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Effects of the wind profile at night on wind turbine sound

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Abstract

Since the start of the operation of a 30 MW, 17 turbine wind park, residents living 500 m and more from the park have reacted strongly to the noise; residents up to 1900 m distance expressed annoyance. To assess actual sound immission, long term measurements (a total of over 400 night hours in 4 months) have been performed at 400 and 1500 m from the park. In the original sound assessment a fixed relation between wind speed at reference height (10 m) and hub height (98 m) had been used. However, measurements show that the wind speed at hub height at night is up to 2.6 times higher than expected, causing a higher rotational speed of the wind turbines and consequentially up to 15 dB higher sound levels, relative to the same reference wind speed in daytime. Moreover, especially at high rotational speeds the turbines produce a 'thumping', impulsive sound, increasing annoyance further. It is concluded that prediction of noise immission at night from (tall) wind turbines is underestimated when measurement data are used (implicitly) assuming a wind profile valid in daytime.

1. Introduction

In Germany several wind turbine parks have been and are being established in sparsely populated areas near the Dutch border. One of these is the Rhede Wind Park in northwestern Germany with seventeen 1.8 MW turbines of 98 m hub height and with 3-blade propellers of 35 m wing length. The turbines have a variable speed increasing with wind speed, starting with 10 r.p.m. (revolutions per minute) at a wind speed of 2.5 m/s at hub height up to 22 r.p.m. at wind speeds of 12 m/s and over.

At the Dutch side of the border is a residential area along the Oude Laan and Veendijk (see Fig. 1) in De Lethe: countryside dwellings surrounded by trees and agricultural fields. The dwelling nearest to the wind park is some 500 m west of the nearest wind turbine (W 16).

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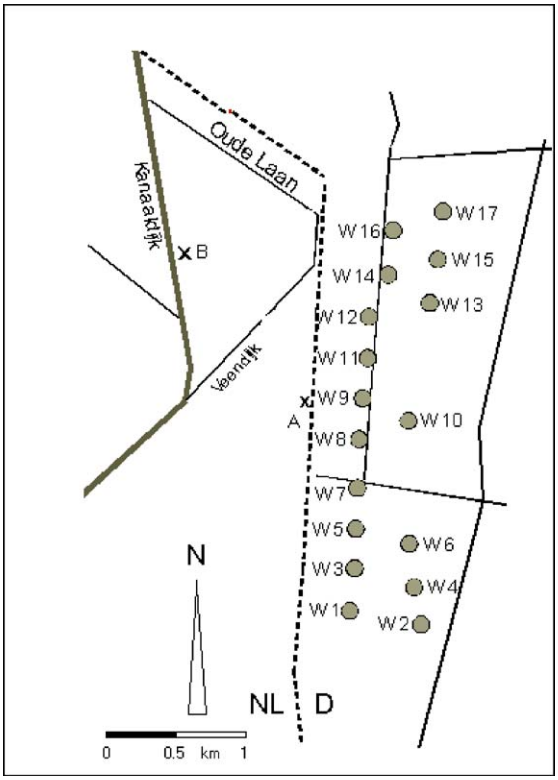

Fig. 1. Location of wind turbines (W_{nn}) and immission measurements (A and B) near the Dutch/German (NL/D) border.

According to a German noise assessment study a maximum immission level of 43 dB(A) was expected, 2 dB below the applied German noise limit. According to a Dutch consultancy immission levels would comply with Dutch (wind speed dependent) noise limits.

After the park was put into operation residents made complaints about the noise, especially at (late) evening and night-time. The residents, united in a neighbourhood group, could not persuade the German operator to put in place mitigation measures or to carry out an investigation of the noise problem and brought the case to court. The Science Shop for Physics had just released a report explaining a possible discrepancy between the calculated and the actual sound immission levels of the wind turbines because of changes in wind profile, and was asked to investigate the consequences of this discrepancy by sound measurements. Although at first the operator agreed to supply measurement data from the wind turbines (such as power output, rotation speed, axle direction), this was withdrawn after the measurements had started. All relevant data therefore had to be supplied or deduced from the author's own measurements.

2. Noise impact assessment

In the Netherlands and Germany noise impact on dwellings near a wind turbine or wind turbine park is calculated with a sound propagation model. Wind turbine sound power levels L_W are used as input for the model, based on measured or estimated data. In Germany a single 'maximum' sound power level (at 95% of maximum electric power) is used to assess sound impact. In the Netherlands sound power levels related to wind speeds at 10 m height are used; the resulting sound immission levels are compared to wind speed-dependent noise limits. Implicitly this assessment is based on measurements in daytime and does not take into account atmospheric conditions affecting the wind profile, especially at night.

In the Netherlands a national calculation model is used [1] to assess noise impact, as is the case in Germany [2]. According to Kerkers [3] there are, at least in the case of these wind turbines, no significant differences between both models.

In both sound propagation models the sound immission level L_{imm} at a specific observation point is a summation over j sound power octave band levels L_{Wj} of k sources (turbines), reduced with attenuation factors $D_{j,k}$:

$$L_{imm} = 10\log\left[\sum_j \sum_k 10^{(L_{Wj}-D_{j,k})/10}\right], \tag{1}$$

where L_{Wj}, assumed to be identical for all k turbines, is a function of rotational speed. $D_{j,k}$ is the attenuation due to geometrical spreading (D_{geo}), air absorption (D_{air}) and ground absorption (D_{ground}): $D_{j,k} = D_{geo} + D_{air} + D_{ground}$.

