Criteria for wind farm noise: Lmax and Lden

Frits Van Den Berg

University of Groningen - Science & Society Group, Nijenborgh 4, 9747AG Groningen, Netherlands
fvdberg@ggd.amsterdam.nl

Wind turbine noise limits are based on either the highest sound immission level (Lmax) or several sound immission levels for a series of wind speed classes (Lmax,v). As yet no procedure has been proposed to determine the day-evening-night sound level (Lden) that is now commonly used in the European Union for all noise sources. Wind speed dependent rating wind turbine noise levels Lr,v can be predicted based on climatological data. This has been verified by measurements over a nine month period for a wind farm at a coastal location in the Netherlands. From these measurements also the long term average sound level Lden can be determined. Lden can also be determined from previously published wind speed measurements at an inland location over one year. The procedure shows that for a wind turbine or wind farm the Lden can be derived from Lmax by taking into account the regional climatology.

1 Introduction

For industrial (*i.e.* non-transportation) noise sources it is customary to determine a single rating noise level (see *e.g.* [1]), that can be compared to a single noise limit per diurnal period (day, evening or night). The rating noise level usually refers to a loudest (with exceptional situations possibly excluded), most prevalent or 'averaged' situation. As the rating level usually reflects a prolonged period of time (a year or more), there may be an averaging over different weather conditions. This may be a simple 'meteo correction' to include noise reducing upwind conditions (to a calculated or measured downwind situation), or –though less common- calculations over situations with different vertical temperature gradients or atmospheric stabilities. Noise limits are more strict in night time to ensure less annoyance at night, but fortunately many noise sources are quiet or at least less noisy at night.

Noise limits for wind turbines are more usually given for a range of wind speeds. The reason for this is that wind turbines produce more sound at higher wind speeds and it was thought that the higher wind speeds would provide more background sound which in turn would mask the increasing wind turbine noise level. It has been shown -especially for modern, tall turbines- that this assumption is incorrect when the atmosphere is stable, which is a common situation in the temperate climate zone after sundown. The reason for this is that in a stable atmosphere the wind at higher altitude is decoupled from the near-ground wind, Then, high hub height wind speeds can occur with simultaneous low near-ground winds speeds and thus high turbine sound levels occur at low background sound levels [2]. In fact, tall wind turbines in relatively flat land can produce (near) maximum sound power at any near-ground wind speed except the very lowest. As a result the masking potential of background sound is not very different from what it is for other industrial sources. In complex terrain the situation is more complicated, though it may lead to the same conclusion [3].

This paper gives two models to predict a wind turbine sound power level. The first model gives a prediction for the loudest, but regularly occurring situation, in agreement with the existing legal requirements in the Netherlands. It will be shown to depend on near-maximum sound power levels or (approximately) $L_{W,max}$. This model is relevant for all situations where noise limits are wind speed dependent.

In the second model a wind speed independent rating level is determined in agreement with EU legislation for all other noise sources. This model yields the day-evening-night sound power level or $L_{W,den}$. With this sound power level and a sound propagation model the well known day-evening-night sound level or L_{den} can be calculated.

The first model has been discussed in the Netherlands for new predictions of wind farm noise to replace the incorrect predictions based on a forever neutral atmosphere, but within the existing legal framework. The second method is proposed for future predictions and implies a change in legal requirements.

2 Model 1 – $L_{W,max}$: climatological prediction

2.1 Stability class and wind speed

The relation between wind speeds at different heights has been given by Holtslag for both an unstable and stable atmosphere and the intermediate neutral atmosphere [4]. The results can be approximated by a simpler, engineering description for the wind speed v_h at height h:

$$v_h = v_{ref} \cdot (h/h_{ref})^m \qquad (1)$$

with h an arbitrary height and h_{ref} a reference height of (usually) 10 m (see, *e.g.* [5]). The models are valid in the lower part (up to ≈ 200m) of the atmosphere. The exponent *m* is a measure for the stability of the atmosphere. The values of *m* in table 1 are recommended for meteorological observations [5] and are considered to be the best numerical approximation for the Pasquill stability classes for rural (in contrast to built up) areas.

