The sound of high winds

van den Berg, G.P.

APPENDICES

Appendix A
List of symbols

Symbol: definition [unit]

α: angle of attack [radian] or [degree];
also: rotor pitch angel [radian] or [degree]
also: constant relating wind velocity to pressure [-]

δ_i^*: displacement thickness of turbulent boundary layer [m]

η_s: Kolmogorov size [m]

κ: von Karman's constant [0.4]

ν: kinematic viscosity of air [$m^2 \cdot s^{-1}$]

ρ: correlation coefficient (1/3 octave band level vs. L_A) [-];
also: air density [kg/m^3]

$\Psi(\zeta)$: stability function [-]

θ: rotor tilt angel [radian] or [degree]

ζ: dimensionless height (h/L) [-]

Ω: turbine rotor angular velocity [$rad \cdot s^{-1}$]

a: induction factor ($1 - V_b/V_h$) [-]

b: correction factor for boundary layer thickness (value: 2 – 4)

c: velocity of sound in air [$m \cdot s^{-1}$]

C: blade chord length [m]; also: air density dependent constant
($C = 20 \cdot \log(0.215\kappa\alpha\rho V_o^2/p_{ref})$ [dB])

C_p: constant ($C_p = 20 \cdot \log(0.215\kappa\alpha) - 9.5$) [dB]

D: diameter [m]

D_h: directivity function [-]

$D_{j,k}$: decrease in octave band sound level j of turbine k with distance [dB]

D_{geo}: decrease in sound level due to geometrical spreading [dB]

D_{air}: decrease in sound level due to air absorption [dB]

D_{ground}: decrease in sound level due to ground absorption and reflection [dB]

dB(A): unit of level after A-weighting

dB(G): unit of level after G-weighting
f: frequency [Hz]
f_{mod}: modulation frequency [Hz]
$f_{peak,TE}$: peak frequency of trailing edge sound [Hz]
$f_{peak,if}$: peak frequency of in-flow turbulence sound [Hz]
f_m : middle frequency of 1/3 octave band [Hz]
f_B: blade passing frequency [Hz]
f_c: screen size related corner frequency ($f_c = 0.3V/D$) [Hz]
f_i: α-dependent factor for TE layer thickness [-]
f_{log}: ratio v_{98}/v_{10} valid in a neutral atmosphere [-]
$f_{(un)stable}$: ratio v_{98}/v_{10} valid in an (un)stable atmosphere [-]
F_{bb}: fluctuation strength [vacil]
F(z): turbulence related function:

$$F(z) = -20 \cdot \log[(z/D)^{1/3} \cdot (\ln(z/z_o) - \Psi)] \text{ [dB]}$$

G(z): turbulence related function:

$$G(z) = -20 \cdot \log[0.2 \cdot (z/\ell_o)^{1/3} \cdot (\ln(z/z_o - \Psi)] \text{ [dB]}$$

h: height [m]
H: turbine height [m]
h_{ref}: reference height for wind velocity (and direction) [m]
k: integer number (of harmonic frequency) [-];
also: exponent of wind velocity in relation with associated turbulent pressure [-]
K_1: constant (128.5 dB)
K_α: α dependent increase in trailing edge sound level [dB]
ℓ: eddy length scale [m]
ΔL: increase in sound level [dB]
L: Monin-Obukhov length [m]
L_A: broad band A-weighted sound level [dB(A)]
L_{A5}: 5-percentile of broad band sound levels over a period [dB(A)]
L_{A95}: 95-percentile of broad band sound levels over a period [dB(A)]
$L_{at}(u)$: pressure level due to atmospheric turbulence [dB]
$L_{at,1/1}(f)$: pressure level due to turbulent wind per octave band [dB]
$L_{at,1/3}(f)$: pressure level due to turbulent wind per 1/3 octave band [dB]
$L_{at,A}$: broad band A-weighted pressure level [dB]
L_{imm}: immission sound level [dB(A)]

L_{eq}: equivalent sound level; $L_{eq,T}$: over time T [dB(A)]

$L_{p,1/3}$: turbulent pressure level at microphone per 1/3 octave band [dB]

$L_{red,1/3}$: 'meteorologically reduced' 1/3 octave band pressure level [dB]

$L_{red,1/1}$: 'meteorologically reduced' octave band pressure level [dB]

