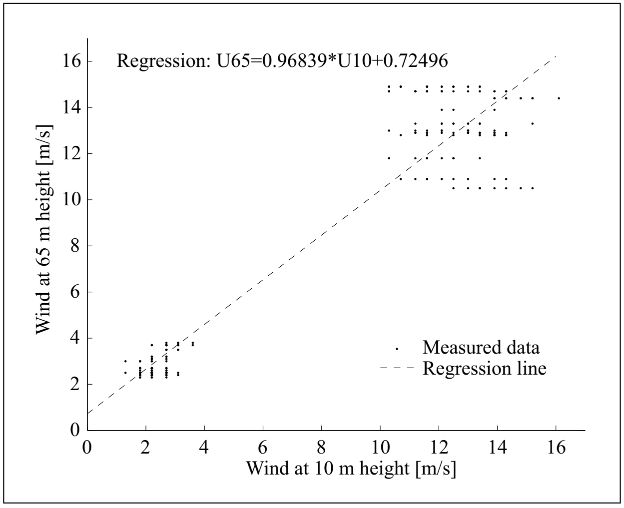

Figure 6. Simultaneously measured wind speeds near tower, at 10 m height and at 65 m height, shown together with regression line.

can be seen from a ray model viewpoint as arising from additional ground reflected sound paths. However, the geometry needs to be rather flat for significant focussing to occur, i.e. low source and receiver heights compared with the propagation range. For the comparatively steep geometry studied here there is no significant focussing at the wind speeds of 0–12 m/s at 10 m height. To substantiate this statement, test calculations were made using the PE method for varying wind speeds, keeping other propagation conditions constant. In addition, results were obtained from the Nord2000 method and the Swedish standard method. The possible effect on the sound propagation of a height-varying temperature was estimated to be even weaker.

The Swedish standard for wind turbine noise determines an assumed maximum value for the total, A-weighted sound pressure level. It corresponds to a case with a wind speed of 8 m/s at 10 m height. The standard distinguishes between propagation over land or water, and propagation over distances longer or shorter than 1000 m. For the current study, the standard noise assessment in dB(A) is

$$L_p(A) = L_W(A) - 8 - 20\log(r) - 0.005r, \qquad (1)$$

where $L_W(A)$ is the total, A-weighted source output power, and *r* is the direct distance from the wind turbine to the receiver point. The factor 0.005 is a damping term that takes into account the air attenuation and the losses due to the ground reflection.

The Parabolic Equation (PE) method is a numerical method for computing the sound field of a monopole source in a refracting atmosphere above a ground surface. For outdoor propagation, the PE method allows for a precise description of the atmosphere as both the sound speed and the ground impedance can vary along the propagation path. The PE method gives accurate results in a spatial region limited by a maximum elevation angle varying with implementation of the method. Here, the maximum elevation angle of the PE method is around 30 degrees, which means that it is applicable to the cases studied here. The PE method used for this study was a Crank-Nicholson implementation, similar to the one described in [16]. Calculations to attain the total, A-weighted sound pressure level were made using the 1/3-octave bands 50–2500 Hz with a resolution of three frequencies per band. The choice of using the resolution of three frequencies per band was made after test calculations with different resolutions, assuming zero wind speed and using the 1/3-octave band source spectrum. For a decreasing resolution, starting at 30 frequencies per band, the deviation stayed within 0.1 dB(A) to the chosen resolution of three frequencies per band; for the lower resolution of one frequency per band, the deviation increased significantly. The ground was characterized by the normalized ground impedance calculated with the Delany and Bazley empirical model, which is based on a single parameter: the effective flow resistivity, σ. The value of the effective flow resistivity was taken from a standard table. Our initial value was $\sigma = 250\,\mathrm{kNsm}^{-4}$, representative for *normal uncompacted ground* [6]. In order to study the possible variability due to either softer or harder ground (e.g. due to rough and less compacted ground, as caused by ploughing, or more compacted ground, possibly frozen or with a high water content) calculations were made also for other values of the flow resistivity: $\sigma = 63\,\mathrm{kNsm}^{-4}$ (*uncompacted, loose ground*), $\sigma = 630\,\mathrm{kNsm}^{-4}$ (*compacted field and gravel*) and $\sigma = 2000\,\mathrm{kNsm}^{-4}$ (*compacted dense ground*) [6]. The relatively hard ground described by $\sigma = 2000\,\mathrm{kNsm}^{-4}$ is assumed to be unlikely for the situation studied here. By using the source frequency spectrum from the emission measurements (Figure 3), the influence of a changing wind speed on the propagation and on the resulting A-weighted level could be studied using the PE method. The effect of air attenuation was inferred on the calculated separate frequency components, assuming average prevailing conditions of 5 °C temperature, 80% relative humidity and a static pressure around 1020 hPa. The calculations following to the Nord2000 method were made in a software called exSOUND2000 using the same input data as described above, with a $\sigma = 250\,\mathrm{kNsm}^{-4}$.