Eq. (1) is valid for a downwind situation. For long-term assessment purposes a meteorological correction factor is applied to (1) to account for an 'average atmosphere'. When comparing calculated and measured sound immission levels in this study no such meteo-correction is applied.

3. Wind turbines noise perception

There is a distinct audible difference between the night and daytime wind turbine sound at some distance from the turbines. On a summer's day in a moderate or even strong wind the turbines may only be heard within a few hundred metres and one might wonder why residents should complain of the sound produced by the wind park. However, on quiet nights the wind park can be heard at distances of up to several kilometres when the turbines rotate at high speed. On these nights, certainly at distances between 500 and 1000 m from the wind park, one can hear a low pitched thumping sound with a repetition rate of about once a second (coinciding with the frequency of blades passing a turbine mast), not unlike distant pile driving, superimposed on a constant broadband 'noisy' sound. A resident living at 1.5 km from the wind park describes the sound as 'an endless train'. In daytime these pulses are not clearly audible and the sound is less intrusive or even inaudible (especially in strong winds because of the then high ambient sound level).

In the wind park the turbines are audible for most of the (day and night) time, but the thumping is not evident, although a 'swishing' sound—a regular variation in sound level caused by the pressure variation when a blade passes a turbine mast—is readily discernible. Sometimes a rumbling sound can be heard, but it is difficult to assign it, by ear, to a specific turbine or to assess its direction.

4. Stability-dependent wind profiles

Usually a fixed relation is assumed between the wind speed v_h at height h and the wind speed v_{ref} at a reference height h_{ref} (usually 10 m), which is the widely used logarithmic wind profile with surface roughness z as the only parameter. See for example the international recommendations for wind turbine noise emission measurements [4,5]. For height h the wind speed v_h is calculated as follows:

$$v_h = v_{ref} \log(h/z)/\log(h_{ref}/z). \tag{2}$$

This equation is an approximation of the wind profile in the turbulent boundary layer of a neutral atmosphere, when the air is mixed by turbulence resulting from friction with the surface of the earth. During daytime thermal turbulence is added, especially when the heating of the earth surface by the sun is significant. At night-time a neutral atmosphere, characterized by the adiabatic temperature gradient, occurs under heavy cloud and/or at relatively high wind speeds. When there is some clear sky and in the absence of strong winds the atmosphere becomes stable because of radiative cooling of the surface: the wind profile changes and can no longer be adequately described by Eq. (2). The effect of the change to a stable atmosphere is that, relative to a given wind speed at 10 m height in daytime, at night there is a higher wind speed at hub height and thus a higher turbine sound power level; also there is a lower wind speed below 10 m and thus less wind-induced sound in vegetation. According to measurements by Holtslag [6] in a non-neutral atmosphere (either stable or unstable) a correction must be added to the logarithmic terms in the wind profile according to Eq. (2):

$$v_h = v_{ref}[\log(h/z) - \Psi_m]/[\log(h_{ref}/z) - \Psi_m], \tag{3}$$

where $\Psi_m = \Psi_m(h/L)$ is a rather elaborate function of height h and Monin–Obukhov length L. L is a stability measure and is positive for a stable, negative for an unstable atmosphere; for a neutral atmosphere L is a large number, either positive or negative. For calculations of sound propagation in the atmosphere Kühner [7] proposes a simple equation used in the German Air Quality Guideline "TA-Luft" [8]:

$$v_h = v_{ref}(h/h_{ref})^m, \tag{4}$$

where m is a number that depends on stability.

Stability can be categorized in Pasquill classes that depend on observations of wind speed and cloud cover (see, e.g. Ref. [9]). They are usually referred to as classes A (very unstable) through F (very stable). In "TA-Luft" a closely related classification is given (again closely related, according to Kühner [7], to the international Turner classification). An overview of stability classes with the appropriate value of m is given in Table 1. In Fig. 2 wind profiles are given as measured by Holtslag [6], as well as wind profiles according to Eqs. (2) and (4).

According to long-term data from Eelde and Leeuwarden [10], two meteorological measurement sites of the KNMI (Royal Dutch Meteorological Institute) in the northern part of the Netherlands, a stable atmosphere (Pasquill classes E and F) at night occurs for a considerable proportion of night-time: 34% and 32%, respectively.

According to Eq. (2) the ratio of wind speed at hub height (98 m) to wind speed at reference height, over land with low vegetation ($z = 3$ cm), would be $f_{log} = v_{98}/v_{10} = 1.4$. According to

Table 1
Stability classes and factor m

Pasquill class	Name	Comparable stability class "TA-Luft" [8]	m
A	Very unstable	V	0.09
B	Moderately unstable	IV	0.20
C	Neutral	III2	0.22
D	Slightly stable	III1	0.28
E	Moderately stable	II	0.37
F	(Very) stable	I	0.41

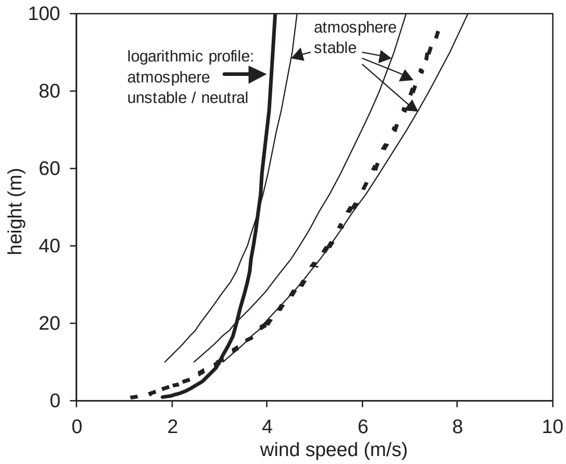

Fig. 2. Measured wind profiles (thin lines, [6]) and wind profile according to TA Luft (dotted line, [8]) in a stable atmosphere, and wind profile according to logarithmic model of formula 2 with $z = 3$ cm (bold line).