L_W: sound power level [dB(A)]

L_{Wj}: j-th octave band sound power level [dB(A)]

M: Mach number = air flow velocity/c (at radius R: M = ΩR/c) [-]

m: stability exponent [-]

$m_{h1,h2}$: *m* determined between heights h_1 and h_2 [-]

mf: modulation factor [-]

n: dimensionless frequency (n = fz/V) [-]

N: number of blades [-]; rotational speed (ΩR/2π) [s^{-1}]

Ph: Power at height h; Ph,lpp; Ph,hp [W]

p: (sound) pressure [Pa]

p_f,: rms pressure in narrow frequency band centered at frequency f [Pa]

$p_{f1/3}$: rms pressure in 1/3 octave band [Pa]

p_{ref}: reference (sound) pressure [20 μPa]

p(0): rms pressure at center of wind screen [Pa]

r: distance [m]

R: rotor radius = blade length [m]

ΔR: increment in R [m]

R_X: range between maximum and minimum sound levels (X= bb or f) [dB]

$R_{X,90}$: range between 5- and 95-percentile of sound levels (X= bb or f) [dB]

Re: chord based Reynolds number (Re = ΩRC/ν); wind screen diameter based Reynolds number [-]

S: ratio of distance along blade and chord length [-]

Sp_i: 1/3 octave band weighing function for TE sound [dB]

SPL_i: sound pressure level of source i [dB]

Sr: Strouhal number [-]

u: longitudinal (along wind) component of turbulent wind velocity [$m \cdot s^{-1}$]

u_f: rms longitudinal component of turbulent wind velocity per unit frequency [$m \cdot s^{-3/2}$]

u*: friction velocity [$m \cdot s^{-1}$]

U: instanteneous wind velocity: U = <U> + u [$m \cdot s^{-1}$]

V: air flow velocity or wind velocity [$m \cdot s^{-1}$]

V_o: reference velocity [1 $m \cdot s^{-1}$]

V_b: induced wind velocity at turbine blade [$m \cdot s^{-1}$]

V_h, V_{xx}: wind velocity at height h or height xx m [$m \cdot s^{-1}$]

$V_{h,b}$, $V_{xx,b}$: induced wind velocity at turbine blade or height h [$m \cdot s^{-1}$]

V_{hub}: wind velocity at wind turbine hub height h [$m \cdot s^{-1}$]

V_i: local (induced) velocity at blade ≈ 2V/3 [$m \cdot s^{-1}$]

V_{ref}: wind velocity at reference height [$m \cdot s^{-1}$]

<x>: time average of variable x

z_o: roughness height; altitude [m]

Subscripts:

1/1: frequency octave band

1/3: 1/3 frequency octave band

A: A-weighted

at: atmospheric turbulence

bb: broad band

f: at frequency of (1/3) octave band

h: at height h, hub

i: component of TE sound (i = p, s, α)

if: in-flow

p: pressure, pressure side

ref: reference

s: suction side

TE: trailing edge

Appendix B
Dominant sources of wind turbine sound

With modern wind turbines there are three important mechanisms that produce sound. These will be reviewed here up to a detail that is relevant to the text in this book.

B.1 *Infrasound: thickness sound*

When a blade moves through the air, the air on the forward edge is pushed sideways, moving back again at the rear edge. For a periodically moving blade the air is periodically forced, leading to 'thickness sound'. Usually this will not lead to a significant sound production as the movement is smooth and thus accelerations relatively small.

When a blade passes the turbine tower, it encounters wind influenced by the tower: the wind is slowed down, forced to move sideways around the tower, and causes a wake behind the tower. For a downwind rotor (*i.e.* the wind passes the tower first, then the rotor) this wake causes a significant change in blade loading.

