consecutive periods of 15 minutes is less than 2.5 dB in 89% of the time and less than 3.5 dB in 96% of the time.

The frequency of changes between 5-minute periods that are 10 minutes apart (that is: with two 5-minute periods in between) is very similar to the distributions in figure VII.4. This means that when there is a change of 3 dB for two consecutive periods, it is unlikely a similar change occurs within the next one or two periods.

VII.4 Reduction of fluctuations in sound level

The level variation due to blade swish increases when the atmosphere becomes more stable because the angle of attack on the blade changes. As a result the turbulent layer at the trailing edge of the blade becomes thicker and produces more sound. In a wind farm the increased level variations from two or more turbines turbines may coincide to produce still higher fluctuations. The increase of blade swish, or rather: blade beating, may be lessened by adapting the blade pitch angle, the increase due to coincidence (also) by desynchronizing turbines.

VII.4.1 Pitch angle

When a blade rotates in a vertical plane the optimum blade pitch angle α is determined by the ratio of the wind velocity and the rotational speed of the blade. As the rotational speed is a function of radial distance (from the hub), blade pitch changes over the blade length and is lowest at the tip. As the wind velocity closer to the ground is usually lower, the wind velocity at the low tip (where the tip passes the tower) is lower than at the high tip. As a result the angle of attack changes within a rotation if blade pitch is kept constant. For a 100 m hub height and 70 m diameter turbine at 20 rpm this change (relative to hub height) is about 0.5° at the lower tip in an unstable atmosphere, increasing to almost 2° in a very stable atmosphere (see section V.1). Added to this is a further change (of the order of 2°) in the angle of attack in front of the tower due to the fact that the tower is an obstacle slowing down air passing the tower. At the high tip the change in angle of attack is -0.3° (unstable) to -1.7° (very stable).

The optimum angle of attack of the incoming air at every position of the rotating blade can be realized by adapting the blade pitch angle to the local wind velocity. Pitch must then increase for a blade going upward and decrease on the downward flight. Such a continuous change in blade pitch is common in helicopter technology. If the effect of stability on the wind profile would be compensated by pitch control, blade swish due to the presence of the tower would still be left. This residual blade swish can be eliminated by an extra decrease in blade pitch close to the tower. If the variations in angle of attack can be reduced to 1° or less, blade swish will cause variations less than 2 dB which are not perceived as fluctuating sound.

VII.4.2 Rotor tilt

If the rotor is tilted backwards, a blade element will move forward on the downward stroke and backward on the upward stroke, thus having a varying velocity component in the direction of the wind. As a result the angle of attack will change while the blade rotates because the flow angle will depend on blade position. If the tilt angle changes from zero to θ, the flow angle at the low tip increases from φ to φ' (see figure III.2). From geometrical considerations (see figure VII.5) of a blade segment tilted around a horizontal axis, it follows that $C\cdot\sin\varphi + r\cdot\tan\theta \quad r\cdot\tan(\theta + \gamma)$, where $\gamma \quad \arctan(C\sin\varphi/r)$. This leads to:

$$\sin\varphi' \quad S\cdot(\tan[\theta + \arctan(\sin\varphi/S)] \quad \tan\theta) \quad \text{(VII.1)}$$

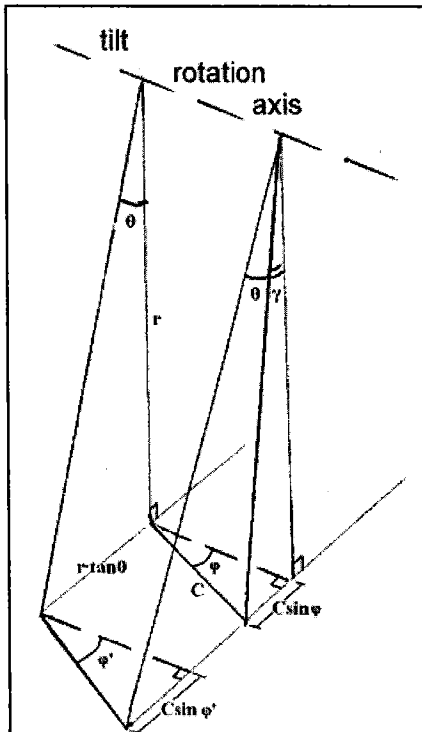


Figure VII.5: change of flow angle φ → φ' when blade is tilted over an angle θ around a horizontal axis

where $S \quad r/C$ is the ratio of radius r and blade width (or chord length) C at radius r. For small blade pitch angles and blade slenderness S between 10 and 40 the increase of blade pitch with tilt (from 0 to θ) can be approximated with:

$$\Delta\varphi \quad \varphi' \quad \varphi \quad 1.1\cdot\varphi\cdot\theta^2 \qquad \text{(angles in radians)} \qquad \text{(VII.2a)}$$

For values of φ, S and θ in the range $\varphi \leq 10°$, $30 \leq S \leq 50$ and $\theta \leq 20°$, the standard deviation of the constant 1.1 is 0.01. With angles expressed in degrees, equation VII.2a reads:

$$\Delta\varphi \quad 33\cdot 10^{5}\cdot\varphi\cdot\theta^2 \qquad \text{(angles in degrees)} \qquad \text{VII.2b)}$$

This means that for a tilt angle of 2° and a 6° blade pitch (tip rotational speed 70 m/s, induced wind velocity 10 m/s, angle of attack 2°), the change in angle of attack (relative to a vertical rotor with zero tilt) is negligible (0.008°). Rotor tilt could now compensate a 1° change in angle of attack at the low tip when the tilt angle is 22°. In this case the horizontal distance between the low tip and the turbine tower increases with approximately 15 m. This will in turn lead to a smaller change in angle of attack as at this distance the velocity deficit due to the presence of the tower is lower. For higher values of the blade pitch angle (*ceteris paribus* implying lower values of the angle of attack) increasing the tilt angle has a bigger effect. A substantial tilt however has major disadvantages as it decreases the rotor surface normal to the wind and induces a flow component parallel to the rotor surface which again changes the inflow angle. It therefore does not seem an efficient way to reduce the fluctuation level

VII.4.3 Desynchronization of turbines

When the atmosphere becomes stable, large scale turbulence becomes weaker and wind velocity is more coherent over larger distances. The result is that different turbines in a wind farm are exposed to a wind with less variations, and near-synchronization of the turbines may lead to coincidence of blade beats from two or more turbines for an observer near the wind farm, and thus higher pulse levels (see section V.2.4). To desynchronize the turbines in this situation, the random variation induced by atmospheric turbulence (such as occurs in an unstable and neutral atmosphere) can be simulated by small and random fluctuations of the blade pitch angle or the electric load of each turbine separately.

In an unstable atmosphere turbulence strength peaks at a non-dimensional frequency n $fz/V \approx 0.01$, where V is the mean wind velocity and z is height (this is according to custom in acoustics; in atmospheric physics traditionally f is non-dimensional and n physical frequency). At z 100 m and V 10 m/s this corresponds to a physical frequency f nV/z 1 mHz. At higher frequencies the turbulence spectral power density decreases with $f^{5/3}$. When atmospheric instability decreases, the maximum shifts to a higher frequency and wind velocity fluctuations in the non-dimensional frequency range of 0.01 to 1 tend to vanish. So, to simulate atmospheric turbulence the blade pitch setting of each turbine (or the load imposed by the generator) must be fed independently with a signal corresponding to noise such as pink (f^{1}) or brown (f^{2}) noise, in the range of appr. 1 to 100 mHz. The (total) amplitude of this signal must be determined from local conditions, but is of the order of 1°.

VII.5 Conclusion

Wind turbine noise has shown to be a complex phenomenon. In the future quieter blades will be available, reducing sound emission by some 2 dB. The only presently available effective measures to decrease the sound impact of modern turbines are to create more distance or to slow down the rotor.

In existing turbines the sound immission level can be decreased by controlling the sound emission, which in turn is decreased by slowing down the rotor speed. When the limit is a single maximum sound immission level, this in fact dictates minimum distance for a given turbine and there is no further legal obligation to control.

In other cases the control strategy will depend on whether the legally enforced limit is a 10-m wind velocity or an ambient background sound level dependent limit. The 10-m wind velocity or the background sound level act as the control system input, blade pitch and/or load on the rotor is the controlled parameter. In both cases a suitable place must be chosen to measure the input parameter. For background sound level as input it is probably necessary to use two or more inputs to minimize the influence of local (near-microphone) sounds. It may however be the best strategy in

relatively quiet areas as it controls an important impact parameter: the level above background or intrusiveness of the wind turbine sound.
Controlling sound emission requires a new strategy in wind turbine control: in the present situation there is usually more room for sound in daytime and in very windy nights, but less in quiet nights.

A clear characteristic of night time wind turbine noise is its beating character. Even if the sound emission level does not change, annoyance may decrease by eliminating the rhythm due to the blades passing the tower. Again, a lower rotational speed will help as this reduces the overall level including the pulse level. A better solution is to continuously change the blade pitch, adapting the angle of attack to local conditions in each rotation. This will also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.
When the impulsive character of the sound is heightened because of the interaction of several turbines in a wind farm, this may be eliminated by adding small random variations to the blade pitch, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

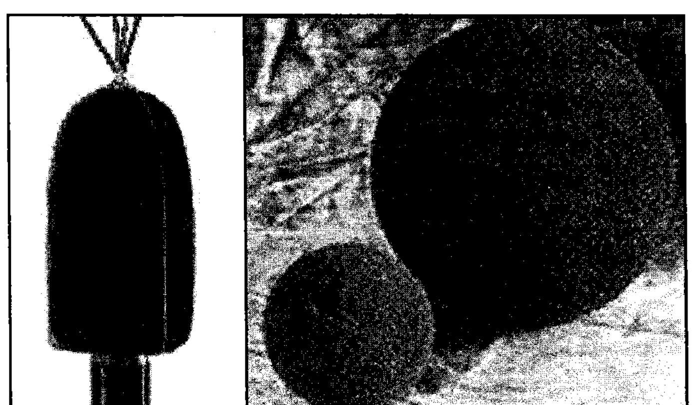


Figure VIII.0: foam wind screens

VIII RUMBLING WIND: wind induced sound in a screened microphone

VIII.1 Overview of microphone noise research

It is commonly known that a wind screen over a microphone reduces 'wind noise' that apparently results from the air flow around the microphone. An explanation for this phenomenon has been addressed by several authors. According to a dimensional analysis by Strasberg [1988] the pressure within a spherical or cylindrical wind screen with diameter D in a flow with velocity V, depends on Strouhal number Sr $\quad fD/V$, Reynolds number Re $\quad DV/\nu$ and Mach number M $\quad V/c$ (where ν is the kinematic viscosity of air and c the velocity of sound). Writing the rms pressure in a relatively narrow frequency band centered at frequency f as p_f, and in dimensionless form by division with ρV^2, Strasberg found: $p_f/\rho V^2 \quad$ *function*(Sr, Re, M). Comparison with measured 1/3 octave band levels from four authors on 2.5 - 25 cm diameter wind screens, in air velocities ranging from 6 to 23 m/s yielded a definite expression for 1/3 octave frequency band:

$$20\cdot\log_{10}(p_{1/3}/\rho V^2) \quad 23\cdot\log_{10}(f_m D/V) \quad 81 \qquad \text{(VIII.1)}$$

where f_m is the middle frequency of the 1/3 octave band. The data points agreed within appr. 3 dB with equation VIII.1 for $0.1 < fD/V < 5$, except for one of the fourteen data series where measured values diverged at $fD/V > 2$. Equation VIII.1 can also be written in acoustical terms by expressing the rms pressure as a sound pressure level relative to 20 μPa:

$$L_{1/3} \quad 40\cdot\log_{10}(V/V_o) \quad 23\cdot\log_{10}(f_m D/V) + 15 \qquad \text{(VIII.2)}$$

Here V_o is a reference velocity of 1 m/s and $\rho \quad 1.23$ kg/m^3 is used (air density at 1 bar and 10 °C). Equation VIII.2 is slightly different from the expression given by Strasberg because SI-units are used and terms in logarithms have been non-dimensionalized.