Eq. (4) and Table 1 this ratio would be 1.2 in a very unstable atmosphere and $f_{stable} = 2.5 = 1.8 f_{log}$ in a (very) stable atmosphere.

The fact that wind speeds at 10 m height may not be a good, unique predictor for hub height wind speeds has been put forward by Rudolphi [11]. He concluded from measurements that wind speed at 10 m height is not a good measure for wind turbine sound power: according to his measurements near a 58 m hub height wind turbine at night the turbine sound level was 5 dB higher than expected. This conclusion was not followed by a more thorough investigation.

The question addressed in this study is: what is the influence of the change in wind profile on the sound immission near (tall) wind turbines?

5. Measurement method

Sound immission measurements were made over 1435 hours, of which 417 hours were at night, within four months at two consecutive locations with an unmanned Sound and Weather

Measurement System (SWMS) consisting of a type 1 sound level meter with a microphone at 4.5 m height with a 9 cm diameter foam wind shield, and a wind meter at 10 m as well as at 2 m height. Every second, wind speed and wind direction (at 10 and 2 m height) and the A-weighted sound level were measured; the measured data are stored as statistical distributions over 5 min intervals. From these distributions all necessary wind data and sound levels can be calculated, such as average wind speed, median wind direction or equivalent sound level and any percentile (steps of 5%) wind speed, wind direction or sound level, in intervals of 5 min or multiples thereof.

Also complementary measurements were done with logging types 1 and 2 sound level meters and a type 1 spectrum analyzer to measure immission sound levels in the residential area over limited periods ([12], not reported here), and emission levels near the wind turbines. Emission levels were measured according to international standards [4,5], but for practical purposes the method could not be adhered to in detail; with respect to the recommended values a smaller reflecting board was used for the microphone ($30 \times 44\,\text{cm}^2$ instead of a 1 m diameter circular board) and a smaller distance to the turbine (equal to tower height instead of tower height + blade length); reasons for this are given in a separate paper [13]. Also it was not possible to carry out emission measurements with only one turbine in operation.

6. Results: sound emission

Emission levels L_{eq} measured very close to the centre of a horizontal, flat board at a distance R from a turbine hub can be converted to a turbine sound power level L_W [4,5]:

$$L_W = L_{eq} - 6 + 10\log(4\pi R^2). \tag{5}$$

From earlier measurements [3] a wind speed dependence of L_W was established as given in Table 2. As explained above, the wind speed at 10 m height is not considered a reliable single measure for the turbine sound power. Rotational speed is a better measure.

Emission levels have been measured, typically for 5 min per measurement, at nine turbines on seven different days with different wind conditions. The results are plotted in Fig. 3; the sound power level is plotted as a function of rotational speed N. N is proportional to wind speed at hub height and could be determined by counting, typically during 1 min, blades passing the turbine mast. This counting procedure is not very accurate (accuracy per measurement is $\leqslant 2$ counts, corresponding to 2/3 r.p.m.) and is probably the dominant reason for the spread in Fig. 3. The best logarithmic fit to the data points in Fig. 3 is

$$L_W = 67.1\log(N) + 15.4\,\text{dB(A)} \tag{6}$$

with a correlation coefficient of 0.98. The standard deviation of measurement values with respect to this fit is 1.0 dB.

Table 2
Sound power level of wind turbines [3]

Wind speed v_{10}	m/s	5	6	7	8	9	10
Sound power level L_W	dB(A)	94	96	98	101	102	103

At the specification extremes of 10 and 22 r.p.m. the (individual) wind turbine sound power level L_W is 82.8 and 105.7 dB(A), respectively.

In Table 3 earlier measurement results [3] are given for the octave band sound power spectrum. Also in Table 3 the results of this study are given: the logarithmic average of four different spectra at different rotational speeds. In all cases spectra are scaled, with Eq. (6), to the same sound power level of 103 dB(A).

To calculate sound immission levels at a specific rotational speed (or vice versa) the sound power level given in Eq. (6), and the spectral form in Table 3 ('this study') have been used.

7. Results: sound immission

The sound immission level has been measured with the unmanned SWMS on two locations. Between May 13 and June 22, 2002 it was placed amidst open fields with barren earth and later low vegetation 400 m west of the westernmost row of wind turbines (location A, see Fig. 1). This site was a few metres west of the Dutch–German border, visible as a ditch and a 1.5–2 m high dike. Between June 22 and September 13, 2002 the SWMS was placed on a lawn near a dwelling 1500 m

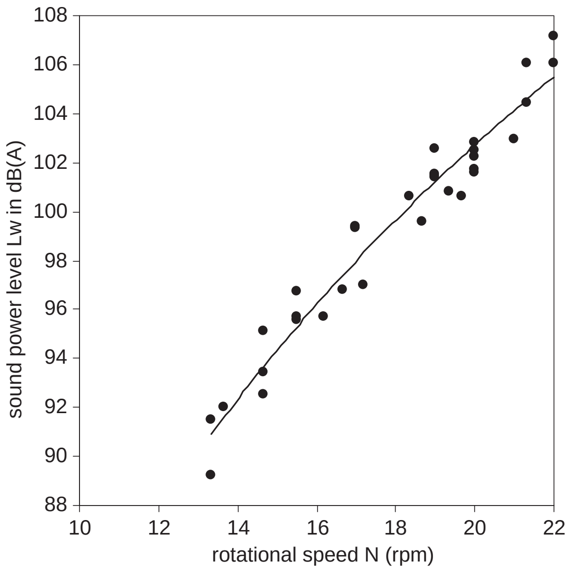

Fig. 3. Measured wind turbine sound power level L_W as a function of turbine rotational speed N.