2.6. Statistical analysis

Associations between two variables were tested with Pearson's moment correlation (r). Multiple linear regression was used for testing the probability that one or several independent variables influenced one dependent variable, in this case sound immission level. The outcomes of the regression tests are presented with the coefficients of the variables in the function (B) and 95% confidence intervals (CI) of the coefficients, complemented with the p-value, i.e. the probability that an association was obtained when there was none. The adjusted R-square value (Adj R-square) for each regression, ranging from −1 to 1, shows the variance of the dependent variable that was explained by the independent variables. All tests were two-sided and a p-value below 0.05 was considered statistically significant.

3. Results

3.1. Comparisons of propagation models

The results of the calculated effect of the wind on sound propagation are displayed in Figure 7 as sound pressure level relative to free field (free field being without ground, wind and air attenuation). Four different results from the PE method are shown, for different flow resistivities, σ, of the ground. Comparing with the initial value of $\sigma = 250\,\mathrm{kNsm}^{-4}$, a deviation less than $\pm 0.7\,\mathrm{dB(A)}$ is found for $\sigma = 63$ and $630\,\mathrm{kNsm}^{-4}$. For the harder ground, $\sigma = 2000\,\mathrm{kNsm}^{-4}$, an additional deviation of the same size is found. For this particular case, the PE results for $\sigma = 250\,\mathrm{kNsm}^{-4}$ show a slightly lower level at zero wind speed compared with the results from the Swedish standard and the Nord2000 method. This also holds for the PE results for $\sigma = 63$ and $630\,\mathrm{kNsm}^{-4}$. With increasing wind speed, the PE results show a decreasing level with increasing wind speed, i.e. not a focussing effect. For the measurement conditions of wind speeds in the range 5–12 m/s, the predicted change by the PE method is small, around 1 dB. The calculated PE results are sensitive to the interference pattern between direct and ground reflected waves. When the wind speed increases, the interference pattern moves through the peak region of the A-weighted source spectrum. However, without including reduced coherence or smearing effects in the PE calculations, as due to turbulence, random ground roughness and the actual geometrically extended source, the results may not be repeated in real-life measured cases. An additional test where turbulence was included in the PE calculations indicated however that this would only give small changes to the resulting A-weighted levels. The results from the engineering method, Nord2000, which is less sensitive to input data related to the interference pattern, show a quite constant level over wind speeds. This further substantiates that no significant focussing due to downward refraction occurs for the studied case. The Swedish standard assumes no effect of wind variation on the sound propagation, whereby the corresponding result is constant over all wind speeds.

3.2. Description of selected measured values

The selected immission sound measurements ($n = 49$) ranged from 23.4 to 42.3 dB(A) and were obtained in wind speeds ranging from 4.6 to 11.8 m/s (Table I). Other meteorological data, from the same occasions as the selected measurements, showed small variation. All variables were approximately normal-distributed, except the temperature gradient which was strongly skewed with a right tail. Of the selected measurements, 17 were measured during daytime and 32 during night.