Morgan and Raspet pointed out that all measurements reported by Strasberg were made in low turbulence flows, such as wind tunnel flow [Morgan *et al* 1992]. Strasberg's result thus referred to the wake created by a wind screen and excluded atmospheric turbulence (as Strasberg had noted himself in his concluding remarks [Strasberg 1988]). Outdoors, however, the flow is turbulent, and induced pressure variations are expected to depend on meteorological parameters also. Morgan & Raspet applied Bernoulli's principle by decomposing the wind velocity U in a constant time-averaged velocity V and a fluctuation velocity u with a time average u 0, to obtain the rms pressure fluctuation p $\rho V u$ [Morgan *et al* 1992] (in this chapter italics are used to denote the rms value x of a variable x: x $\sqrt{x^2}$). This method can be compared to Strasberg's model for a microphone in turbulent water flow [Strasberg 1979]. Measurements in wind velocities of 3 13 m/s at 30.5 m and 1.5 m height for different screen diameters (90 and 180 mm) and screen pore sizes (10, 20, 40 and 80 ppi) yielded:

$$p \quad \alpha \cdot \rho (V u)^k \tag{VIII.3}$$

with α ranging from 0.16 to 0.26 and k from 1.0 to 1.3 [Morgan *et al* 1992]. For some measurements Morgan *et al* showed spectra over almost the same frequency range where equation VIII.1 is valid ($0.1 < fD/V < 5$). The spectra have a positive slope up to 3 Hz, possibly due to a non-linear instrumental frequency response. At higher values the slope is roughly comparable to what Strasberg found, but values of $20 \cdot \log_{10}(p_{1/3}/\rho V^2)$ are generally 8 20 dB higher as predicted by equation VIII.1, implying that atmospheric turbulence dominated expected wake turbulence.

Zheng and Tan tried to solve this problem analytically [Zheng *et al* 2003]. Their analysis applies to low frequency variations, so the velocity variation u is uniform over the wind screen. Zheng & Tan state that this assumption seems to be valid for a low screen number D/λ (< 0.3), the ratio between screen diameter and wavelength. Ignoring viscous effects (*i.e.* infinite Reynolds number), and calculating the pressure variation p(0) at the center of a spherical wind screen caused by pressure variations at the surface induced by a wind velocity U V + u, they found p(0) -½·ρVu or:

$$p(0) \quad \tfrac{1}{2} \rho V u \tag{VIII.4}$$

Comparison with equation VIII.3 shows that now α 0.5 and k 1.

Finally, in this overview, Boersma [1997] found that sound spectra due to wind measured at 1.5 m above flat, open grassland were in good agreement with Strasberg's results. However, Boersma used 95 percentile levels (L_{95}) which he estimated to be 6 to 13 dB lower than equivalent sound levels in the range considered ($30 < L_{95} < 70$ dB) [Boersma 1997], but he did not apply a level correction. So, in fact he found that his wind related spectra had slopes comparable to Strasberg's, but with a 6 13 dB higher value, not unlike the Morgan & Raspet spectra.

So, from literature we conclude that air turbulence creates pressure fluctuations especially at low frequencies, but the origin -wake or atmospheric turbulence- has not been definitely resolved.

In this chapter we will try to estimate the level of pressure variations due to atmospheric turbulence, *i.e.* the 'sound' pressure level taken from a sound level meter caused by turbulence on the microphone wind screen. First we will describe the spectral distribution of atmospheric turbulence and the effect this turbulence has on a screened microphone. Then we will turn to measured spectra related to wind, obtained by the author as well as by others. Finally the results will be discussed.

VIII.2 Atmospheric turbulence

A wind borne eddy that is large relative to the microphone wind screen (hence the change of wind velocity is nearly the same all over the wind screen) can be regarded as a change in magnitude and/or direction of the wind velocity [Zheng *et al* 2003]. The change in the magnitude of the velocity causes a change in pressure; the change in direction is irrelevant for a spherical wind screen as nothing changes relative to the sphere. As we saw in the previous section, when the velocity U is written as a constant (average) wind velocity V and a fluctuating part u, and similarly P $P_{average}$ + p, the relation between the rms microphone pressure fluctuation p and the rms wind velocity fluctuation u is p $\alpha\rho V u$. For inviscid flow α 0.5. For finite Reynolds numbers ($Re/10^4 \approx 0.5$ 15 for wind screens of 4 20 cm and wind velocities of 2 12 m/s), screening is better [Zheng *et al* 2003], and $\alpha \leq 0.5$; Morgan & Raspet [1992] found α 0.16 0.26. The pressure level due to atmospheric turbulence can be expressed as a sound pressure level L_{at} (with reference pressure $p_{ref} \quad 20\ \mu Pa$):

$$L_{at}(u) \quad 20 \cdot \log_{10}(\alpha \rho V u / p_{ref}) \qquad \text{(VIII.5)}$$

which is frequency dependent because of u.

VIII.2.1 Turbulence spectra

Turbulent velocity fluctuations v and w also exist perpendicular to the average wind velocity, in the vertical (w) as well as horizontal (v) direction, and are of the same order of magnitude as in the longitudinal direction [Jensen *et al* 1982]. Zheng & Tan [2003] showed that the effect of these fluctuations on the pressure at the microphone can be neglected in a first order approximation, as it scales with v^2 and w^2 and is therefore second order compared to the effect of the component u in line with the average wind velocity V that scales as Vu.

Atmospheric turbulence is treated in many papers and textbooks (such as [Jensen *et al* 1982, Zhang *et al* 2001]), also in reference to acoustics (see, *e.g.*, [Wilson *et al* 1994]). Here a short elucidation will be presented, leading to our topic of interest: turbulence spectra.
Atmospheric turbulence is created by friction and by thermal convection. Turbulence due to friction is a result of wind shear: at the surface the wind velocity is zero whereas at high altitudes the geostrophic wind is not influenced by the surface but a result of large scale pressure differences as well as Coriolis forces resulting from earth's rotation. In between, in the atmospheric boundary layer wind velocity increases with height z, equation III.2 is valid and for convenience repeated here :

$$V \quad (u_*/\kappa) \cdot [\ln(z/z_o) \quad \Psi] \qquad \text{(VIII.6)}$$

For $-1 < \zeta < 1$, $\Psi(\zeta)$ is of the same order of magnitude as the logarithmic term in equation VIII.6 ($2 < \ln(z/z_o) < 6$ for $1 < z < 5$ m, $1 < z_o < 10$ cm). Hence, at the same height and roughness length, V may still change appreciably due to (in)stability.

The friction created by wind shear produces eddies over a range of frequencies and lengths, their size determined by z and V. These eddies break up in ever smaller eddies and kinetic turbulent energy is cascaded to smaller sizes at higher frequencies, until the eddies reach the Kolmogorov size η_s ($\approx$ 1 mm) and dissipate into heat by viscous friction. It has been shown by Kolmogorov that for this energy cascade, in the so-called inertial subrange of the turbulent spectrum, the frequency dependency follows the well known 'law of 5/3': the spectrum falls with $f^{5/3}$.
It is customary in atmospheric physics to express turbulence frequency in dimensionless form n, with n fz/V (in fact n and f are usually interchanged, but we will use f for dimensional frequency, as is usual in acoustics). The seminal Kansas measurements showed that the squared longitudinal velocity fluctuation u_f^2 per unit frequency in a neutral atmosphere depends on frequency as [Kaimal *et al* 1972]:

$$f \cdot u_f^2/u_*^2 \quad 105n\cdot(1+33n)^{5/3} \qquad \text{(VIII.7)}$$

The experimentally determined constants in this equation, the non-dimensional turbulent energy spectrum, are not exact, but are close to values determined by others [Garrat 1992, Zhang *et al* 2001]. For n << 1, the right-hand side approximates 105n, which, with n fz/V and equation VIII.6, leads to $u_f^2 \quad 105\cdot u_*^2\cdot z/V \quad 105\kappa^2 zV\cdot[\ln(z/z_o) \quad \Psi]^2$. Applying this to VIII.5, the induced pressure level per unit of frequency appears to be independent of frequency, but increases with wind velocity (~ 30·logV).
For n >> 1 the right-hand side of equation VIII.7 reduces to $3.2\cdot(33n)^{2/3}$, leading to $u_f^2 \quad 0.3\cdot u_*^2\cdot(V/z)^{2/3}\cdot f^{5/3}$, which describes the inertial subrange. The frequency where the wind velocity spectrum VIII.7 has a maximum is n_{max} 0.05 or f_{max} 0.05V/z. As sound measurement are usually at heights $1 < z < 5$ m, f_{max} is less than 1 Hz for wind velocities V < 20 m/s,

When insolation increases the surface temperature, the atmosphere changes from neutral to unstable and eddies are created by thermal differences with sizes up to the boundary layer height with an order of magnitude of 1 km. Turbulent kinetic energy production then shifts to lower frequencies. In contrast in a stable atmosphere, where surface temperature decreases because of surface cooling, eddy production at low frequencies (corresponding to large eddy diameters) is damped and the spectral maximum shifts to a higher frequency up to appr. n 0.5 for a very stable atmosphere. As low-altitude wind velocities ($z < 5$ m) in a stable atmosphere are restricted to relatively low values (for higher wind velocities, stability is disrupted and the atmosphere becomes neutral), the spectral maximum may shift up to $0.5V/z \approx 3$ Hz. The inertial subrange thus expands or shrinks at its lower boundary, but its frequency dependency follows the 'law of 5/3'.

VIII.2.2 Effect on microphone in wind screen

The spectrum of longitudinal atmospheric turbulence in the inertial subrange was described in the previous section with the (squared) rms value of velocity variation per unit frequency $u_f^2 \quad 0.3 \cdot u_*^2 \cdot (V/z)^{2/3} \cdot f^{\ 5/3}$. It is convenient to integrate this over a frequency range f_1 - f_2 to obtain a 1/3-octave band level ($f_m \quad 2^{\ 1/6} \cdot f_2 \quad 2^{1/6} \cdot f_1$) with centre frequency f_m: $u_{1/3}^{\ 2} \quad 0.046 \cdot u_*^{\ 2} \cdot (f_m \cdot z/V)^{\ 2/3} \qquad [0.215 \cdot u_* \cdot (f_m \cdot z/V)^{\ 1/3}]^2$. Substituting u_* from equation VIII.6 and applying the result to equation VIII.5 for 1/3 octave band levels $L_{at,1/3}(f_m) \quad 20 \cdot \log(\alpha\rho V u_{1/3}/p_{ref})$, yields:

$$L_{at,1/3}(f) \quad 40 \cdot \log(V/V_o) \quad 6.67 \cdot \log(zf/V) \quad 20 \cdot \log[\ln(z/z_o) - \Psi] + C \qquad \text{(VIII.8)}$$

Here the frequency index m as well as the logarithm index 10 have been dropped, as will be done in the rest of the text. In equation VIII.8 C $20 \cdot \log(0.215\kappa\alpha\rho V_o^{\ 2}/p_{ref}) \quad 62.4$ dB for $\kappa \quad 0.4$, $\alpha \quad 0{,}25$, $\rho \quad 1{,}23$ kg/m^3 and pressure level is taken re $p_{ref} \quad 20$ µPa. For octave band levels $L_{at,1/1}(f)$ the constant C in the right hand side of VIII.8 is 67.2 dB.