Table 3
Octave band spectra of wind turbines at $L_W = 103$ dB(A)

Frequency	Hz	63	125	250	500	1000	2000	4000	L_W
This study	dB(A)	82	92	94	98	98	93	88	103
[3]	dB(A)	85	91	95	98	98	92	83	103

west of the westernmost row (location B), with both low and tall trees in the vicinity. On both locations there were no reflections of turbine sound towards the microphone, except via the ground, and no objects (such as trees) between the turbines and the microphone. Apart from possible wind induced sound in vegetation relevant sound sources are traffic on rather quiet roads, agricultural activities, and birds. As, because of the trees, the correct (potential) wind speed and direction could not be measured on location B, wind measurement data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A.

At times when the wind turbine sound is dominant, the sound level is relatively constant within 5 min intervals. In Fig. 4 this is demonstrated for two nights. Thus measurement intervals with dominant turbine sound could be selected with a criterion based on a low variation in sound level: $L_5 - L_{95} \leqslant 4$ dB, where L_5 and L_{95} are 5 and 95 percentile sound level. In a normal (Gaussian) distribution this would equal $\sigma \leqslant 1.2$ dB, with σ the standard deviation.

On location A, 400 m from the nearest turbine, the total measurement time was 371 h. For 25% of this time the wind turbine sound was dominant, predominantly at night (72% of all 105 nightly hours) and hardly during daytime (4% of 191 h) (see Table 4).

At location B, 1500 m from the nearest turbine, these percentages were almost halved, but the turbine sound remained dominant for over one-third of the time at night (38% of 312 h). The trend in percentages agrees with complaints mostly concerning noise in the (late) evening and at night and their being more strongly expressed by residents closer to the wind park.

In Fig. 5 the selected (i.e., with dominant wind turbine sound) 5 min equivalent immission sound levels $L_{eq,5\,\mathrm{min}}$ are plotted as a function of wind direction (left) and of wind speed (right) at 10 m height, for both location A (above) and B (below). It is not clear why the KNMI wind speed data (used for location B) cluster around integer values of the wind speed.

Also the wind speed at 10 and 2 m height at location A are plotted (in 5A and 5B, respectively), and the local wind speed (influenced by trees) at 10 m at location B (5C). The immission level data points are separated in two classes where the atmosphere was stable or neutral, according to

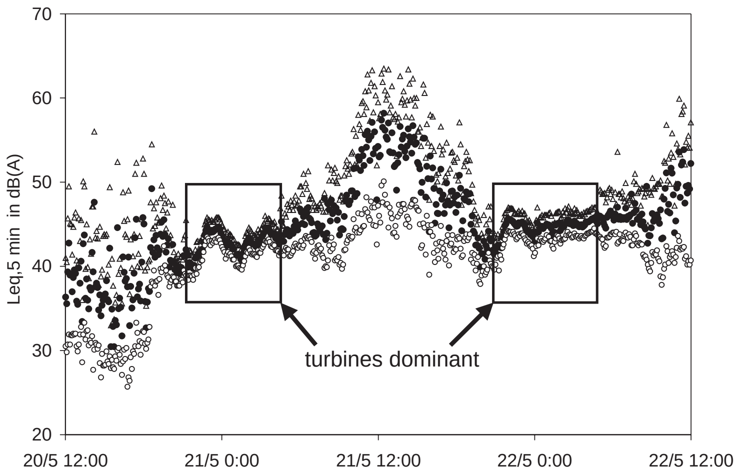

Fig. 4. 48 h registration of immission level ($L_5 = \triangle$; $L_{eq} = \bullet$; $L_{95} = \bigcirc$) per 5 min at location A; turbines are considered the dominant sound source if $L_5 - L_{95} \leqslant 4$ dB.

Table 4
Total measurement time in hours and selected time with dominant wind turbine sound

Location	Total time	Night 23:00–6:00	Evening 19:00–23:00	Day 6:00–19:00
A: Total	371	105	75	191
A: Selected	92	76	9	7
	25%	72%	12%	4%
B: Total	1064	312	183	569
B: Selected	136	119	13	4
	13%	38%	7%	0.7%