Stability class according to Pasquill	*m*
A very unstable	0,07
B moderately unstable	0,07
C weakly unstable	0,10
D neutral	0,15
E weakly stable	0,35
F moderately to very stable	0,55

Table 1: stability and stability exponent *m*

Because of the sequence of daytime heating and night time cooling of the ground and the air above it (stronger in summer, less in winter) there is a diurnal course in atmospheric stability in the temperate climate zone. Over large water surfaces this diurnal heating and cooling is less intense and atmospheric stability may tend to a more seasonal course: the surface is relatively warm in autumn and winter and relatively cold in spring and summer. Close to the sea the situation is therefore more complicated: with an offshore wind the diurnal course will dominate, but with an onshore wind the seasonal influence will dominate.

The wind speed at hub height can be calculated from the wind speed at 10 m height (formula 1) for all Pasquill classes in table 1. In table 2 the results are given for three typical landward situations: a sunny day with less than 50% cloud coverage, a neutral atmosphere, and at night with less than 50% cloud coverage. Hub height is taken as 80 m, which is fairly typical for modern turbines. For 10-m wind speeds ≥ 6 m/s there is little or no difference in hub height wind speeds; only with strong heating (unstable atmosphere) the wind speed is lower than in neutral conditions. At lower 10-m wind speeds, hub height wind speeds can vary over a wide range. For a 10-m wind speed of 3 m/s the hub height wind speed on a sunny day is but a little larger and a typical wind turbine will just start to generate, whereas in a more or less clear night the hub wind speed –at 3 m/s 10-m wind speed- may be up to 9 m/s at which speed a turbine may almost produce full power.

A stable atmosphere occurs at 10-m wind speeds up to approximately 6 m/s, a very stable atmosphere at wind speeds up to approximately 4 m/s. The decrease in 80 m wind speed at between 3 and 4 m/s and again between 5 and 6 m/s 10-m wind speed is a result of loss of stability and stronger coupling between near-ground and higher altitude winds.

V_{10}		weak			moderate			strong
	m/s	2	3	4	5	6	7	8
(partially) clear day / unstable atmosphere								
m		0,07	0,07	0,07	0,07	0,10	0,10	0,10
V_{80}	m/s	2,3	3,5	4,6	5,8	7,4	8,6	9,8
Cloudy and/or low sun / neutral atmosphere								
m		0,15	0,15	0,15	0,15	0,15	0,15	0,15
V_{80}	m/s	2,7	4,1	5,5	6,8	8,2	9,6	10,9
(partially) clear night / stable atmosphere								
m		0,55	0,55	0,35	0,35	0,15	0,15	0,15
V_{80}	m/s	6,3	9,4	8,3	10,4	8,2	9,6	10,9

Table 2: wind speeds at 10 and 80 m height, depending on stability exponent *m*

2.2 Representative situation

In the Netherlands a stable atmosphere (Pasquill classes E and F) occurs for a high percentage of the time between sunset and sunrise, varying from 15% at the very coast to 40% in landward locations [6]. According to the legally required Dutch instructions the relevant situation for the assessment of the noise level ('representative situation') is the loudest diurnal period if that situation occurs more often than once a month [7]. A situation occurring for 15% to 40% of the time must therefore be considered a representative situation. Thus, for an 80 m hub height wind turbine and in the night and evening period a sound power level must be used in agreement with the hub height wind speeds in table 2.

As an example it will be shown how to calculate representative sound power levels. For this example data from the popular Vestas V80-2MW turbine in the high power mode will be used. The relation between the hub height (80 m) wind speed V_h and the sound power level $L_{W,hp}$ can be written as a fourth power polynomial valid for the range $4 < V_h < 12$ m/s:

$$L_{W,hp} = -0.0023 \cdot V_h^4 + 0.146 \cdot V_h^3 - 2.82 \cdot V_h^2 + 22.6 \cdot V_h + 39.5 \quad \text{dB(A)} \quad (2)$$

$L_{W,hp}$ is nil for $V_h < 4$ m/s and $L_{W,hp} = 107$ dB(A) for $V_h > 12$ m/s [6].