3.3. Relationship between measured and calculated immission levels at different wind speeds

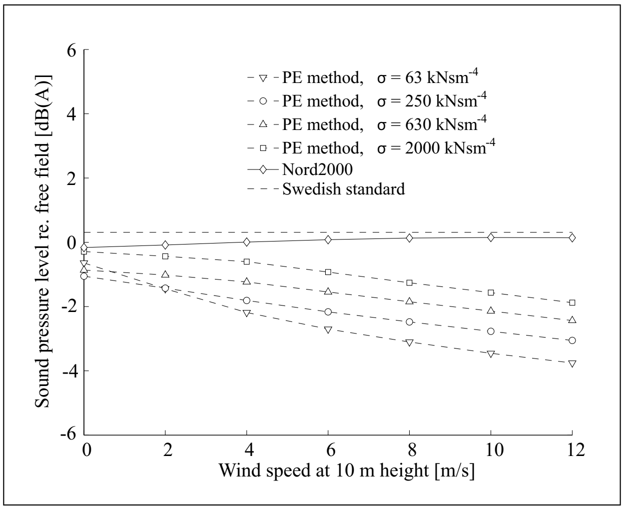

Figure 7. Results from calculating the effect of wind on the sound propagation using the PE method and the Nord2000 method, shown as A-weighted level relative to free field. For the PE method four different grounds have been modelled corresponding to different σ-values. The same source spectrum (as shown in Figure 3) is assumed for all wind speeds. The corresponding result according to the Swedish standard is independent on wind speed and is shown as a constant level.

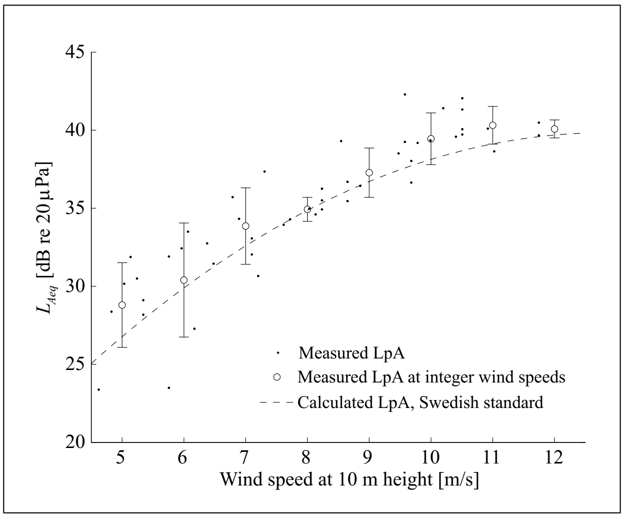

Figure 8. Measured immission levels for downwind cases and calculations according to Swedish standard. Measured levels grouped to integer wind speeds are shown as mean value and standard deviation.

The measured immission levels, as well as the calculated levels using the Swedish standard, are plotted against the wind speed in Figure 8. The agreement is fairly good between the calculated values and the mean values from grouping the measured levels to integer wind speeds, and the differences lie within one standard deviation of the measured values. There was, however, a rather large variation in the measured values at each wind speed, displaying a standard deviation of about 2 dB on average. Listening to the recordings also showed that the wind turbine could be heard also at relatively high wind speeds, up to 12 m/s. Concluding from the calculations using the PE method, the variability of the measurements cannot fully be explained by possible changes in ground conditions, e.g. due to tem-

Table I. Description of the selected immission sound measurements and meteorological data ($n = 49$).

	Mean	SD	Min	Max
A-weighted sound pressure level	35.2	4.67	23.4	42.3
Wind speed (m/s)	8.1	2.03	4.6	11.8
Static pressure at measurement wagon (Pa)	1004.2	10.58	986.0	1028.0
Temperature at hub height (degree C)	2.97	1.15	0.54	4.78
Temperature at measurement wagon, 2 m (degree C)	2.65	1.65	-0.9	5.1
Temperature gradient at WT (degree C)	-0.006	0.0088	-0.020	0.030
Deviation from ideal downwind direction (degree)	25.6	13.71	0.0	45.0

perature and water content. In addition, the variability in air attenuation due to changes in temperature, relative humidity and static pressure was for the prevailing conditions calculated to account for a maximum deviation of only ±0.2 dB(A).

3.4. Difference in measured immission levels at different meteorological situations

The variation in sound levels at a given wind speed were further explored in a series of regression models. The relationship between wind speed at 10 m height and the A-weighted sound pressure level were first modelled as a polynomial of second degree consistent with the relationship depicted in Figure 8 (Table II). The influence of a change in wind direction was studied by entering a variable describing the deviation from an ideal downwind direction in Model 1 (Table II). The influence of the wind speed on the A-weighted sound pressure level remained, but there was also a statistically significant influence of the wind direction. A larger deviation of wind direction lowered the A-weighted sound pressure level given a certain wind speed.