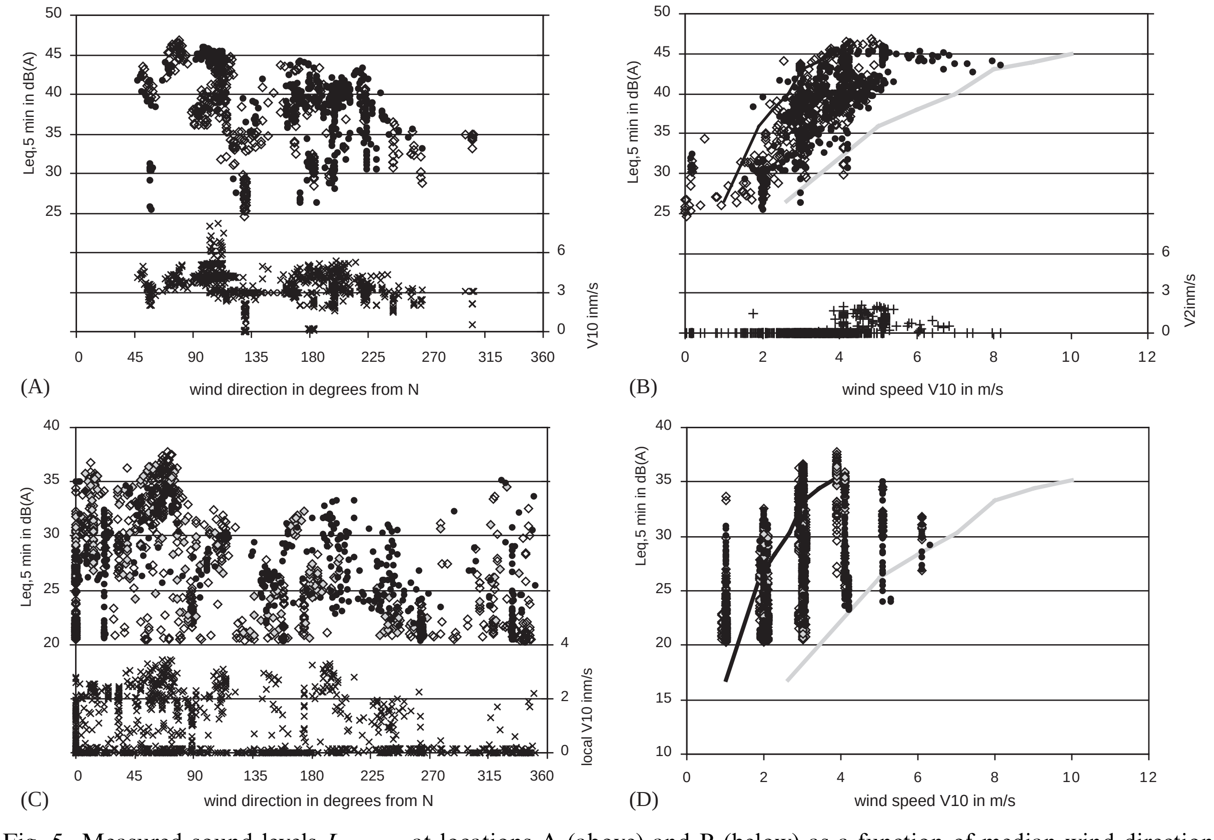

Fig. 5. Measured sound levels $L_{eq,5\,\mathrm{min}}$ at locations A (above) and B (below) as a function of median wind direction (left) and average wind speed (right) at reference height (10 m), separated in classes where the atmosphere at Eelde was observed as stable (◇) or neutral (●). Also plotted are expected sound levels according to logarithmic wind profile and wind speed at reference height (grey lines in B and D), and at a 2.6 higher wind speed (black lines in B and D). Figures A, B and C also contain the wind speed v_{10} (A), v_2 (B), and the local v_{10} (C) disturbed by trees, respectively.

observations of wind speed and cloud cover at Eelde. Eelde is the nearest KNMI site for these observations, but it is 40 km to the west, so not all observations will be valid for the area of the study.

In Fig. 5B a grey line is plotted connecting calculated sound levels with sound power levels according to Table 2 (the lowest value at 2.5 m/s is extrapolated [12]), implicitly assuming a fixed logarithmic wind profile according to Eq. (2). If this line is compressed in the direction of the abscissa with a factor 2.6, the result is a (black) line coinciding with the highest 1 h values ($L_{eq,1\,h}$) at each wind speed. Apparently, at these immission levels, the wind speed is 2.6 times higher than expected. In Fig. 6 this is given in more detail: all 5 min measurement periods that satisfied the L_5–L_{95}-criterion, with at least 4 periods per hour, were taken together in consecutive hourly periods and the resulting $L_{eq,T}$ ($T = 20$–60 min) was calculated. These 83 L_{eq}-values are plotted against the average wind speed v_{10} over the same time T. Also plotted in Fig. 6 are: the expected immission levels calculated from (1), implicitly assuming a logarithmic wind profile according to (2), so $f_{log} = 1.4$; the immission levels assuming a stable wind profile (4) with $m = 0.41$, so $f_{stable} = 2.5 = 1.8 \cdot f_{log}$; the maximum immission levels assuming $f_{max} = 3.7 = 2.6 \cdot f_{log}$, in agreement with a wind profile (4) with $m = 0.57$. The best fit of all data points ($L_{eq,T}$) in Fig. 6 with $1 < v_{10} < 5.5$ m/s is $L_{eq,T} = 32 \cdot \log(v_{10}) + 22$ dB (correlation coefficient 0.80); this fit agrees within 0.5 dB with the expected level according to the stable wind profile. The best fit of all 5 min data-points in Fig. 5B yields the same result.

Thus on location A the highest one hour averaged wind speeds at night are 2.6 times the expected values according to the logarithmic wind profile in Eq. (2). As a consequence, sound levels at (during night-time) frequently occurring wind speeds of 3 and 4 m/s are up to 15 dB higher than expected, 15 dB being the vertical distance between the expected and highest 1-h immission levels at 3–4 m/s (upper and lower lines in Figs. 5B and 6).