Equation VIII.7 does not apply to frequencies where eddies are smaller then the wind screen. The contribution of small eddies will decrease proportional to the ratio of eddy size (ℓ^2, where ℓ is the eddy length scale and $f \quad V/\ell$) and wind screen surface πD^2. When this ratio decreases more eddies will simultaneously be present at the screen surface and resulting pressure fluctuations at the surface will more effectively cancel one another in the interior of the wind screen. The pressure variation in the wind screen centre resulting from one eddy is proportional to the size of the eddy relative to the screen surface, *i.e.* ℓ^2/D^2, but also the screen centre pressure resulting from the random contributions of all N eddies on the screen surface is proportional to $\sqrt{N}$, where $N \sim D^2/\ell^2$. The resulting screen centre pressure is thus proportional to individual eddy pressure p_f and $(\ell^2/D^2)\cdot\sqrt{(D^2/\ell^2)} \quad \ell/D \quad V/fD$. Consequently a factor $-20\cdot\log(fD/V)$ must be added to the resulting rms pressure level.

In wind noise reduction measured by Morgan there is a change in frequency dependency at screen number $D/\ell \approx 1/3$ ([Morgan 1993], see also [Zheng *et al* 2003]). We therefore expect at sufficiently high frequencies the pressure level at the microphone to decrease proportional to $20\cdot\log(D/\ell)$, relative to the level in equation (VIII.8), and this decrease must vanish when $D/\ell \quad Df/V < 1/3$, *i.e.* below the cut-off frequency $f_c \quad V/(3D)$. As the change will be gradual, a smooth transition can be added to equation VIII.8:

$$L_{at,1/3}(f) \quad 40\cdot\log(V/V_o) \quad 6.67\cdot\log(zf/V) \quad 20\cdot\log[\ln(z/z_o)-\Psi] +$$

$$10\cdot\log(1+(f/f_c)^2) + C \qquad \text{(VIII.9a)}$$

With usual screen diameters 5 25 cm and wind velocities 1 - 20 m/s, the cut-off frequency is in the range of 1 to 100 Hz. With the common 10 cm diameter wind screen f_c will usually be in the infrasound region. Equation VIII.9a can be rewritten with Strouhal number $Sr \quad fD/V$ as independent variable of a 'meteorologically reduced' 1/3 octave band level L_{red}:

$$L_{red,1/3} \quad L_{at,1/3} \quad 40\cdot\log(V/V_o) + 20\cdot\log[(z/D)^{1/3}\cdot(\ln(z/z_o)-\Psi)]$$

$$6.67\cdot\log(Sr) \quad 10\cdot\log[1+(3Sr)^2] + C \qquad \text{(VIII.9b)}$$

The levels according to equation VIII.9 have been plotted in figure VIII.1 for different wind velocities and with $z \quad 20\cdot D \quad 40\cdot z_o \quad 2$ m, $\Psi \quad 0$. For $f < 0.5\cdot f_c$ the term before C is less then 1 dB and equation VIII.9a reduces to equation VIII.8. For frequencies $f >> f_c$ the term before C in equation VIII.9b reduces to $-20\cdot\log(3Sr)$ and equation VIII.9b can be written as:

$$L_{red,1/3} \quad 26.67\cdot\log(Sr) + C - 9.5 \qquad \text{(VIII.10a)}$$

This can be rewritten in a aerodynamic terms as:

$$L_{p,1/3} \quad 20\cdot\log(p_{1/3}/\rho V^2) \quad 26.67\cdot\log(\mathrm{Sr}) + F(z) + C_p \qquad \text{(VIII.10b)}$$

where and $F(z)$ $20\cdot\log[(z/D)^{1/3}\cdot(\ln(z/z_o)-\Psi)$ and C_p $20\cdot\log(0.215\kappa\alpha)$ 9.5 -43 dB. For $F(z)$ -20 dB (*e.g.* a 10 cm diameter wind screen at a z 2 m, z_o 5 cm and Ψ 0) the right hand side of equation VIII.10b is -26.67·log(Sr) 63. Comparing this with Strasberg's result (equation VIII.1 and gray lines in figure VIII.1) we see that the frequency dependency is slightly different, and levels are 13 - 19 dB higher (0.5 < Sr < 20), which is of the order of what we found in the measurements by Boersma and Raspet *et al* (see section VIII.1). The change in slope, visible at Strouhal number Df_c/V 1/3 in figure VIII.1, is a feature not explained by the earlier authors.

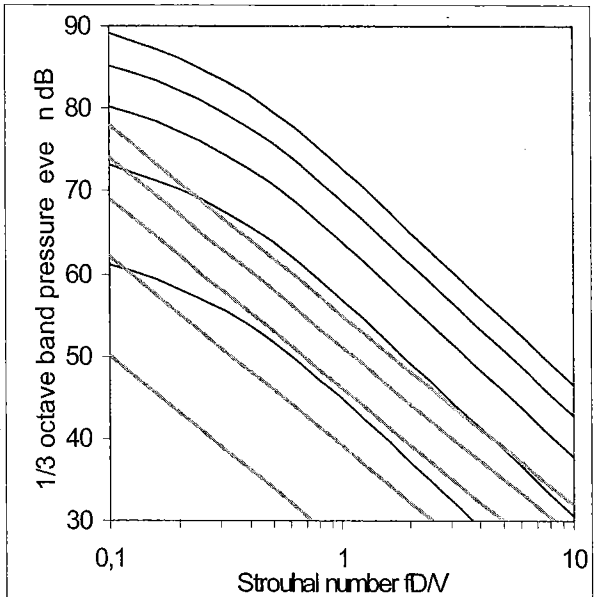


Figure VIII.1: black lines: calculated 1/3 octave band levels $L_{at,1/3}$ due to atmospheric turbulence at wind velocities of (bottom to top) 2, 4, 6, 8 and 10 m/s; F(z) = -18 dB; gray lines: levels at same wind velocities according to Strasberg

VIII.2.3 Frequency regions

From the theory above it can now be concluded that the wind induced pressure level on a (screened) microphone stretches over four successive frequency regions:

i. at very low frequencies (less than a few Hz) the turbulence spectrum is in the energy-producing subrange; 1/3 octave band pressure level $L_{at,1/3}$ is independent of frequency (white noise), but increases with wind velocity;
ii. at frequencies up to f_c 0.3V/D, which is usually in the infrasound region, the turbulence spectrum is in the inertial subrange, $L_{at,1/3}$ ~ 46.7·logV and ~ 6.7·log$f$;
iii. at higher frequencies, but still in the inertial subrange, eddies average out over the wind screen more effectively at increasing frequency

($L_{at,1/3}$ ~ 26.7·log*f*), but pressure level increases faster with wind velocity ($L_{at,1/3}$ ~ 66.7·logV) ;

iv. at frequencies beyond $0.1V/\eta_s$ (see [Plate 2000, p. 585]) atmospheric turbulence enters the dissipation range and turbulence vanishes. This is in the range $Sr \quad fD/V > 0.1D/\eta_s \approx 100\cdot[D/\mathrm{m}] \quad D/\mathrm{cm}$.

The inertial subrange (ii and iii) is of most interest here, as it is within the commonly used range of acoustic frequency and level.

VIII.2.4 Wind induced broad band A-weighted pressure level

In figure VIII.2 1/3-octave band levels according to equation VIII.9 are plotted for different wind velocities for z $50\cdot z_o$ $20\cdot D$ 2 m (or F(z) -20.5 dB with Ψ 0). Also levels are plotted after A-weighting to show the relevance to most acoustic measurements, where wind induced noise may be a disturbance added to an A-weighted sound level. At the frequency where turbulent eddies enter the dissipation subrange ($f \approx 0.1V/\eta_s$), no data are plotted as the turbulent velocity spectrum falls very steeply and induced pressure levels are considered negligible. A-weighted pressure levels $L_{at,A}$ can be calculated by summing over all 1/3-octave bands. The wind velocity dependency can then be determined from the best fit of $L_{at,A}$ vs. V:

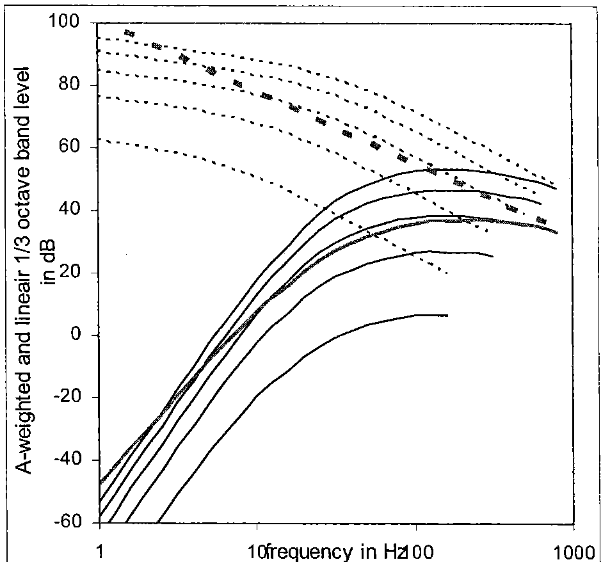


Figure VIII.2: calculated lineair (dashed) and A-weighted (solid lines) 1/3-octave pressure levels due to atmospheric turbulence on a screened microphone with F(z)+C=42 dB, D = 0.1 m and wind speeds 2, 4, 6, 8, 10 m/s (black, bottom to top); bold grey lines: 1/3 octave band levels according to Strasberg for 10 m/s

$$L_{at,A} \quad 69{,}4\cdot\log(V/V_o) \quad 26.7\cdot\log(D/\ell_o) + F(z) + C \quad 74.8 \qquad \text{(VIII.11a)}$$

where ℓ_o 1 m is a reference length. Equation VIII.11a has the same structure as VIII.10a, but a rather higher slope with logV because higher frequencies (with lower A-weighting) are progressively important, and a much smaller constant term as a result of A-weighting. The slope decreases with wind screen diameter and is 65.5 dB when D   1.25 cm (unscreened ½" microphone), but is constant within 1 dB for 5 < D/cm < 50. Equation VIII.11a is not very sensitive for the cut-off at f $0.1V/\eta$: if spectral levels are integrated over all frequencies, total level does not increase significantly at high wind velocities, and with less than 3 dB at low wind velocities. It will be noted that the slope with wind velocity is slightly higher than for individual spectral levels for $f > fc$ (66.7 dB, see equation VIII.10a, due to lower A-weighting at the increasingly higher frequencies. If we put $G(z)$ $F(z)$ $6.7\cdot\log(D/\ell_o) + 14$ $20\cdot\log[0.2\cdot(z/\ell_o)^{1/3}\cdot(\ln(z/z_o$ $\Psi)]$, and use 10D for convenience, equation VIII.11a becomes:

$$L_{at,A} \quad 69.4\cdot\log(V/V_o) \quad 20\cdot\log(10D/\ell_o) + G(z) + C \quad 68.8 \qquad \text{(VIII.11b)}$$

Now for z_o 2,5 - 6 cm and Ψ 0, G(2 m)   0 ± 1 dB. This means that for a 10 cm wind screen and measurement over a flat area with a low vegetation cover in neutral conditions $L_{at,A} \approx 69.4\cdot\log(V/V_o)$ 6.4 dB(A). Figure VIII.3 is a plot of equation VIII.11 with G(z)   0, C   62 dB. Also plotted in figure VIII.3 is the relation according to Strasberg, obtained by A-weighting and integrating equation VIII.2 over f.