In table 3 the calculated sound power levels are shown for a neutral as well as stable atmosphere, using formula 2 and the wind speeds from table 2. For every wind speed V_{10} the highest possible stability class is used (so: class F if $V_{10} < 3$ m/s, class D if $V_{10} > 5,5$ m/s and class E in between), because that is the relevant conditions to determine the sound level.

The results show that even at low 10-m wind speed the sound power level can be close to its maximum value. That is why it is referred to as the Lmax model. Also, at weak or moderate near-ground wind speed the sound power level in a stable atmosphere proves to be rather higher than in a neutral atmosphere at the same near-ground wind speed.

Table 3 is valid for flat land in the temperate climate zone. However, the percentage of time that each of the given situations will occur may vary between places.

In a paper to be presented at Internoise2008 this model will be compared to results from long term measurements.

V_{10}	m/s	2	3	4	5	6	7	8
	neutral							
m	-	0,15	0,15	0,15	0,15	0,15	0,15	0,15
V_{80}	m/s	2,7	4,1	5,5	6,8	8,2	9,6	10,9
LW	dBA	-	-	100,7	103,8	105,3	106,2	107,4
	very stable		stable		neutral			
m	-	0,55	0,55	0,35	0,35	0,15	0,15	0,15
V_{80}	m/s	6,3	9,4	8,3	10,4	8,2	9,6	10,9
LW	dBA	102,8	106,1	105,4	106,9	105,3	106,2	107,4

Table 3: wind speeds at 80 m height in a neutral and (very) stable atmosphere, depending on 10-m wind speed and stability exponent *m*, and accompanying sound power levels of a Vestas V80-2MW wind turbine

Model 2 – $L_{W,den}$: sound power distribution

The distribution of wind speeds at hub height directly yields the distribution of sound power levels, from which the average sound power level can be calculated. To determine the sound power level per diurnal period, the wind speed distribution must also be available per diurnal period.

2.3 Wind speed distributions

These distributions have been determined for two different locations in the Netherlands: the landward location Cabauw and the coastal location Lutjewad. At Cabauw there is a 200 m mast for meteorological measurements by the KNMI (Royal Netherlands Meteorological Institute) with wind speed measurements at 10, 20, 40, 80, 120 and 200 m height. At Lutjewad there is a 60 m mast used by CIO (Centre for Isotope Research) with wind speed measurements at 7, 40 and 60 m height. Both locations are in predominantly agricultural area with low vegetation. Cabauw is 40 km SSE of Amsterdam and 50 km from the North Sea. Lutjewad is right behind the dike along the Waddensea coast in the north of the country, 25 km NW of the city of Groningen. Detailed information on both stations is given on the KNMI and CIO websites [8, 9].

KNMI and CIO have provided half hour averaged wind speeds at all available measurement heights over a period of 11 years (01-02-1986 to 31-01-1997) and 7 years (01-01-2001 to 31-12-2007), respectively. Relevant hub heights for modern wind turbines, here assumed to range from 60 to 100 m and in 20 m steps, do not all coincide with measurement heights. Wind speeds at the heights not directly measured have been obtained from the KNMI data by interpolating between the two nearest measurement heights available, from the Lutjewad data by extrapolating from the measurement heights at 40 and 60 m, in both cases using formula (1). First the stability exponent *m* is calculated from two measured wind speeds, then this value of *m* is used to extrapolate from the wind speed at the lower height to the desired height. In figure 1A the result is given for 80 m altitude at Lutjewad for the three diurnal periods. Figure 1A shows that the night time distribution has a higher maximum at a higher wind speed than the daytime distribution, with the evening distribution in between. In terms of the Weibull distribution, both the scale and shape parameters increase when going from day to night. This is also true for the other heights (60 and 100 m) and for both locations, though the differences in scale parameter (peak wind speed) decrease with decreasing height.