The same lines as in 5B, but valid for location B, are plotted in Fig. 5D; immission levels here exceed the calculated levels, even if calculated on the basis of a 2.6 higher wind speed at hub height. This is the result of shortcomings of the calculation model for long distances, at least for

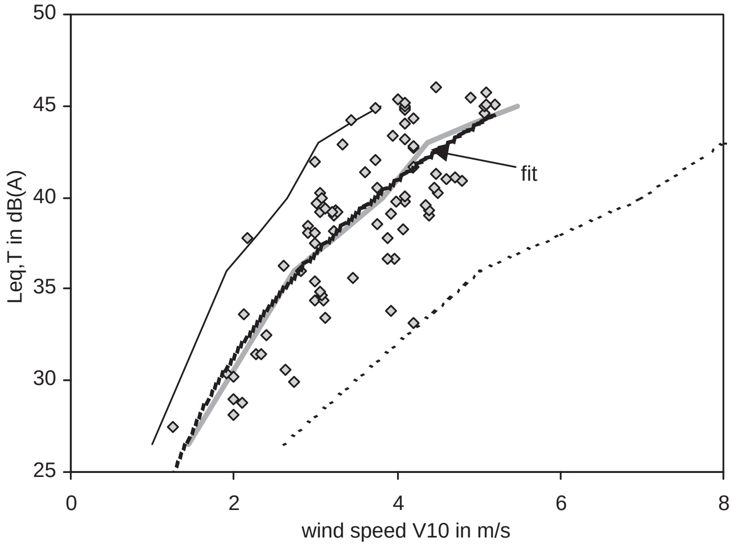

Fig. 6. Measured sound levels $L_{eq,T}$ ($T = 20$–60 min) at location A with best fit; and expected sound levels according to a logarithmic wind profile ($v_{98}/v_{10} = f_{log} = 1.4$; dotted line), a stable wind profile ($v_{98}/v_{10} = 1.8 \cdot f_{log}$; thick grey line) and maximum wind speed ratio ($v_{98}/v_{10} = 2.6 \cdot f_{log}$; thin line).

night-time conditions: from the long-term measurements at location B and short term (one night) at other locations ([12], not reproduced here) it follows that sound immission levels calculated according to the standard model used in the Netherlands [1], underestimate measured levels at night with ca. 1 dB at distances of 550–1000 m increasing to about 3 dB at distances up to 1900 m.

As is clear from the wind speed at 2 m height plotted in Fig. 5B, there is only a very light wind near the ground even when the turbines rotate at high power. This implies that in a quiet area with low vegetation the ambient sound level may be very low. The contrast between the turbine sound and the ambient sound is therefore higher at night than during the daytime.

Although at most times the wind turbine sound dominates the sound levels in Fig. 5, it is possible that at low sound levels, i.e., at low rotational speeds and low wind speeds, the L_5–L_{95}-criterion is met while the sound level is not entirely determined by the wind turbines. This is certainly the case at levels close to 20 dB(A), the sound level meter noise floor.

The long-term night-time ambient background level, expressed as the 95-percentile (L_{95}) of all measured night-time sound levels on location B, was 23 dB(A) at 3 m/s (v_{10}) and increasing with 3.3 dB/(m s^{-1}) up to $v_{10} = 8$ m/s [12]. Comparing this predominantly non-turbine background level with the sound levels in Figs. 5B and D, it is clear that the lowest sound levels may not be determined by the wind turbines, but by other ambient sounds (and instrument noise). This wind speed dependent, non-turbine background sound level L_{95} is, however, insignificant with respect to the highest measured levels. Thus, the high sound levels do not include a significant amount of ambient sound not coming from the wind turbines. This has also been verified on a number of evenings and nights by personal observation.

8. Comparison of emission and immission sound levels

From the 30 measurements of the equivalent sound level $L_{eq,T}$ (with T typically 5 min) measured at distance R from the turbine hub (R typically $100\sqrt{2}$ m), a relation between sound power level L_W and rotational speed N of a turbine could be determined: see Eq. (6).

This relation can be compared with the measured immission sound level $L_{i,T}$ ($T = 5$ min) at location A, 400 m from the wind park (closest turbine), in 22 cases where the rotational speed was known. These measurements were taken at different times to the emission measurements. The best logarithmic fit for the data points of the immission sound level L_{imm} as a function of rotational speed N is

$$L_{imm} = 57.6 \log(N) - 30.6 \text{ dB(A)} \tag{7}$$

with a correlation coefficient of 0.92 and a standard deviation of 1.5 dB. Both relations from Eqs. (6) and (7) and the data points are given in Fig. 7. The difference between both relations is $L_W - L_{imm} = 9.5 \log(N) + 46.0$ dB. For the range 14–20 r.p.m., where both series have data points, the average difference is 57.9 dB, the maximum deviation from this average is 0.8 dB (14 r.p.m.: 57.1 dB(A); 20 r.p.m.: 58.6 dB(A); see lower part of Fig. 7). It can be shown by calculation that about half of this deviation can be explained by the variation of sound power spectrum with increasing speed N.