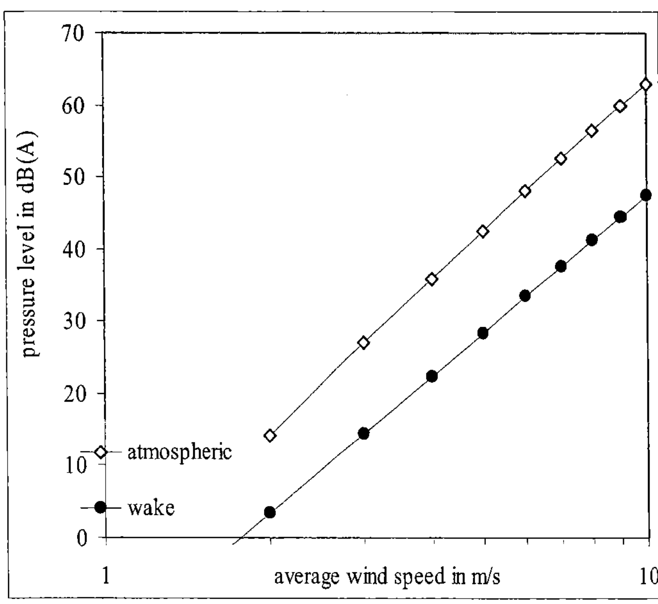


Figure VIII.3: calculated A-weighted broad band pressure level caused by atmospheric or wake turbulence with G(z)+C = 62.4 dB and D = 0.1 m

VIII.3 Comparison with experimental results

VIII.3.1 Measured spectral pressure levels

Several authors have performed measurements to determine spectral levels due to wind, including wind induced sound pressure fluctuations. We will use data from Larsson and Israelsson [1982], Jakobsen and Andersen [1983] and Boersma [1997] from screened as well as unscreened microphones. Table VIII.1 gives an overview of measurement parameters. None of the authors give the degree of stability, but in Jakobsen's data $\Psi \leq 0$ (night), in Boersma's $\Psi \geq 0$ (summer's day). Jakobsen mentions roughness height of the location (a golf course), Boersma grass height ($\approx$ 10 cm), Larsson only mentions measurement height over grass at either 1.25 or 4 m, without specifying which height applies to a measurement result. To prevent using spectra at large values of $|\Psi|$ no data at low wind velocities (< 2 m/s at microphone) are used. This is also recommendable as at low wind velocity sound not related to wind is more likely to dominate. We preferably use L_{eq} data. However, these are not available from Boersma. Boersma used 95 percentile levels (L_{95}), but we have L_{50} values from the original data. Though Boersma quotes $L_{Aeq} \approx L_{A50}$, we will use $L_{Aeq} \approx L_{A50} + 3$, in agreement with long term data on wind noise [Van den Berg 2004b] and assume this to be valid for every frequency band. If measurements yielded octave band levels, 4.8 dB was subtracted to obtain the 1/3 octave band level at the same frequency.

Also L_{eq} values are presented from measurements made by the author at several locations; at one location (Zernike) for the purpose of wind noise measurements, and otherwise (Horsterwold, Kwelder) selected for having little other noise. Here also the degree of atmospheric stability is unknown, as at the time of measurement it was not known to be a relevant factor. The 'Zernike' measurements were done at the university grounds (latitude 53°14'43", longitude 6°31'48") with both the microphone (in a spherical foam screen of 2.5, 3.8 or 9.5 cm diameter) and the wind meter at 1.2 or 2.5 m over grass at least several hundred meters from trees, and an estimated roughness height of 5 cm. They were performed in daytime in December 2003 and august 2004 with a fair wind under heavy clouding.

The ‘Kwelder’ measurements were made in daytime or evening in July and August of 1996 at an open area at the Dutch coast (latitude 53°25’46”, longitude 6°32’40”), consisting of level land overgrown with grass and low weeds and close to tidal water. Sound measurements were taken at a height of 1.5 m at times when no sound could be heard but wind-related sound and distant birds. The microphone was fitted with a spherical 9.5 cm diameter foam wind screen. Wind velocity at microphone height at 1.5 m was estimated from measured wind velocity at 5 m height with equation VIII.6, z_o estimated as 2 cm. Finally the ‘Horsterwold’ measurements were made in December 2001 in an open space with grass and reeds (latitude 52°18’3”, longitude 5°29’38”) between 5 to 10 m high trees at a distance of approximately 30 m but further in the windward direction, in a mostly clouded night. Wind velocity and sound were measured at 2 m height, the wind screen was a 9 cm diameter foam cylinder. Due to the differences in vegetation, roughness length here was difficult to estimate, and was determined by fitting measurement results to the expected level (resulting in 60 cm and a more limited range of values of Ψ to fit).

At very low frequencies in our Zernike measurements the 1/3 octave band levels were corrected for non-linear response. The frequency response of the B&K ½" microphone type 4189 is specified by Brüel & Kjaer [B&K 1995] and is effectively a high pass filter with a corner frequency of 2.6 Hz. The response of the Larson Davis type 2800 frequency analyser is flat (±1 dB) for all frequencies.
To plot spectra we calculate the reduced pressure level $L_{red,1/3}$, leaving only the screen diameter based Strouhal number Sr fD/V as the independent variable. Octave band pressure levels $L_{red,1/1}$ are substituted by $L_{red,1/3}$ + 4.8. As atmospheric stability is as yet unknown, the stability function is set to zero. If wind velocity was not measured at microphone height, the logarithmic wind profile (equation (VIII.6 with Ψ 0, or III.3) is used to determine V_{mic} from the wind velocity at height h.

Linear spectra of 1/3-octave levels are plotted in the left part of figure VIII.4 for the unscreened microphones. Also plotted is the spectrum according to Larsson *et al* [1982], valid for the inertial subrange. Due to the small size of the unscreened microphone (1.25 cm) part of the spectrum lies in the dissipation range at frequencies $f > 0.1V/\eta \approx 100V/m$, corresponding to Sr > 100D/m 1.25.

In figure VIII.4B spectra are plotted from screened microphones, from the data from Larsson, Jakobsen and Boersma. As these spectra were determined with a range of screen diameters, the change from the inertial to the dissipation subrange extends over a range of non-dimensional frequencies (Strouhal numbers). Finally figure VIII.4C shows spectra from the Horsterwold, Zernike and Kwelder measurements. In all figures spectra deviate from the predicted spectrum at high Strouhal numbers because either the lower measurement range of the sound level meter is reached or

Table VIII.1: wind induced noise measurement characteristics

author	period	location	zo (cm)	H_{wind} (m)	H_{mic} (m)	V_{mic} (m/s)	D (cm)	T (min.)	N [1]	F (Hz)	band width [6]
Larsson *et al*	late summer - early autumn	grass lawn	5 [2]	mic	1.25 or 4	2 – 7	no [4]	6	9	63-8k	1/1
							9.5	obs. [5]	9		
Jakobsen *et al*	summer – dec, night	golf course	2	10	1.5	3 – 7	9.5 / 25	? [5]	5 / 5	63-8k	1/1
Boersma	summer, day	grass land	3 [2]	2	1.5	3 – 7	no [4]	160	9	6-16k	1/3
						2 – 9	9	430	7	6-16k	
this study:											
Horster-wold	night, clouded	grass, reeds	60 [3]	10	2	4 - 6	9.5	230	4	31-8k	1/1
Kwelder	summer, day	grass, herbs	2 [2]	5	1.5	3 - 5	9.5	40	6	6-16k	1/3
Zernike	summer, clouded day	grass land	5 [2]	1.5	2.5	5	2.5/3.8 /9.5	30	3	6-1k	1/3
	winter, clouded day				1.2	4	3.8/9.5	20	2	1-1k	

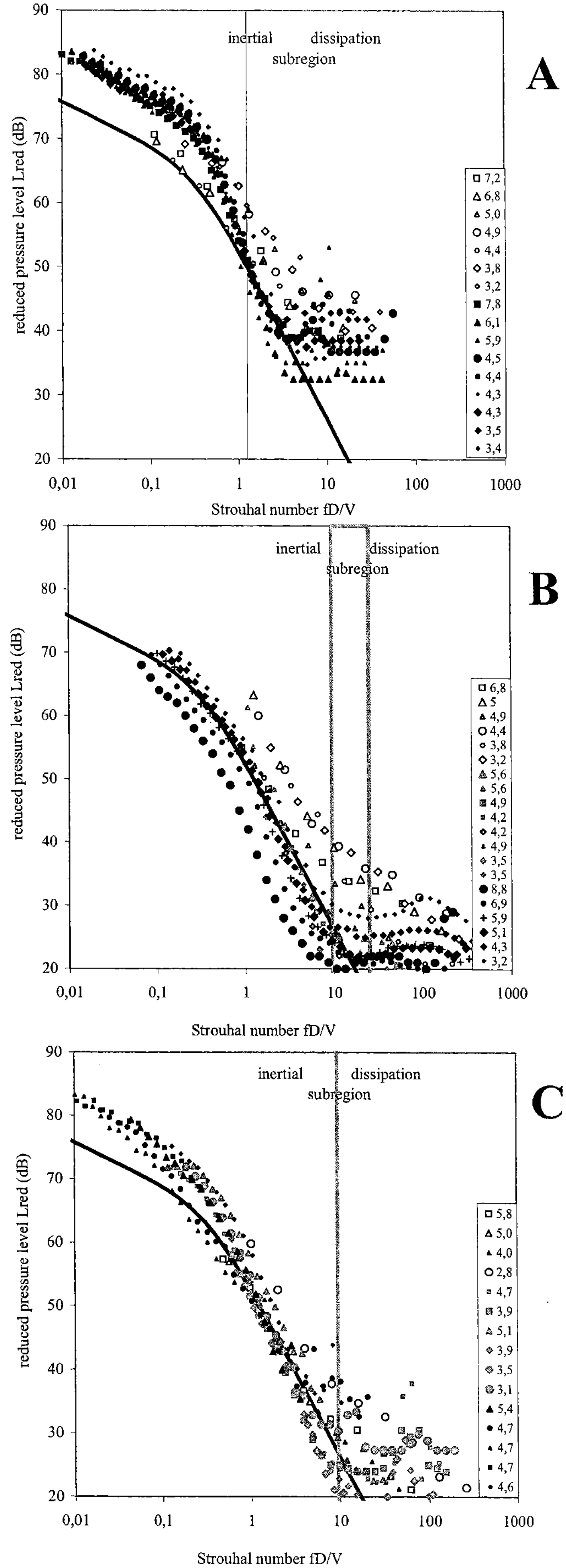
notes: 1: # of measurements 2: estimated; 3: fitted; 4: no = unscreened;
5: observations of unknown length; 6: 1/1 or 1/3 octave band

Figure VIII.4:
reduced 1/3 octave band pressure levels at different wind velocities (in legend: V in m/s), bold line is predicted spectrum;

A: unscreened microphone, from Larsson (open symbols) and Boersma (black symbols);

B: screened microphone, from Larsson (open symbols), Jakobsen (grey) and Boersma (black symbols);

C: screened microphone, measurements in Horsterwold (open symbols), Kwelder (grey) and Zernike (black symbols).