The change in wind velocity near the tower means that the angle of attack of the air on a blade changes and lift and drag on the blade change more or less abruptly. This change in mechanical load increases the thickness sound power level at the repetition rate of the blade passing frequency f_B. For modern turbines $f_B = N \cdot \Omega/(2\pi)$ typically has a value of approximately 1 Hz. As the movement is not purely sinusoidal, there are harmonics with frequencies $k \cdot f_B$, where k is an integer. Harmonics may occur up to 30 Hz, so thickness sound coincides with the infrasound region (0–30 Hz). Measured levels at 92 m from the two-bladed 2 MW WTS-4 turbine showed that measured sound pressure levels of the individual blade harmonics were less than 75 dB, and well predicted by calculations of wind-blade interaction near the turbine tower [Hubbard *et al* 2004, Wagner *et al* 1996]. The envelope of the harmonics peaks at the fifth harmonic (k = 5 with f_B = 1 Hz), indicating a typical pulse time of $(5\ \text{Hz})^{-1}$ = 0,2 s which is 20% of the time between consecutive blade passages. The WST-4 is a downwind turbine with an 80 m tubular tower, where the wind velocity deficit was estimated to be 40% of the free wind velocity [Hubbard *et al* 2004]. For modern, upwind rotors the velocity deficit in front of the tower is smaller. As a consequence the change in blade loading is less than for downwind turbines. From data collected by Jakobsen it appears that the infrasound level at 100 m from an upwind turbine is typically 70 dB(G) or less, whereas near downwind turbines it is 10 to 30 dB higher. As 95 dB(G) corresponds to the average infrasound hearing threshold [Jakobsen 2004], infrasound from (upwind) wind turbines does not appear to be so loud that it is directly perceptible.

B.2 Low frequencies: in-flow turbulent sound

Because of atmospheric turbulence there is a random movement of air superimposed on the average wind velocity. The contribution of atmospheric turbulence to wind turbine sound is named 'in-flow turbulence sound' and is broad band sound stretching over a wide frequency range. For turbulent eddies larger in size than the blade this may be interpreted as a change in the direction and/or velocity of the incoming flow, equivalent to a deviation of the optimal angle of attack. This leads to the same phenomena as described in section B.1, but changes will be random (not periodic) and less abrupt. For turbulent eddies the size of the chord length and less, effects are local and do not occur coherently over the blade. When the blade cuts through the eddies, the movement normal to the wind surface is reduced or stopped, given rise to high accelerations and thus sound.
In-flow turbulence sound has a maximum level in the 1/3 octave band with frequency

$$f_{peak,if} = (St \cdot 0.7R \cdot \Omega)/(H - 0.7R) \qquad (B.1)$$

where Strouhal number St is 16.6 [Grosveld 1985, Wagner *et al* 1996]. Most sound is produced at the high velocity, outer parts of the blades. For a modern, tall, three-bladed wind turbine with hub height H = 100 m, blade length R = 35 m and angular velocity $\Omega = 2\pi f_B/3 = 2$ rad·s^{-1} (20 rpm), $f_{peak,if}$ = 11 Hz which is in the infrasound region. Measured fall-off from $f_{peak,if}$ is initially approx. 3 dB per octave, increasing to 12 dB per octave at frequencies in the audible region up to a few hundreds of hertz [Grosveld 1985, Wagner *et al* 1996].

B.3 High frequencies: trailing edge sound

Several flow phenomena at the blade itself or in the turbulent wake behind a blade cause high frequency sound ('airfoil self-noise'). Most important for modern turbines is the sound from the turbulent boundary layer at the rear of the blade surface where the boundary layer is thickest and turbulence strength highest. Trailing edge sound has a maximum level in the 1/3 octave band with frequency

$$f_{peak,TE} = 0.02 \cdot \Omega \cdot R \cdot / (\delta^* \cdot M^{0.6}) \qquad (B.2)$$

where Mach number M is based on airfoil velocity. The displacement thickness of the turbulent boundary layer is:

$$\delta^* = b \cdot 0.37 \cdot C \cdot Re^{-0.2}/8 \qquad (B.3)$$

for a zero angle of attack. Re is the chord based Reynolds number [Brooks *et al* 1989]. The experimental factor b accounts for the empirical observation that the boundary layer is a factor 2 to 4 thicker than predicted by theory [Lowson 1995, Wagner *et al* 1996]. For air of 10 °C and atmospheric pressure, a typical chord length C = 1 m, and other properties as given above (section B.2), $f_{peak,TE}$ = 1700/a Hz. With b = 2 to 4, $f_{peak,TE}$ is 450 – 900 Hz. The spectrum (see Sp_i below) is symmetrical around $f_{peak,TE}$ and decreases with 3 dB for the first octave, 11 dB for the next; the contribution from further octave bands is negligible [Brooks *et al* 1989].