The sound immission level can be calculated using Eq. (1). For location A, assuming all turbines have the same sound power L_W, this leads to $L_W - L_{imm} = 58.0$ dB. This is independent

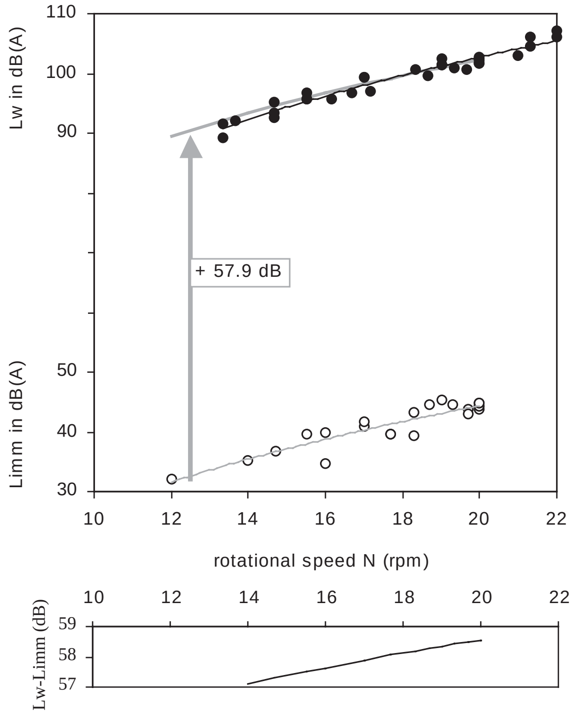

Fig. 7. Turbine sound power levels L_W measured near wind turbines (●) and immission levels L_{imm} measured at 400 m from wind park (○): averages differ 57.9 dB; (below) increase of difference L_W–L_{imm} with rotational speed.

of sound power level or rotational speed, as it is calculated with a constant spectrum averaged over several turbine conditions, i.e., speeds. The measured difference (57.9 dB) matches very closely the calculated difference (58.0 dB).

The variation in sound immission level at a specific wind speed v_{10} in Figs. 5B and D is thus seen to correspond to a variation in rotational speed N, which in turn is related to a variation in wind speed at hub height, not to a variation in v_{10}. At location A, N can be calculated from the measured immission level with the help of Eq. (7) or its inverse form $N = 3.4 \times 10^{L_{imm}/57.6}$.

9. Effect of atmospheric stability

In Fig. 5 measurement data have been separated into two sets according to atmospheric stability in Pasquill classes, supplied by KNMI from their measurement site Eelde, 40 km to the west of our measurement site. Although the degree of stability will not always be the same for Eelde and our measurement location, the locations will correlate to a high degree in view of the relatively small distance between them. For night-time conditions ‘stable’ refers to Pasquill classes E and F (lightly to very stable) and corresponds to $V_{10} \leqslant 5$ m/s and cloud coverage $C \leqslant 50\%$ or $V_{10} \leqslant 3.5$ m/s and $C \leqslant 75\%$, ‘neutral’ (class D) corresponding to all other situations. Although from Fig. 5 it is clear that the very highest sound levels at an easterly wind ($\approx 80°$) do indeed occur in stable conditions, it is also clear that in neutral conditions too the sound level is higher than expected for most of the time, the expected values corresponding to the grey lines in Figs. 5B and D, derived from daytime conditions. According to this study the sound production, and thus wind speed, at 100 m height is often higher than expected at night, in a stable, but also in a neutral atmosphere. On the other hand, even in stable conditions sound levels may be lower than expected (i.e., below the grey lines), although this rarely occurs. It may be concluded from these measurements that a logarithmic wind profile based only on surface roughness does not apply to the night-time atmosphere in our measurements, not in a stable atmosphere and not always in a neutral atmosphere.

10. Impulsive sound

At night the sound from the wind park contains repetitive pulses, unlike the sound in daytime. According to the long-term auditory observation of residents this pulse-like character or 'thumping', is more pronounced and more annoying at high turbine rotational speed. Fig. 8 shows a recording of the sound pressure level every 50 ms over a 180 s period, taken from a DAT-recording on a summer night (June 3, 0:40 h) on a terrace of a dwelling at 750 m west of the westernmost row of wind turbines (this sound includes the reflection on the façade at 2 m). There is a slow variation of the 'base line' (minimum levels) probably caused by variations in wind speed and atmospheric sound transmission. There is furthermore a variation in dynamic range: a small difference between subsequent maximum and minimum levels of less than 2 dB is alternated by larger differences. In the lower part of Fig. 8 part of the sequence is amplified and shows at first a somewhat irregular pattern of dynamic range 1–1.5 dB leading to a more regular pattern of a pulse every second with a pulse height of 3–4 or 5–6 dB. This pattern is compatible with a complex of three pulse trains with pulse height of about. 1 dB and slightly different repetition frequencies

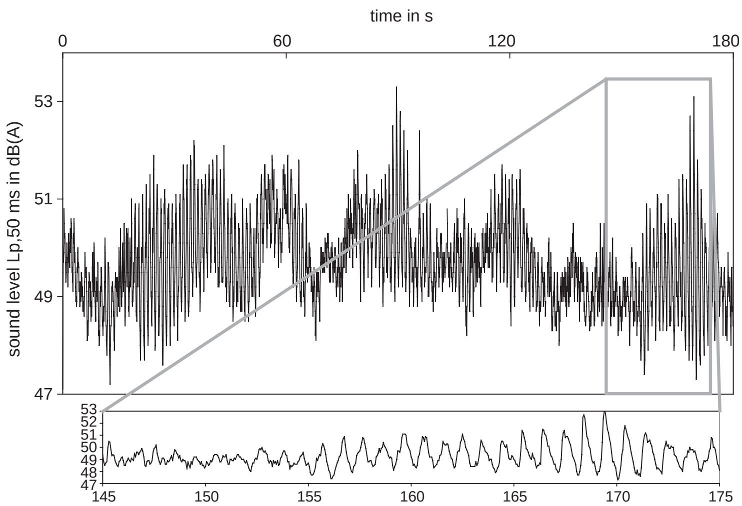

Fig. 8. Sound pressure level caused by wind turbines per 50 ms near dwelling at 750 m from nearest turbine (including reflection at façade at 2 m) over a 3 min period; part of the sequence is amplified below.

of about 1 Hz. When the pulses are out of phase (around 150 s in Fig. 8), there are only 1 dB variations. When 2 of them are in phase (around 160 s) pulse height is doubled (+3 dB), and tripled (+5 dB, 170 s) when all three are in phase. The rotational speed of the turbines at the time was 20 r.p.m., so the repetition rate of blades passing a mast was 1 Hz.