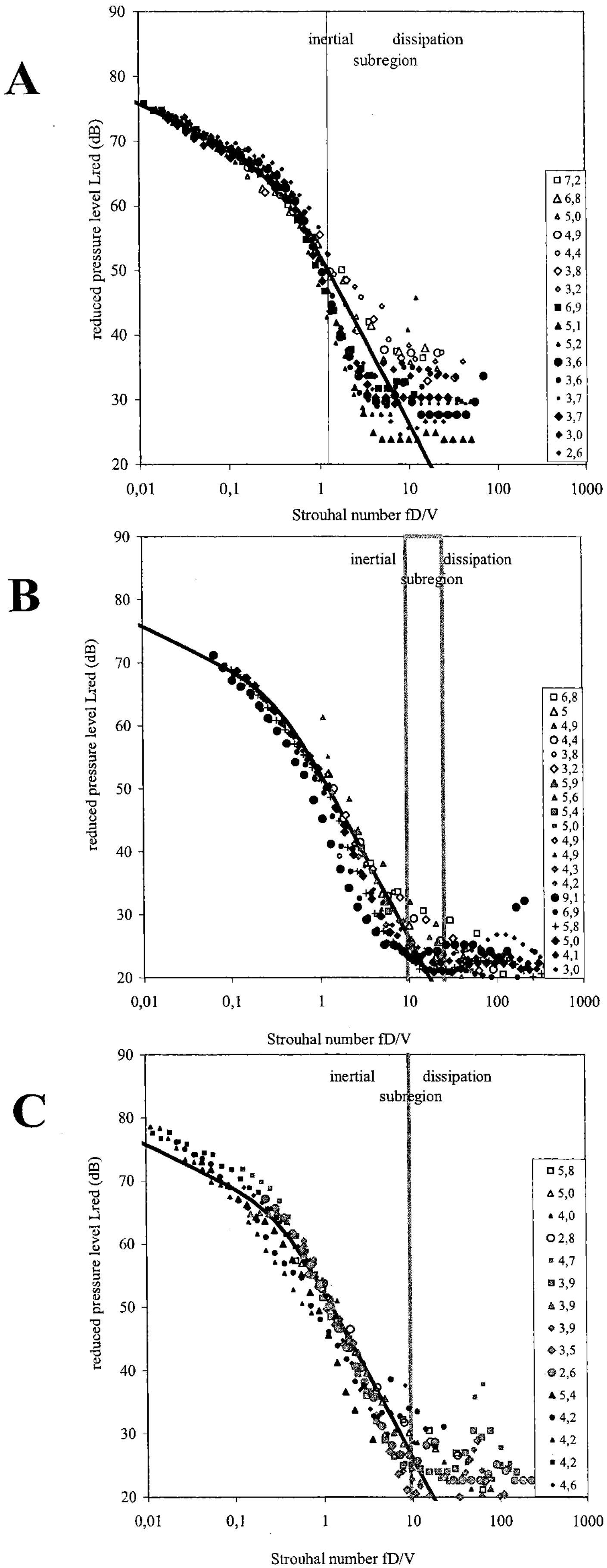


Figure VIII.5: same as figure VIII.4, but after fitting with stability function

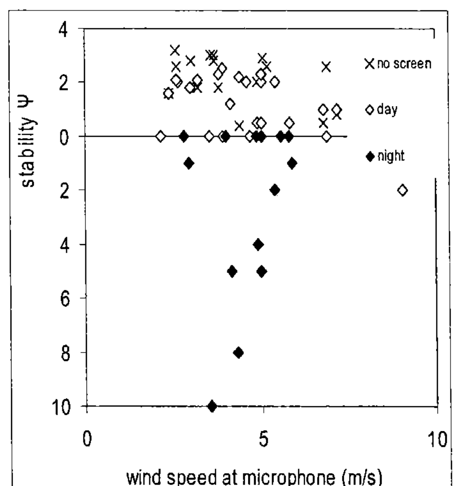


Figure VIII.6: values of the stability function Ψ found by fitting reduced spectral levels L_{red} with theoretical spectrum, for measurements in day or night time, and for unscreened microphones in daytime ambient sound dominates the wind-induced pressure level. Also, at these high Strouhal numbers most values are in the dissipation range where the present model is not valid.

In figure VIII.4 atmospheric stability has not been taken into account yet (in fact $\Psi \quad 0$ was used), due to lack of data to determine Ψ. In stable conditions ($\Psi < 0$) L_{red} will be higher, in unstable conditions ($\Psi > 0$) lower, causing the plotted spectra to shift vertically if the proper value $\Psi \neq 0$ is applied.
If wind velocity at microphone height is deduced from wind velocity at another height, the shift is more complex, as stability then also affects the term $40 \cdot \log(V/V_o)$ as well as the ordinate value $Sr \quad fD/V$. The approach taken here is to vary Ψ to obtain a best fit to the theoretical value of the L_{red} levels at non-dimensional frequencies in the inertial subrange. The fitted spectra are plotted in figure VIII.5. The values of Ψ that gave the best fits are plotted in figure VIII.6, categorized in daytime and night time measurements (where one would expect $\Psi \geq 0$ and $\Psi \leq 0$, respectively). Measurements with unscreened microphones are indicated separately, and are in daytime for Boersma's measurements and probably also for Larsson's, so one would expect $\Psi \geq 0$.

VIII.3.2 Measured broad band pressure levels

Several authors give a relation between broad band A-weighted sound pressure level L_A and wind velocity [Boersma 1997, Larsson *et al* 1982, Jakobsen *et al* 1983]. According to Boersma $L_A \sim 22.6 \cdot \log(v)$ (with v measured at 2 m height, L_A at 1.5 m), to Larsson $L_A \quad 4.4 \cdot v + 27.5$ (v and L_A measured at the same height), to Jakobsen $L_A \quad 6.8 \cdot v \quad 2.6$ (v measured at 10 m, L_A at 1.5 m). However, as Boersma clearly shows, most of the A-weighted sound is due to ambient wind induced sound, especially at low wind velocities. So we cannot use these relations for just sound induced by wind on the microphone.

A practical situation where the influence of wind on the microphone + wind screen could be investigated directly offered itself when on May 28, 2000 a storm occurred during our 'Wieringerwaard' measurements. The microphone, in a 9 cm foam cylinder, and a wind meter were both placed at a height of 4.6 m, 2 m apart, in front of a big farmer's shed 5 m to the west of the microphone (latitude 52°48'41", longitude 4°52'23"). A second, 'free wind' windmeter at 10 m height was placed further away to measure undisturbed wind. Around the measurement location were fields with potato plants of 20 - 30 cm height. As it was May, an unstable atmosphere is expected in daytime, leaning to neutral when the wind velocity increases.

Some measurement results are given in figure VIII.7 (all values are 10 minute averages of samples measured at a rate of $1\ s^{1}$). In the left part of the figure the 'free' wind velocity v_{10} is seen to increase to 20 m/s (72 km/h) in the course of the day after a relatively quiet night. The wind velocity v_{mic} near the microphone increased at practically the same rate between 6 and 12 o'clock, but then abruptly falls from 13 m/s to 2 m/s and thereafter remains at a low value even while the 'free' wind velocity is still increasing. Up to 12 o'clock the sound level (equivalent A-weighted level per 10 minutes) increases in proportion to the wind velocity reaching a maximum of 84 dB(A), but then falls abruptly to 50 dB(A) at the same time the local wind velocity collapses. In this morning the unobstructed wind began in the east and gradually turns south. When at 12 o'clock the wind passes behind the shed, the microphone is suddenly taken out of the wind. There is no reason that the *sound* reaching the microphone changes significantly during this change, but due to the sudden wind velocity reduction the measure sound pressure level drops to 50 dB(A). After that the sound pressure level increases again as long as the storm is gaining strength. The measured pressure level above 60 dB(A) is pure wind-induced 'pseudo' sound, that is: sound resulting from moving air, not from airborne sound.

In the right part of figure VIII.7 the A-weighted equivalent (pseudo-) sound pressure level per 10 minutes over the same period as in the left part of figure 7, is plotted as a function of wind velocity at the microphone. There is an obvious direct correlation between pressure level and wind velocity at higher wind velocities ($V \geq 6$ m/s) in contrast to the levels at

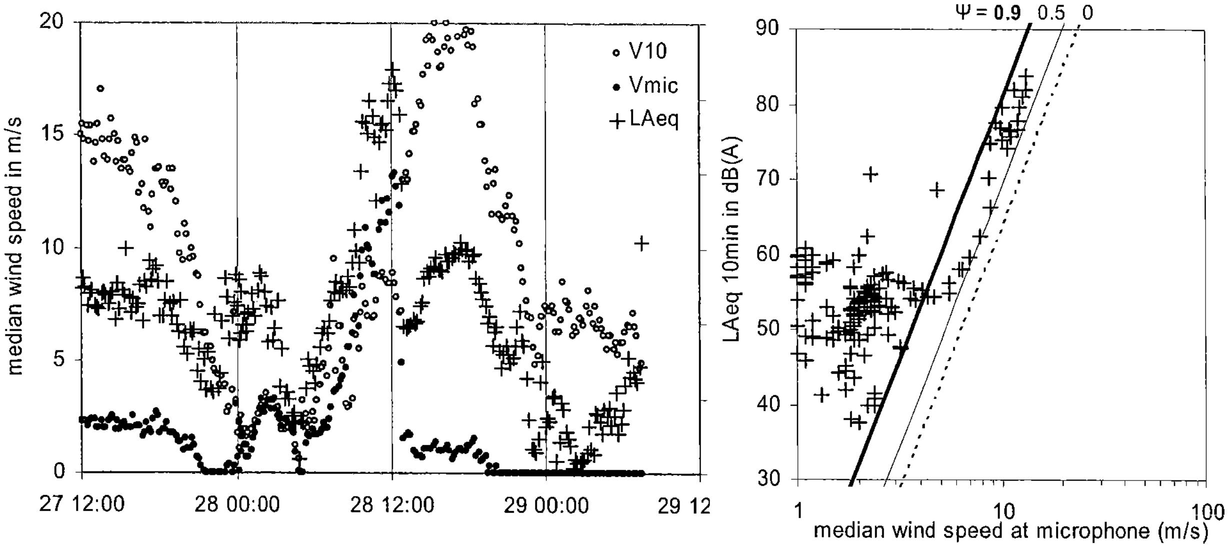


Figure VIII.7: measurements during a storm in front of a big shed; left: 10 minute averages of wind speed at microphone and at 10 m height and sound pressure level Leq; right: Leq as a function of microphone wind speed and predicted sound pressure level (G(4.6) = 8.2 dB)

lower wind velocities. Again, the stability factor Ψ is not known, but in daytime and in strong winds it must be small and positive. The lines in figure VIII.7 show the calculated pressure levels for plausible values 0 < Ψ < 1 (with z_o 20 cm), encompassing the measured values.