2.4 Sound power distributions

The hub height wind speed determines the turbine sound power level. The relation between both is determined by measurements, preferably by using the hub height wind

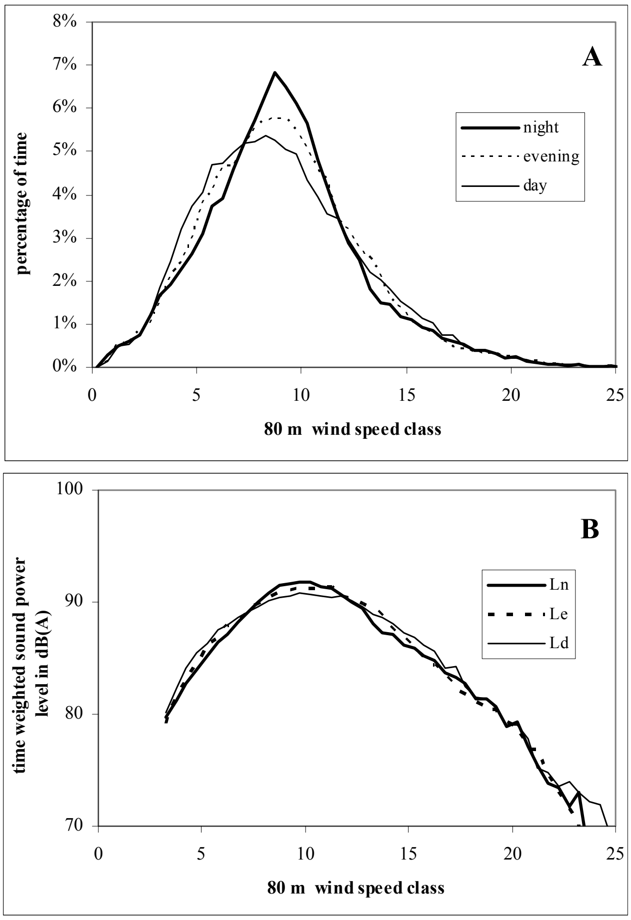

Figure 1: distributions per diurnal period of (A) 80-m wind speed at coastal location Lutjewad, and of (B) time-weighted sound power level of a N80-2.5MW at same location

speed (directly or from the electric power output); the 10-m wind speed is the second choice [10] and may lead to incorrect results if the atmosphere is non-neutral. Again, the variable speed Vestas V80-2MW is used as a typical modern wind turbine, with a sound power level according to formula (2). Two more examples will be calculated: the same turbine in another power setting (lower speed) and the Nordex N80-2.5MW turbine. In the lowest sound power setting of the V80-2MW the best fourth power polynomial fit (for $4 < Vh < 12$ m/s) is:

$$L_{W,lp} = -0.022 \cdot V_h^4 + 0.78 \cdot V_h^3 - 10 \cdot V_h^2 + 55.3 \cdot V_h - 12.3 \quad \text{dB(A)} \quad (3)$$

and $L_{W,lp} = 105$ dB(A) for $V_h > 12$ m/s [6].

For the Nordex N80-2.5 MW [11] a best fit of the relation between hub height wind speed and sound power level for this turbine is:

$$L_{W,N} = -0.0019 \cdot V_h^4 + 0.0644 \cdot V_h^3 - 0.82 \cdot V_h^2 + 5.41 \cdot V_h - 86.6 \quad \text{dB(A)} \quad (4)$$

for the range $3 < V_h < 12$ m/s and LW,N = 105.5 dB(A) for $V_h > 12$ m/s. In figure 2 the three best fits to the sound power curves are plotted.

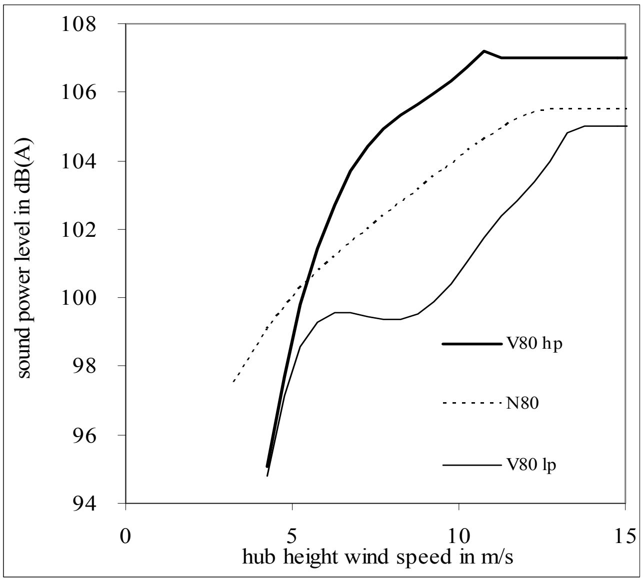

Figure 2: best fits for relation sound power vs. hub height (80 m) wind speed for a Vestas V80-2MW in high power and low power mode, and a Nordex N80-2.5MW