The low number of pulse trains, compared to 17 turbines, is compatible with the fact that only a few turbines dominate the sound immission at this location. The calculated immission level is predominantly caused by two wind turbines (numbers 11 and 12: see Fig. 1, contributing 35% of the A-weighted sound energy), less by two others (9 and 14; 21%), so only 4 turbines contribute more than half of the sound immission energy.

A pulse-like character was not expected; e.g., in a recent Dutch report [14] it was stated that wind turbines do not produce impulsive noise. However, when measurements are made at a single turbine, as is usual, no pulses will be audible according to the explanation given above.

11. Annoyance

The immission sound level at location A is for most of the time (at least 72% of night-time hours) higher than expected. At the most frequent night-time wind speeds (v_{10}) of 3 and 4 m/s the sound level is up to 15 dB more than expected. Also at location B, at a considerable distance (1500 m) from the wind park, the immission level is for a considerable amount of time (at least 38% of night-time hours) higher than expected. At location B and at wind speeds of 2–4 m/s the actual sound level is up to 18 dB higher than expected, of which 3 dB are due to limitations of the calculation model, and 15 dB to the underestimate of wind speed at hub height. With these higher sound levels and the impulsive character of the sound more annoyance than predicted is to be expected.

Pedersen et al. [15] have investigated the annoyance around wind turbines in the south of Sweden. Their paper gives preliminary results, and definitive results have yet to published [personal communication Pedersen]. They found highly annoyed residents at (calculated) sound levels as low as 32.5–35 dB(A). This study shows that tall wind turbines may in fact be up to 18 dB noisier than the calculated values suggest. A further increase in annoyance may be expected because of the pulse-like character of the wind turbine noise, especially at high rotational speeds.

12. Conclusions

Sound immission measurements have been made at 400 m (location A) and 1500 m (location B) from the wind park Rhede with 17 tall (98 m hub height), variable speed wind turbines. It is usual in wind turbine noise assessment to calculate immission sound levels assuming wind speeds based on wind speeds v_{10} at reference height (10 m) and a logarithmic wind profile. This study shows that the sound immission level may, at the same wind speed v_{10} at 10 m height, be significantly higher (up to 18 dB) during night-time than in the daytime. Another, 'stable' wind profile predicts a wind speed v_h at hub height 1.8 times higher than expected and agrees excellently with the average measured night-time sound immission levels. Wind speed at hub height may still be higher; at low wind speeds v_{10} up to 4 m/s, the wind speed v_h is at night is up to 2.6 times higher than expected.

Thus, the logarithmic wind profile, depending only on surface roughness and not on atmospheric stability, is not a good predictor for wind profiles at night. Especially for tall wind turbines, estimates of the wind regime at hub height based on the wind speed distribution at 10 m, will lead to an underestimate of the immission sound level at night: at low wind speeds ($v_{10} \leqslant 4$ m/s) the actual sound level will be higher than expected for a significant proportion of time. This is not only the case for a stable atmosphere, but also, to a lesser degree, for a neutral atmosphere.

The change in wind profile at night also results in lower ambient background levels then expected: at night the wind speed near the ground may be lower than expected from the speed at 10 m and a logarithmic wind profile, resulting in low levels of wind induced sound from vegetation. The contrast between wind turbine and ambient sound levels is therefore more pronounced at night.

Measured sound immission levels at 400 m from the nearest wind turbine almost perfectly match (average difference: 0.1 dB) sound levels calculated from measured emission levels near the turbines. From this it may be concluded that both the emission and immission levels could be determined accurately, even though the emission measurements were not quite in agreement with the recommended method. As both levels can be related through a propagation model, it may not be necessary to measure both; the immission measurements can be used to assess immission as well as emission sound levels.

There is, however, a growing discrepancy with distance; at distances of 1–2 km the calculated level may underestimate the measured level by 3 dB. This is most probably a consequence of the fact that the actual (night-time) atmospheric sound transmission is not adequately modelled in the sound transmission model.

At night the turbines cause a low pitched thumping sound superimposed on a broadband 'noisy' sound, the 'thumps' occurring at the rate at which blades pass a turbine tower. It appears that the characteristic, but usually small 'swishing' pulses that can be heard at the rate at which blades pass a turbine tower, coincide because turbines operate nearly synchronously. Two coinciding pulse trains thus give a 3 dB higher pulse level, three a 5 dB higher pulse level. The measured pulse levels and frequencies agree with values expected from nearly synchronous pulse trains generated by a small number of wind turbines.

The number and severity of noise complaints near the wind park are at least in part explained by the two main findings of this study; actual sound levels are considerably higher than predicted, and wind turbines can produce sound with an impulsive character.

The relatively high wind speeds at turbine hub height at night also have a distinct advantage; the electric power output is higher than predicted and benefits the operator of the wind turbine.

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