According to Brooks *et al* [1989] trailing edge sound level can be decomposed in components SPL_p and SPL_s due to the pressure and suction side turbulent boundary layers with a zero angle of attack of the incoming flow, and a component SPL_a that accounts for a non-zero angle of attack α. For an edge length ΔR each of the three components of the immission sound level at distance r can be written as [Brooks *et al* 1989]:

$$SPL_i = 10 \cdot \log(\delta_i^* \cdot M^5 \cdot \Delta R \cdot D_h / r^2) + Sp_i + K_1 - 3 + K_i \qquad (B.4)$$

and total trailing edge immission sound level as:

$$SPL_{TE} = 10\cdot\log(\Sigma_i\ 10^{SPLi/10}) \qquad (B.5)$$

where the index i refers to the pressure side, suction side or angle of attack part (i = p, s, α). The directivity function D_h equals unity at the front of the blade (θ = 180°) and falls off with $\sin^2(\theta/2)$. Because of the strong dependence on M (~ M^5, equation B.4) trailing edge sound is dominated by sound produced at the high velocity parts: the blade tips.

Sp_i gives the symmetrical spectral distribution of the trailing edge sound spectrum centered on $f_{peak,TE}$ and is maximum (0 dB) at this centre frequency. The constant K_1 - 3 = 125.5 dB applies when the chord based Reynolds number exceeds $8\cdot10^5$ and the pressure-side turbulent boundary displacement thickness $\delta_i^* > 1$ mm, as is the case for modern tall turbines. K_i is non-zero only if i = α.

For positive angles of attack α < 10° the boundary layer thickness δ^* shrinks with a factor $f_p = 10^{-0.042\alpha}$ at the pressure-side and δ^* grows at the suction-side with a factor $f_s = 10^{0.068\alpha}$. Because $\delta_\alpha^* = \delta_s^*$, $f_\alpha = f_s$. K_α has a large negative value for α = 0. For 1° < α < 10° and M = 0.2 the calculated values of K_α (see formula 49 in [Brooks *et al* 1989] with $K_\alpha = K_2 - K_1 + 3$) are plotted in figure B.1 and these can be approximated by:

$$K_\alpha = -0.35\cdot\alpha^2 + 5.5\cdot\alpha - 14.4 \text{ (α in degrees)} \qquad (B.6)$$

With equation B.4, equation B.5 can be rewritten as:

$$SPL_{TE} = 10\cdot\log(\delta^*\cdot M^5\cdot\Delta R\cdot D_h/r^2) + K_1 - 3 +$$

$$+ 10\cdot\log(\Sigma_i\ 10^{(10\cdot\log(fi)+Spi + Ki)/10}) \qquad (B.7)$$

The last term in B.7 is the α-dependent part. For the peak frequency 1/3 octave band level (Sp_i = 0) the last term in equation B.7 is 3 dB for α = 0 and 3.4 dB for α = 1°, then increasing with 1.5 dB per degree to 14.5 dB at α = 9°. The level increase $\Delta SPL_{TE}(\alpha) = SPL_{TE}(\alpha) - SPL_{TE}(\alpha=0)$ is given in table B.1 and plotted in figure B.1. The best lineair approximation in the range 1° < α < 10° is:

$$\Delta SPL_{TE}(\alpha) = 1.5 \cdot \alpha - 1.2 \text{ (dB)} \quad \text{(B.8)}$$

with α in degrees (or $\Delta SPL_{TE}(\alpha) = 86 \cdot \alpha - 1.2$ dB with α in radians).

Table B1: increase of trailing edge sound level with angle of attack α

A	1º	2º	3º	4º	5º	6º	7º	8º	9º
$\Delta SPL_{TE}(\alpha)$ (dB)	0.4	1.4	2.9	4.6	6.4	8.0	9.4	10.6	11.5

The blade swish that is audible near a turbine is a variation in level of less than 3 dB (in daytime) [ETSU 1996]. It must correspond to a change in sound level of 1 dB to be heard at all. An increase of 1 dB corresponds to an increase in α with 0.7°, an increase of 3 dB corresponds to 2.9°. So, for a swish level of 2 ± 1 dB, we estimate the change in α at the tower passage as 1.8º ± 1.1º. Part of this is due to the lower wind velocity at the lower blade tip relative to the rotor average, the rest is due to the slowing down of the wind by the tower.