VIII.3.3 Screen reduction

For two of our Zernike summer measurements (see table VIII.1) with place and atmospheric conditions unchanged within the measurement period, the difference between 1/3 octave band pressure levels measured with an approximately spherical 2.4 cm wind screen and a spherical 9.5 cm wind screen are plotted in figure VIII.8. Also

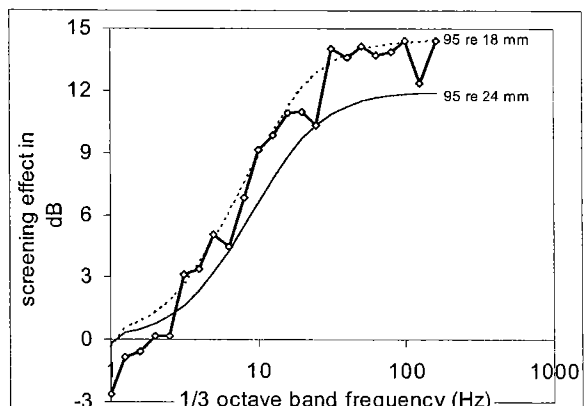


Figure VIII.8: measured (line with markers) and calculated screening effect of a 9.5 cm relative to a 2.4 or 1.8 cm wind screen plotted is the calculated screening effect based on equation VIII.9a, with only both term before C differing between both measurements. It appears that the measured screening effect is on average approximately 1 dB higher than the calculated level. It is not clear why the difference in screening is negative at frequencies below 2 Hz. For a somewhat smaller wind screen (18 mm < D < 24 mm) the average screening effect would agree better with the calculated effect.

VIII.4 Discussion

The model developed in this paper starts with the assumption that wind induced 'sound' pressure levels on a microphone are caused by atmospheric turbulence. Then, at low non-dimensional frequencies (Sr << 0.3) spectral levels are determined entirely by atmospheric turbulence. In this frequency range a wind screen has no effect. At higher frequencies, where pressure fluctuations tend to cancel one another more effectively as their scale decreases relative to the wind screen diameter, a wind screen acts as a first order low pass filter for turbulent fluctuations. In this frequency range (Sr > 0.3) a wind screen diminishes the effect of turbulence, and better so if it is bigger.

Wind induced pressure levels are determined not just by wind velocity and screen diameter, but also by two factors that are relevant for the production of turbulence: atmospheric instability and surface roughness. The stability factor Ψ and roughness height z_o are determinants for thermal and frictional turbulence, respectively. These determinants are usually not taken into account with respect to wind induced noise and are consequently not reported. Atmospheric stability therefore had to be estimated by varying the value of Ψ until a best fit was obtained of measured spectra to the calculated spectrum. Roughness length, when unknown, was assumed to be comparable to vegetation height.

The values of Ψ that resulted in the best fits are shown in figure VIII.6. They can also be compared to values obtained from long term measurements at the Cabauw measurement site of the Royal Netherlands Meteorological Institute (KNMI). The Cabauw site is in open, flat land west of the central part of the Netherlands (see Chapter VI) and may be considered representative for locations in comparable terrain in the north and central parts of the Netherlands (Boersma's and our measurements), Denmark (Jakobsen *et al*) and the Swedish Uppsala plain (Larsson *et al*). The KNMI provided us with a data file containing 30 minute averages of the Monin-Obukhov length L over one year (1987). From this the dimensionless height ζ z/L can be calculated and then the stability factor Ψ (see text below equation VIII.6). In figure VIII.9 the frequency distribution is shown of all 17520 (2·24·365) values of Ψ, for two altitudes: 2 m and 5 m. Also the frequency distribution is shown of the 42 values of Ψ resulting from our fitting procedure. The distribution of our fitted values resemble the distribution of actually occurring values (in 1987) and thus seems plausible.

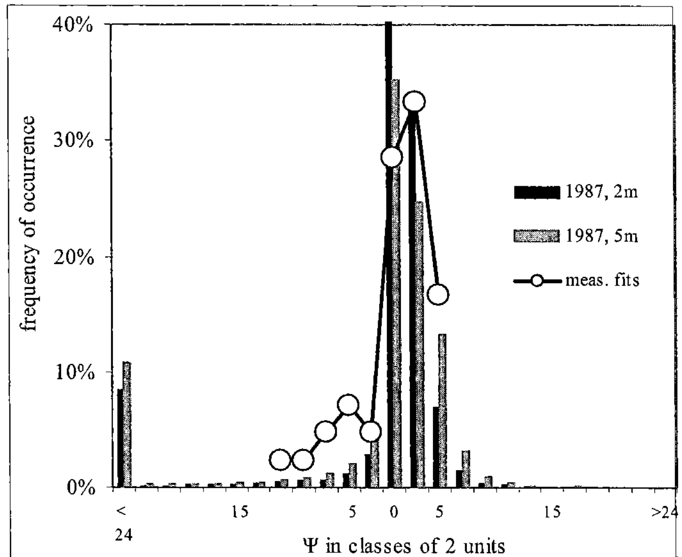


Figure VIII.9: frequency distributions of stability factor Ψ at 2m and 5 m height, based on ½ hour observations over 1987 and resulting from fitted spectra

Two constants are not known accurately: α, assumed to have a value 0.25, and the ratio of screen diameter and eddy size at the corner frequency, where 3 was used. If the Sr-related slopes are as in equation VIII.9b, the best fit of all data points in figure VIII.5 at Sr < 2.5 is a line $L_{red,1/3}$ $-6.7 \cdot \log(Sr)$ $10 \cdot \log[1+ (3.8 \cdot Sr)^2] + 62.0$. This fit is within 2.2 dB of the calculated value (equation VIII.9b). It follows that the ratio ℓ/D (3.8) where screen averaging over eddies sets in may be greater than assumed (*viz.* 3), and the constant term may be somewhat smaller, which could be a result of a lower value of α than assumed (0.24 instead of 0.25.

For 2.5 < Sr < 16 the best fit is on average 2.1 dB above the calculated value. The standard deviation of the measured 1/3 Strouhal octave band levels is less than 3.5 dB at Sr < 2.5 and up to 7 dB at 2.5 < Sr < 16.

VIII.5 Applications

As microphone wind noise appears to be closely correlated to atmospheric turbulence, acoustic measurements can alternatively be used to measure turbulence spectra or turbulence strength, especially in the inertial subrange. This provides a new way to determine (*e.g.*) friction velocity or atmospheric stability. As the measured signal decreases above the corner frequency f_c V/(3D) this frequency is best chosen high, which can be achieved with a small, bare microphone.

The present model can be used to distinguish wind induced noise from other wind related sound. An application is the measurement of wind turbine sound or (without an operating wind turbine) ambient background sound in relatively strong winds. If the measurement is on a wind exposed site it is probable that at high wind velocities wind induced noise influences or even dominates either wind turbine sound or proper ambient sound. A measured level can now be corrected for wind induced sound with a calculated wind noise level. In less exposed sites it is usually not clear in what degree the measured levels are influenced by wind induced noise. To calculate wind induced noise levels additional measurements are necessary to determine roughness height and atmospheric stability. Stability can be estimated from wind velocity measurements on two heights, using equation VIII.6. Roughness height can be estimated from tabulated values or from wind velocity measurement at two heights in a neutral atmosphere, at times when the logarithmic wind profile is valid (equation VIII.6 with Ψ 0). In neutral and stable conditions wind induced noise levels are not very sensitive to errors in roughness height: with an error of a factor of 2 in z_0 10 cm, the level changes less than 2 dB if microphone height is 3 m or more.

VIII.6 Conclusion

Measured spectra, reduced with a term for wind velocity and turbulence strength, coincide well with calculated values for unscreened as well as screened microphones in the range where the theoretical model (equation VIII.9) is valid. To test the model more thoroughly, measurements should include a determination of roughness length and atmospheric stability, in addition to the usual measurement of wind velocity and measurement height.

The model shows that to avoid high wind induced pressure levels, measurements are best performed at low wind velocity and with a large diameter wind screen, which is common knowledge in acoustics. The overall reduction ΔL_A from a bigger wind screen relative to a smaller one is determined by the ratio of the screen diameters D_1 and D_2: ΔL_A $20 \cdot \log(D_2/D_1)$ (from equation VIII.11b, $D > 5$ cm). A wind screen does not reduce noise from atmospheric turbulence at frequencies $f < V/(3D)$.
The model also shows that, to reduce wind induced sound, it helps to measure over a low roughness surface and at night (stable atmosphere), as both factors help to reduce turbulence, even if the (average) wind velocity on the microphone does not change. With reduced turbulence, wind induced pressure levels will finally reach the level given by Strasberg (equation VIII.1 or VIII.2), where turbulence is the result of the wake caused by the wind screen.
One might be tempted to think that a higher measurement altitude would also help to reduce wind noise (as this would make $G(z)$ in equation VIII.11b more negative, thus reducing $L_{at,A}$). However, in practice increasing altitude will lead to higher wind velocities, especially so in a stable atmosphere, and the first term in equation VIII.11b would more then compensate the decrease in $G(z)$. It is therefore preferable to measure at low altitude if less wind noise is desired.

IX GENERAL CONCLUSIONS

The research aims formulated in the introductory chapter (section I.6) have been addressed separately in the previous chapters. In this chapter we present an overview of all results. The results are presented in a logical order, which is not entirely in the sequence of the previous chapters.

IX.1 Effect of atmospheric stability on wind turbine sound

It is customary in wind turbine noise assessment to calculate the sound level on neighbouring premises by assuming hub height wind velocities predicted using a logarithmic wind profile. This wind profile depends only on surface roughness and is valid in a neutral atmosphere. However, it is not a predictor for wind profiles in either an unstable or stable atmosphere. Especially in a stable atmosphere a wind profile can be very different from the logarithmic, neutral profile and the hub height wind velocity is higher than predicted by the neutral profile. As more wind at hub height makes a variable speed wind turbine rotate at a higher speed, the sound power level may be significantly higher in a stable atmosphere at the same wind 10-m velocity V_{10} (which usually occurs when the sun is down and no strong near-ground wind is present) than in an unstable atmosphere (usually when the sun is up). This is especially relevant for modern, that is: tall and variable speed, wind turbines.
A stability dependent wind profile predicts the wind velocity at hub height more accurately. When a correct wind profile is used, calculated immission sound levels agree with measured night-time sound immission levels.

Sound immission measurements have been made at distances up to 2 km from the Rhede wind farm containing seventeen 98 m hub height, variable speed wind turbines, and at 280 m from a single 45 m hub height, two speed wind turbine at Boazum. Measured immission sound levels at 400 m west of the Rhede wind farm almost perfectly match (average difference: 0.1 dB) sound levels calculated from measured emission levels near the turbines. At distances up to 2 km the calculated level may underestimate the measured level, but the discrepancy is small: 1.5 dB or less.[1] Thus, from the measurements both the emission and immission sound levels could be determined accurately. As both levels can be related through a propagation model, it may not be necessary to measure both: immission measurements can be used to assess immission as well as emission sound levels of an entire wind farm.