The three approximations have been used for hub heights of 60, 80 and 100 m, even though the manufacturers may not produce the types mentioned for all these mast heights. The relations (2) – (4) have been used to transform wind speeds to sound power levels. To obtain a relevant distribution a time correction is added to account for the fact that each wind speed class occurs over a limited amount of time (T_{V80}) of the total observed period T_{all} of several years. To this end in each wind speed class V_{80}, the sound power level L_W is calculated to which a time correction $10 \cdot \log(T_{V80}/T_{all})$ is added. The result is a time weighted sound power level distribution $L_W - 10 \cdot \log(T_{V80}/T_{all})$ in which each class value yields the contribution of that class to the total sound power level per diurnal period. Figure 1B gives an example for the N80-2.5MW using the wind speed distributions in figure 1A, so it shows the time weighted sound level distribution at 80 m hub height at the coastal location Lutjewad.

2.5 Calculation of $L_{W,den}$

Summation of all values in each distribution gives the average sound power level per diurnal period or $L_{W,d}$, $L_{W,e}$ and $L_{W,n}$. Finally these can be summed to yield the desired rating sound power level $L_{W,den}$:

$$L_{W,den} = 10 \cdot \log[12 \cdot 10^{LWd/10} + 4 \cdot 10^{(LWe+5)/10} + 8 \cdot 10^{(LWn+10)/10}) - 10 \cdot \log(24) \quad dB(A) \quad (5)$$

In table 4 the average sound power levels per diurnal period are shown for both locations and three hub heights. It appears that the day, evening and night levels are almost the same, though the night levels are usually somewhat higher (0 – 0.5 dB), most so at higher hub heights. Also, table 4 shows that $L_{W,den}$ increases with height due to the increase of wind speed with height.

Also, in table 4 the differences are given between $L_{W,den}$ and the sound power level $L_{W,7m/s}$ at a 10-m wind speed of 7 m/s. For the V80 in high power and for the N80 the wind speed class contributing most to the total level (= the maximum value in figure 1B) is at 10 ± 1 m/s at Lutjewad and at 8.5 ± 1 m/s at Cabauw. This corresponds to a 10-m wind speed in standard conditions (neutral atmosphere with 5 cm roughness height) of 7,3 ± 0.5 m/s at Lutjewad and 6.3 ± 0.5 m/s at Cabauw. For the V80 in low power the wind speed class contributing most is 13,3 m/s at Lutjewad and 10.3 (100 m) or 6.8 (80 and 60 m) m/s at Cabauw, corresponding to a standard 10-m wind speed of 9.5 ± 0.5 m/s and 6 ± 1 m/s, respectively. A 7 m/s 10-m wind speed is thus a fairly typical wind speed determining the dominant contribution ($L_{W,7m/s}$) to the total sound power level $L_{W,den}$. The difference $L_{W,den} – L_{W,7m/s}$ = 5.8 ± 2 dB and depends on height, location and turbine type.

Note that for a constant source with sound power level L_C, $L_{W,den}$ - L_C = 6.4 dB, for a constant source only active in the night period $L_{W,den}$ - L_C = 5.2 dB.

$L_{W,den}$ can also be expressed relative to a sound power level at 8 m/s 10-m wind speed: $L_{W,den} – L_{W,8m/s}$ = 4.7 ± 1.5 dB.