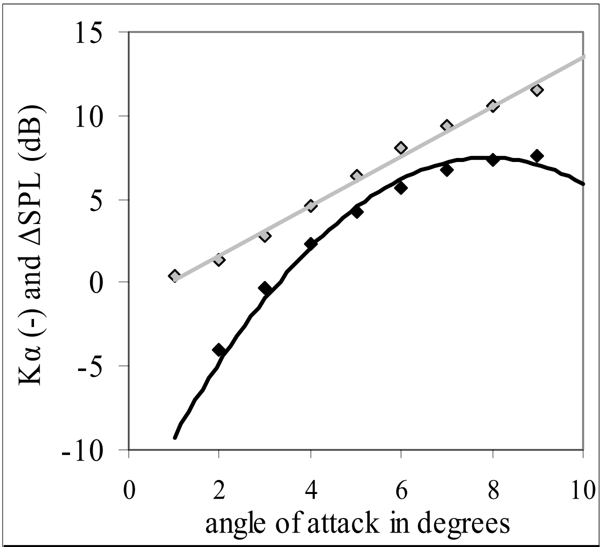


Figure B.1: non-zero angle of attack correction K_α (black diamonds) and resulting added sound pressure level ΔSPL (gray diamonds) with best fits in range $1^o < \alpha < 10^o$

For small angles the change of wind velocity with angle of attack α at radius R is $dV_{wind} = \Omega \cdot R \cdot d\alpha$, or

$$dV_{wind} = 0.017 \cdot \Omega \cdot R \cdot d\alpha \quad \text{(B.9)}$$

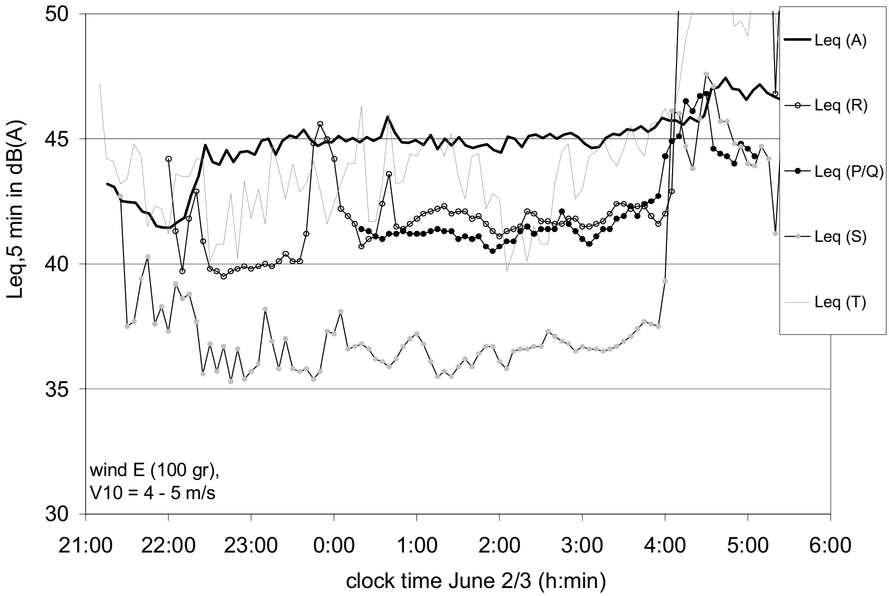
with α in degrees.

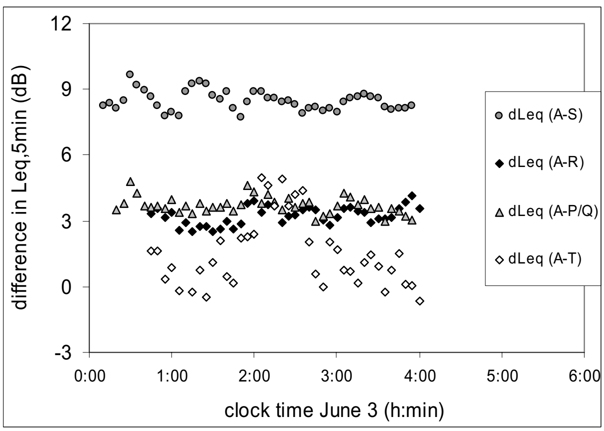
So for a modern turbine at high speed ($\Omega \cdot R \approx 70$ m/s at tip at 20 rpm) the wind velocity deficit where the blade tip passes the tower and $\alpha = 1°$ (0.017 radians) is 1.2 m/s. In a free 14 m/s wind, *i.e.* 9.3 m/s at the rotor, this is 13%. This deficit is due to the influence of the tower as well as the (daytime) wind profile.