The level of aerodynamic wind turbine noise depends on the angle of attack: the angle between the blade and the incoming air flow. Increasing atmospheric stability also creates greater changes in the angle of attack over each rotation, resulting in stronger turbine sound fluctuations. It can be shown theoretically for a modern turbine rotating at high speed that, when the atmosphere becomes very stable, the fluctuation in turbine sound level increases to approximately 5 dB. This value is confirmed by measurements at a single wind turbine where the maximum sound level periodically rises 4 to 6 dB above the minimum sound level within short periods of time. At some distance from a wind farm the fluctuations from two or more turbines may arrive simultaneously for a period of time and increase the fluctuation level further at the observer's position up to approximately 9 dB. This effect develops in a stable atmosphere because the spatial coherence in wind velocity over distances at the size of an entire wind farm increases. As a result turbines in the farm are exposed to a more constant wind and rotate almost synchronously. Because of this near-synchronicity, the fluctuations in sound level will for some time coincide at some locations, causing an amplification of the fluctuation. The place where such an amplification occurs will sweep over the area with a velocity determined by the difference in rotational frequency. The magnitude of this effect thus depends on stability, but also on the number of wind turbines and their distances to the observer.

Blade passing frequency is the parameter determining the modulation frequency of wind turbine sound. Human perception is most sensitive to

[1] In one night the sound level at over 2 km from the wind farm was much higher than calculated, probably because of an inversion layer adding more downward refracted sound. This apparently rare occurrence at the Rhede wind farm could be more significant where high inversion layers occur more often.

modulation frequencies close to 4 Hz and the modulated sound has a frequency of approximately 1000 Hz. The hypothesis that fluctuations are important is supported by descriptions given by naïve listeners as well as residents: turbines sound like 'lapping', 'swishing', 'clapping', 'beating' or 'like the surf'. It is probable that this fluctuating character is responsible the relatively high annoyance caused by wind turbine sound and a deterioration of sleep quality.

Atmospheric stability also affects the energy yield of wind turbines: relative to the 'standard' (neutral) atmosphere, a stable atmosphere increases the yield, especially for modern tall turbines. The reverse is true for an unstable atmosphere, though to a lesser degree. Perhaps atmospheric stability was not recognized as an important determinant for wind power as the underestimated night time yield is compensated partly by the overestimated daytime yield. The annual effect will depend on the average magnitude as well as the prevalence of atmospheric stability.

IX.2 Effect of atmospheric stability on ambient background sound

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

IX.3 Wind noise on a microphone

To avoid high wind induced pressure levels in windy conditions, outdoor measurements are best performed with a large diameter wind screen. The overall reduction from a bigger wind screen relative to a smaller one is determined by the ratio of the screen diameters. A wind screen does not reduce noise from atmospheric turbulence at very low frequencies.[1]

In a stable atmosphere the low near-ground wind velocity creates less wind noise on the microphone. As a result, sound measurements during a stable night are much less influenced by wind induced microphone noise (and other sounds as well, since nights are usually more quiet) than in a neutral or unstable atmosphere. The results in this book shows that wind turbine sound can be measured accurately at great distances (up to 2 km) if the atmosphere is stable.

The model developed in this thesis shows that, in order to reduce wind induced sound, it helps to measure over a low roughness surface and in a stable atmosphere, as both factors help to reduce turbulence, even if the average wind velocity on the microphone does not change. But in a stable atmosphere near-ground wind velocities will usually be low, decreasing wind induced noise further. With increasing stability, wind induced pressure levels will drop and finally reach a low level determined by turbulence in the wake of the wind screen.

IX.4 Degree of atmospheric stability

Stability is a property of the atmosphere, in principle occurring all over the earth. It depends on surface properties and weather conditions which determine the magnitude and evolution over time of the heat balance in the atmospheric boundary layer. Most important are differences in heat transfer at the surface (water, soil) and in the atmosphere (atmospheric humidity and clouds, wind mixing). With current knowledge, the effects of stability on the wind profile over flat ground can be modelled satisfactorily. In mountaineous areas terrain induced changes on the wind profile influence the stability related changes and the outcome is less easily predicted: these changes can weaken as well as amplify the effect of atmospheric stability.

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[1] frequencies below V/(3D), where V is the wind speed at the microphone and D the wind screen diameter

Results from various onshore, relatively flat areas show that in daytime the ratio of the wind velocity at 80 m (hub height) and the wind velocity at reference height of 10 m is 1.25 to 1.5. This ratio is in agreement with the usual logarithmic wind profile for low roughness lengths (low vegetation). At night the situation is quite different and the ratio has a much wider range with values from 1.7 to 4.3. At night high altitude wind velocities thus can be (much) higher than expected from logarithmic extrapolation of 10-m wind velocities.

IX.5 Measures to mitigate stability related effects

Presently available measures to decrease the immission sound level from modern turbines are to create more distance to a receiver or to slow down the rotor, preferably by an optimized control mechanism. Quieter blades as such will always be advantageous, but expected changes are modest and will not eliminate the beating or thumping character due to atmospheric stability.

Controlling the stability related sound emission requires a new strategy in wind turbine control and wind farm design. In the present situation there is usually more latitude for sound (and energy) production in daytime, but less during quiet nights. A strategy for onshore wind farms might be to use more of the potential in daytime, less at night.

A control strategy may depend on whether the legally enforced limit is a 10-m wind velocity or an ambient background sound level dependent limit. The 10-m wind velocity or the background sound level can act as the control system input, with blade pitch the controlled variable. In both cases a suitable place must be chosen to measure the input parameter. For background sound level as input it is probably necessary to use two or more inputs to minimize the influence of local (near-microphone) sounds. An ambient background controlled emission level may be the best strategy in relatively quiet areas as it controls an important impact parameter: the level above background or intrusiveness of the wind turbine sound.

Even if the sound emission level does not change, annoyance may be diminished by eliminating the rhythm due to the beating character of the sound. A solution is to continuously change the blade pitch, adapting the

angle of attack to local conditions during rotation. This will probably also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the mechanical load 'pulses' on the blades accompanying the sound pulses.
Increased fluctuation due to the interaction of sound from different turbines can be eliminated by adding small random variations to the blade pitch or rotor load, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

IX.6 Recommendations

When night time is the critical noise period, wind turbine sound levels should be assessed taking into account stable atmospheric conditions. When the impulsive character of the sound is to be assessed, this should be carried out in times of a stable atmosphere, as that is the relevant condition for impulsiveness.

When ambient sound is considered as a sound masking wind turbine sound, neither sound should be related to wind velocity at 10 meter reference height via a (possibly implicit) neutral or 'standard' wind profile. A correct, stability dependent wind profile should be used. In flat and certainly in mountainous terrain one should determine directly the relationship between hub height wind velocity on the one hand and ambient background sound at an immission location on the other hand, in order to eliminate any badly correlated, intermediate wind velocity.

Also, in the assessment of wind turbine electrical power production the sole use of a neutral wind profile (a 'standard atmosphere') should be abandoned as it yields data that are not consistent with reality.

When comparing stable and unstable atmospheric conditions, the difference in sound power as well as in sound limits can lead to new control strategies and onshore wind farm concepts. Presently only distance is a factor used to minimize noise impact. A wind farm can be optimized with a strategy that maximizes power output while keeping sound power within limits. When daytime immission levels do comply with the noise

limits, but nighttime immission levels do not, a control system can be implemented to reduce the turbine speed when necessary.
In new turbine designs continuous blade pitch control could be applied to increase energy yield and reduce annoyance at the same time by eliminating the thumping character of the emitted sound.

X EPILOGUE

This is the end of my tour of discovery, of over two years of reading about and trying to understand atmospheric physics and wind turbines, of measurements and theory, of applying knowledge and expertise in physics and acoustics to a new topic. Of course there is much more to discover: indeed, it looks like wind turbines have become more fascinating now their sound has proved to be more complex than a simple constant noise from the sky, driven only by wind with a constant profile. This may motivate researchers and consultants to put more effort in better predictions of wind turbine noise, and considering again noise exposure to local residents.

This period began with publishing the results of the measurements at the Rhede wind farm and it ended, seemingly symbolically, with the first International Conference on Wind Turbine Noise in Berlin in October 2005. At that conference there was a general acknowledgment that wind turbine sound is not the simple issue we once thought it was. At the conference many delegates agreed that, looking back, the internationally used 'standard wind profile' might have been misleading people by suggesting it was, everywhere and always, the best wind profile. Although the widely used IEC-61400 standard certainly does not state that, a less careful reader might think it did, finding no alternative profile in the standard. Thus, it becomes a question of careful communication and taking into account that acoustic consultants do (did?) not have the knowledge to apply the standard in 'non standard' conditions. Paul Botha [2005] proposed to do away with 10-m wind velocities entirely and relate background sound directly to hub height wind velocity. This is a sensible idea as it relates the two factors that are most relevant, wind turbine sound and ambient sound, without an intermediate variable (10-m wind velocity). It will lead to better insight in the masking capability of background sound: the ability to mask (make inaudible) unwanted sound is not only dependent on wind velocity, but also on atmospheric stability and wind direction.

The Berlin conference helped me solve a riddle. Malcolm Hayes had written me before that according to his observations blade swish is caused by the blade that is going down, not by the blade being in the downward position (passing the mast). This seems contradictory to my conclusion that blade beating is due to blades passing the mast. Oerlemans [2005] showed that close to the tower Malcolm was right, but this could not explain blade swish far away from a turbine. So what we heard depended on the distance to the turbine, which is also true for other sound phenomena: further away from the turbine the sound has a lower pitch, the pulses can be amplified by synchronicity of turbines and it can be louder under an inversion layer. This point again illustrates that one must be careful when generalizing observations.

I don't expect the problem of the distinct, beating character of wind turbine sound to be solved easily. Though I am convinced the sound character is a major factor in wind turbine noise annoyance, a 5 dB penalty for an impulsive character of the sound may indeed impede wind farm projects as a wind farm will need more 'empty space'. Also, the sound is not as impulsive as gun shots or hammering are, giving way to a discussion on whether it is 'really' impulsive (5 dB penalty) or not (no penalty). Is it possible to have a truly independent opinion in a legally created dichotomy with such significant consequences?
Several technical possibilities to minimize the noise have been outlined in this book, but we need not just depend on technical solutions. A change in public relations can also make a difference: proponents must accept that wind turbine noise is not (always) 'benign', that the noise may affect people, and that people who are complaining are not always just a nuisance. And no, we still do not understand wind turbine noise immission entirely, so proponents should watch their WARYDU attitude.

"….. about 80 per cent of the population supports wind power in the surveys investigated in this paper. On the local level the support of wind power in areas with operating wind power plants is equally high. (….) This, however, does not mean that protests will not appear. It takes only one devoted opponent to start for instance a legal procedure against a planning permit. This is one of the reasons why public conflicts over wind power plants have become the rule rather than the exception. Lack of communication between the people who shall live with the turbines, and the developers, the local bureaucracy, and the politicians seems to be the perfect catalyst for converting local scepticism, and negative attitudes into actual actions against specific projects. Conversely, information and dialogue is the road to acceptance."