turbine type	hub height (m)	$L_{W,d}$	$L_{W,e}$	$L_{W,n}$	$L_{W,den}$	$L_{W,den}$-$L_{W,7m/s}$	$L_{W,d}$	$L_{W,e}$	$L_{W,n}$	$L_{W,den}$	$L_{W,den}$-$L_{W,7m/s}$
		Lutjewad					Cabauw				
Vestas V80,hp	100	105,3	105,5	105,9	112,2	5,9	104,3	104,7	104,8	111,1	4,8
	80	105,1	105,3	105,6	111,9	5,6	104,0	104,3	104,4	110,7	4,4
	60	104,8	104,8	105,1	111,4	5,1	103,7	103,7	103,7	110,1	3,8
Vestas V80,lp	100	101,4	101,6	101,9	108,2	7,8	100,2	100,4	100,4	106,8	6,4
	80	101,2	101,2	101,4	107,7	7,3	99,8	100,0	99,9	106,3	5,9
	60	100,8	100,7	100,8	107,2	6,8	99,5	99,5	99,4	105,9	5,5
Nordex N80	100	103,4	103,6	104,0	110,3	6,4	102,4	102,7	102,8	109,1	5,2
	80	103,2	103,3	103,7	110,0	6,1	102,2	102,4	102,4	108,7	4,8
	60	102,9	102,9	103,1	109,5	5,6	102,0	102,0	102,0	108,4	4,5

Table 4: day, evening and night time averaged sound power levels, and total sound power level $L_{W,den}$ at a landward (Cabauw) and coastal (Lutjewad) location. Columns $L_{W,den}$-$L_{W,7m/s}$ gives difference between $L_{W,den}$ and sound power level $L_{W,7m/s}$ at a 10-m wind speed of 7 m/s

3 Conclusion

For the assessment of wind turbine noise, hub height wind speeds cannot be predicted from 10-m wind speeds only. Additional information is necessary about the degree of atmospheric stability and –though less important in rural settings in relatively flat land - roughness height. When the noise limit is wind speed dependent, a prediction of the representative sound power level according to Dutch legislation can be based on general climatological information.

A new way to rate wind turbine noise is to determine a day-evening-night level (L_{den}), as common in the European Union for other noise sources. To obtain a value for L_{den}, the wind speed distribution at hub height must be known. It appears that the associated sound power level $L_{W,den}$ is a relatively robust value, with minor differences between day, evening and night levels, a slow increase with height, and only a 1.2 dB difference between a coastal and landward location. $L_{W,den}$ is 5.8 ± 2 dB higher than the sound power level at 10 m/s hub height wind speed, corresponding to a 10-m wind speed of 7 m/s in 'standard conditions' (a neutral atmosphere with 5 cm roughness height).

Acknowledgments

Model 1 occurred to me with the help of Arno Eisses of TNO. The data used in Model 2 have been provided by Fred Bosveld of KNMI and Rolf Neubert of CIO.

References

[1] "ISO-9613.2: Attenuation of sound during propagation outdoors. Part 2: General method of calculation", International Organization for Standardization (1996)

[2] Van den Berg G.P.: "Effects of the wind profile at night on wind turbine sound", *Journal of Sound and Vibration* 277 (4-5), pp. 955-970 (2004)

[3] Van den Berg G.P.: "Wind profiles over complex terrain", *proceedings Second International Meeting on Wind Turbine Noise*, Lyon, September 20–21 (2007)

[4] Holtslag: A.A.M.: "Estimates of diabatic wind speed profiles from near-surface weather observations", *Boundary-Layer Meteorology* 29, pp. 225–250 (1984)

[5] "Meteorological Monitoring Guidance for Regulatory Modeling Applications", *report EPA-454/R-99-005,* U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards (2000)

[6] Van den Berg G.P.: "Wind turbine power and sound in relation to atmospheric stability", *Wind Energy*, 11 (2), pp. 151-169 (2008)

[7] "Handleiding meten en rekenen Industrielawaai" ("Manual for measuring and calculating industrial noise"), Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), den Haag (1999) (in Dutch)

[8] http://www.knmi.nl/research/atmospheric_research/pagina_1_Cabauw.html, consulted April 2008

[9] http://www.rug.nl/ees/onderzoek/cio/projecten/atmosphericgases/index, consulted April 2008

[10] "Wind turbine generator systems – Part 11: Acoustic noise measurements techniques", *IEC standard 16400-11:1998(E)*, Geneva (1998)

[11] "Locatieonderzoek windpark A28", *report MD-WR2004.0233*, Gemeenten Nijkerk, Ermelo en Putten (2004) (in Dutch)