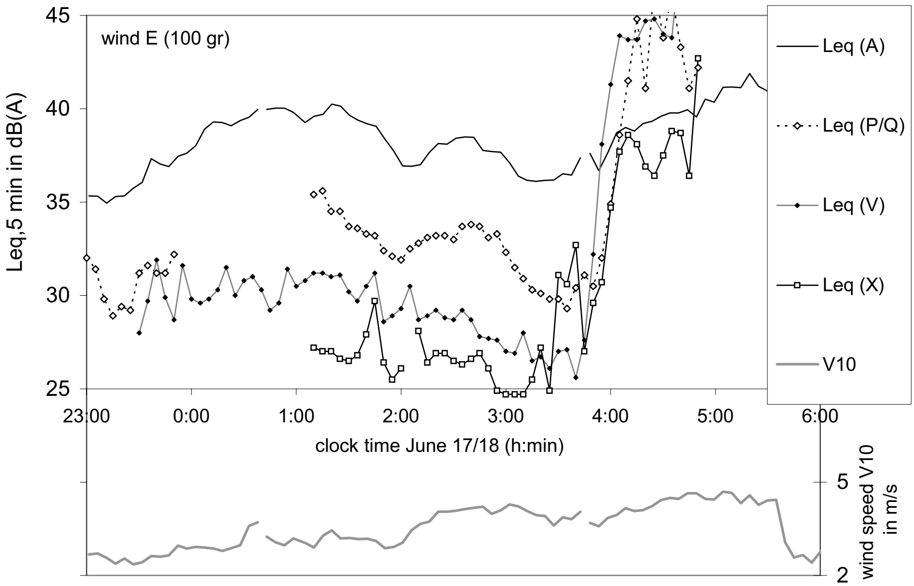
Appendix C

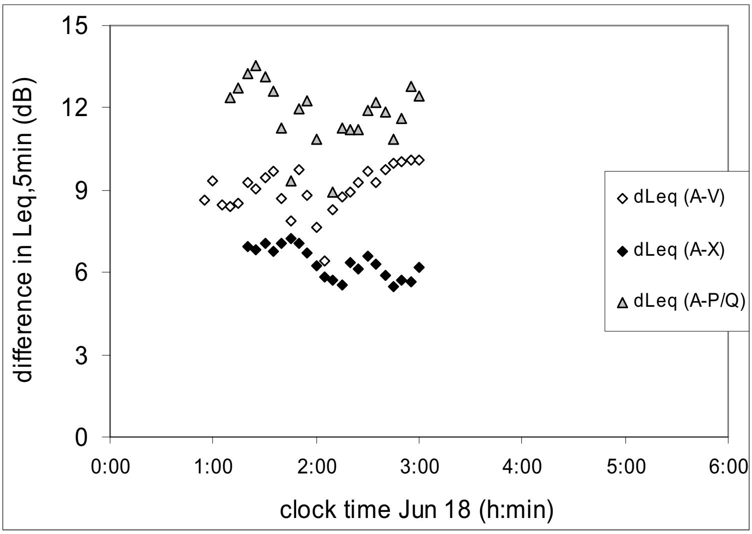
Simultaneous registrations of sound immission level

Additional information to section IV.10: measurements at locations A and P through X (see map figure IV.2) in year 2002. Graphs show measured values of $L_{eq,5min}$ at locations near Rhede wind farm and differences relative to measured value at location A. Wind velocity and wind direction and time of measurement are mentioned in the figures.






wind E (100 gr)
Leq,5 min in dB(A)
clock time June 17/18 (h:min)
wind speed V10 in m/s
Leq (A)
Leq (P/Q)
Leq (V)
Leq (X)
V10


difference in Leq,5min (dB)
clock time Jun 18 (h:min)
dLeq (A-V)
dLeq (A-X)
dLeq (A-P/Q)