The influence of meteorological variables other than wind speed was tested by entering three variables into the base model: static air pressure, temperature and an indicator of inverse temperature gradient. The latter was derived by comparing the temperature at the hub of the wind turbine with that of the ground and dichotomizing the measurements into those undertaken when the temperature at hub was higher than that at ground (inverse temperature gradient indicating stable atmosphere) and the rest (standard situation). Twelve of the 49 selected measurements were classified as stable. Of these, 3 were recorded during daytime and 9 during night time. The difference in prevalence of the two types of atmospheres at day versus night could not be statistically verified. An inverse temperature situation, higher temperature and lower static pressure were more strongly associated with higher A-weighted sound pressure levels than a standard situation (Table II, Model 2). No differences between day and night were found when the binary variable day/night was entered into the model, despite leaving the other variables in the model or taking them out (data not shown). Also, the relative humidity did not show any influence on the variation of sound levels in any of the models (data not shown). In this study, deviation from ideal downwind direction was not, as expected, independent of all the other meteorological variables but correlated with static pressure ($r = 0.395$, $p < 0.01$). It was therefore not possible to test wind direction simultaneously with other meteorological variables in the same model.

4. Discussion

The standard model of sound propagation predicted the measured immission sound levels of wind turbine noise within one standard deviation at a distance of approximately 530 m at downwind conditions, hence it can be concluded that the standard model performed satisfactorily. The variation of sound pressure levels within an integer wind speed was however large. It was concluded from calculations, using the parabolic equation method and an implementation of the Nord2000 method, that the influence of wind speed on the sound propagation, as the strongest influencing parameter, was small, probably due to the height of the source and rather short propagation range studied here. However, the wind strongly affects the source strength. Statistical modelling, though, showed that meteorological parameters other than wind speed could explain part of the variance in sound immission levels. Of those, the most interesting was the influence of the temperature gradient. A positive temperature gradient is an indication of a stable atmosphere, mostly occurring at night time. In conditions of stable atmosphere it has previously been found that both sound pressure levels and levels of amplitude modulations may be considerably higher at the immission point [13]. Further studies of the prevalence of occurrence of this condition and its relation to human response would be valuable. The statistical modelling also showed an influence of wind direction on sound immission level. This is in accordance with previous studies on the source directivity of wind turbines [17], which show a directivity pattern with a maximum at downwind (or upwind) direction even though the deviation is minor within 45° from the source-receiver line.

To summarize, the average measured immission levels were predicted with satisfactory accuracy using the standard method, and the prediction was not improved by taking meteorological influence on sound propagation into account. As meteorological factors were associated with variations in measured immission levels, their relative importance for noise generated at the wind turbine need to be furthered assessed.

Table II. Regression models with the dependent variable A-weighted sound pressure level. For each model, all variables were entered simultaneously. $^{a)}$: Variable coefficient. $^{b)}$: 95% confidence intervals for the coefficient. $^{c)}$: Probability to obtain an association when there is none. $^{d)}$: Adjusted R-square describing the variance in sound pressure level that is explained by the variance of the variables in the model.

	B$^{a)}$ (95% CI$^{b)}$)	p-value$^{c)}$
Base model (Adj R-square$^{d)}$: 0.81; $p < 0.001$)		
Wind speed (m/s)	4.72 (2.13 to 7.31)	<0.001
Square wind speed (m^2/s^2)	-0.17 (-0.32 to -0.07)	<0.05
Model 1 (Adj R-square$^{d)}$): 0.85; $p < 0.001$)		
Wind speed (m/s)	4.85 (2.56 to 7.14)	<0.001
Square wind speed (m^2/s^2)	-0.18 (-0.32 to -0.04)	<0.05
Deviation from ideal downwind direction (degrees)	-0.07 (-0.11 to -0.03)	<0.001
Model 2 (Adj R-square$^{d)}$): 0.84; $p < 0.001$)		
Wind speed (m/s)	4.25 (1.71 to 6.78)	<0.01
Square wind speed (m^2/s^2)	-0.16 (-0.31 to -0.01)	<0.05
Static pressure at measurement wagon (Pa)	-0.14 (-0.24 to -0.04)	<0.01
Temperature at hub height (degrees C)	0.88 (0.14 to 1.63)	<0.05
Temperature gradient at WT (standard/inverse)	1.98 (0.40 to 3.55)	<0.05

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