Steffen Damborg (Danish Wind Industry Association) in "Public Attitudes Towards Wind Power", a "survey of surveys" from several countries, 2002; posted on *http://www.windpower.org/en/news/articles* (consulted December 3, 2005)

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I want to express my sincere gratitude to a number of people.
Foremost is Diek (prof dr ir H Duifhuis) who for 20 years has been a true, though most of the time distant colleague, and who immediately responded positive to my request to be my promotor. The same, but for a shorter period, holds for my second promotor Ton (prof dr A J M Schoot Uiterkamp). Both were very confident in my capacities and my work and they also allowed me to change the subject without much ado.[1] "The point is, Frits", they lectured me, "that you demonstrate your scientific capability, the subject as such is not that important". And it is not by obligation that I also mention my wife Luci, who for two years gracefully took most of my share in cooking and household chores.

There are some others I would like to commemorate. My colleague Aart van der Pol who was always interested in new work and new ideas and sharp in his comments. Terry Mazilsky, one of the beleaguered residents, who read the first and the final chapters for language and clarity. My friend Dorothé Faber with whom I discussed my work from a very different, non-technical perspective. And the students and secretaries who had to abide with too little attention devoted to them and me again and again forgetting things. I hope they felt I did try to support them even though I was busy or being elsewhere in my thoughts. Much the same goes for my daughters Inge and Maya, who will meet me at the end of this period as my beloved paranymphs.

Two organizations have supported my research. The province of Groningen has subsidized the measurement project at the Rhede wind farm to support the residents and thus helped to produce a report and after that a scientific publication on the effect of atmospheric stability. The British Renewable Energy Foundation gave a grant to elaborate my thoughts on

[1] Originally my thesis was to be about Sound monitoring in quiet areas, and Diek, Ton and I discussed the nature of sound and quietness and our response to it; this changed when I became ever more involved in wind turbines.

the beating character of wind turbine sound, which led to my second publication on wind turbine noise. The KNMI gave support by providing data that helped me prepare the presentation about the wind statistics.

My Faculty of Mathematics and Natural Sciences allowed me to spend half of my working time for two years on this promotion. Unfortunately there was no money for a substitute, so I had to fit my usual work in the other half of the time. It has been busy sometimes, but I am lucky to have work that I like (well, most of it) and is worthwhile, so I never count the hours from 9 to 5. It is, I think, significant that I have a position in a University based Science Shop, because that position enables me to spend time on projects for the benefit of citizen groups with no net financial return. This book shows that citizens may need the help of science to support their claims and improve their situation, which is not available elsewhere except perhaps at high costs. On behalf of the people I have helped I am grateful our University and Faculty are still firm supporters of the Science Shop idea.[1]

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[1] Don't count your chickens before they are hatched! At the time this book was finalized, 21 years after the Science Shop for Physics started, it was announced that because of large financial deficits the Faculty executive board proposed to close down all four faculty science shops.

SUMMARY

Ch. I

This study was started after complaints of residents that the sound of a wind farm was louder and more annoying than predicted, especially when there was little wind in the evening or at night. The explanation appeared to be the occurrence of another wind profile than that used to predict the noise impact (the wind profile describes how the wind velocity increases with height). There are probably several reasons why this was not found earlier: 1) because wind turbines become taller, there is a growing discrepancy between prediction and practice; 2) measurements are usually done in daytime when the wind profile resembles more closely the commonly used standard profile; 3) based on the sound that occurs in daytime, it is hard to imagine the sound can be so different at night; 4) "there are always people complaining", so complaints are not always a reason for a thorough investigation; 5) at least some wind energy proponents prefer to downplay the disadvantages rather than solve them.

Ch. II

According to Dutch legislation and international guidelines the sound production of a wind farm can only be checked by measurements when the wind farm operator cooperates. The consequence is an implicit partiality in favor of the operator detrimental to independent verification. Because of the level of detail of instructions measurements and assessments are hampered and there is no margin for the very expertise of an investigator. For a lay person understanding the jargon was already utterly impossible and he cannot but hire an expensive expert to argue his case.

From this study one can conclude that through the use of a restricted model of reality, *viz.* a forever neutral atmosphere, experts have lost sight (temporarily) of the true reality in which a neutral atmosphere is not very prevalent. It is precisely the occurrence of complaints that may indicate such errors.

Ch. III

The sound of modern wind turbines is generated mainly by the flow of the wind along the blades. In this process a turbulent boundary layer develops at the rear side of the blade where trailing edge sound of relatively high

frequencies originates and which is radiated into the environment. This turbulent boundary layer becomes thicker and produces more sound when the wind flows in at a greater angle.
The inflowing wind is turbulent itself. The blade cuts through these turbulent movements and as a result again sound is generated: in-flow turbulence sound. Here lower frequencies dominate. Finally a blade also radiates sound when the forces on the blade change because of a local variation in wind velocity. This happens every time the blade passes the tower because there the wind is slowed down by the tower. On the one hand this causes more trailing edge sound due to the change in inflow angle, on the other hand more infrasound is generated because of the sudden sideways movement at the rate of the blade passing frequency.

For all these sounds loudness increases when the speed increases. Because the tip has the highest speed the sound of a wind turbine mainly comes from the blade tips. Moreover, for human hearing the trailing edge sound is most important because it is in an area of frequencies that we can hear well.

It is often assumed that there is a fixed relation between the wind velocity at hub height and at a reference height of 10 meter. This is the relation valid in a neutral or 'standard' atmosphere. No other relations are given in legislation or international guidelines for wind turbine sound that are valid in other conditions of the atmosphere, *viz.* the stable and unstable conditions.
The atmosphere is *unstable* when in daytime the air near the ground is relatively warm from contact with the surface heated by solar insolation. In that case vertical air movements originate and the wind profile is not equal to the profile in a neutral atmosphere, though it does not differ strongly. A *stable* atmosphere however has a markedly different wind profile. The atmosphere is stable when the air close to the ground is relatively cold due to contact with the ground surface when this cools down at night by radiating heat. A stable atmosphere occurs especially in nights with a partial or no cloud cover and the wind is not too strong (close to the ground). In a stable atmosphere the turbulence has decreased substantially

and as a result layers of air are less strongly coupled. The lower layer of air is thus less taken along with the wind that at higher altitudes keeps on blowing, giving rise to greater differences between wind velocities at different heights.

Ch. IV

The present study was performed mainly near the Rhede wind farm close to the Dutch German border. The farm consists of 17 1.8 MW turbines of 98 m hub height and three 35 m blades. The level of the incoming sound has been measured at a number of locations. The sound could be measured up to a distance of 2 km. It proved that, contrary to predictions, already at a weak wind (at 10 m height) the turbines could rotate at almost top speed and consequentially produce much sound.

It appeared that a wind profile proper to stable conditions could explain the measured sound levels excellently. At the same wind velocity at a reference height of 10 meter, wind turbines in a stable atmosphere generate more sound than in a neutral atmosphere, while at the same time the wind velocity near the ground is so low that the natural ambient sound due to rustling vegetation is weaker. As a result the contrast between wind turbine sound and natural ambient sound is more pronounced in stable conditions than it is in neutral conditions.

Ch. V

When the wind profile after sunset changes while the atmosphere becomes more stable, the difference in wind velocity over the rotor increases. This causes a change in the level of the trailing edge sound. At the low tip this is reinforced because the inflow angle already was less favourable due to the wind being slowed down by the presence of the mast. The differences in wind speed lead to variations in the sound radiated by the blade tips that reach their highest values when a tip passes the mast. For a modern, tall wind turbine the calculated variation is approximately 5 dB at night, whereas it is approximately 2 dB in daytime. This is perceived as a more pronounced fluctuation of the sound.

A more stable atmospheric boundary layer moreover implies that there is less atmospheric turbulence, so wind turbines in a farm will experience a more equal and constant wind. As a result, in a stable atmosphere wind turbines can, more than in daytime, run almost at the same speed and then

diverge again. With several turbines the fluctuations in sound can reinforce one another when they reach the ear of an observer simultaneously. With two turbines (at the same distance) this leads to an increase in level of 3 dB, with three turbines to an increase of 5 dB.
In measurements this reasoned upon effect indeed occurred. With a single 45 m high wind turbine at a distance of 280 m at night variations of 6 dB were found. Near the wind farm the variations were usually 5 dB, but they could rise to approximately 9 dB, as expected when the fluctuations of several turbines coincide.
From other research and from descriptions of residents one can establish that the sound of a wind turbine or wind farm becomes more annoying because of ' swishing', 'sloshing', 'clapping', 'beating' or ' thumping'. All descriptions mention a periodic variation on top of a constant noisy sound. This corresponds to the calculated and measured modulation of trailing edge sound. From psycho-acoustic research it has been shown earlier that human sensitivity to sound fluctuations is high at frequencies that occur in the night time sound of modern wind turbines. If this fluctuating sound is sufficiently loud in a bedroom it can cause sleep disturbance.

In the temperate climate zone a stable atmosphere is to be expected between sunset and sunrise over land if there is a -partly- clear sky (because clouds hinder the radiation of heat) and the wind is not too strong (because a strong wind promotes vertical heat exchange). From an analysis of measurements of the KNMI at Cabauw, in the central part of the Netherlands, up to an altitude of 200 m, it appears that there is a diurnal and seasonal pattern in the wind profile that correlates with the diurnal and seasonal variation in the heat exchange between the earth's surface and the atmosphere. The fact that at sunset the wind often lies down is a consequence of the increasing atmospheric stability, and this decrease in wind velocity close to the ground is accompanied by an increase at higher altitudes. This has significant consequences for the energy production of a wind turbines, where the rotor height plays an important part. If one starts from the measured wind velocities at Cabauw at 10 m height and a forever neutral atmosphere, the annually averaged electrical power generated by a 80 m high, 2 MW (reference) wind turbine would amount to almost

500 kW. However, based on the real, measured wind speed at 80 m height the annual power in reality amounts to 600 kW. So, because of atmospheric stability there is, relative to a neutral atmosphere, a significantly higher yield at night time hours, that even amply compensates for the lower yield in daytime hours.

The higher wind velocity at night on the rotor also causes a higher level of generated sound. If again one starts from the measured wind velocities at Cabauw at 10 m height and an atmosphere assumed to be neutral, the average sound power level generated by the reference wind turbine is 102 dB(A). In reality, however, it is 2 dB higher. This is also an average over an entire year; in separate nights the difference can be substantially higher, *e.g.* when a turbine rotates at (almost) top speed at a time it was expected to not produce at all because of the low 10 m wind velocity.

The degree of atmospheric stability at Cabauw is hardly different from what was observed at the Rhede wind farm. At other locations in countries in the temperate zone stability occurs to a similar extent. The consequences of atmospheric stability as described here, will thus occur at many wind farms that exist or are to be built in the temperate zone. However, above large bodies of water stability is rather a seasonal than a diurnal phenomenon, en in mountainous terrain the consequences of stability on the wind profile can be strengthened as well as weakened due to changes induced by height variations in the area.

The sound of a wind turbine or wind farm can thus become more annoying after sunset for two reasons: it becomes louder and the sound exhibits stronger fluctuations. At a given rotor diameter a blade can only be made less noisy with a different design or by slowing down the speed. A decrease in speed however reduces the generated electrical power and must therefore be applied only when necessary. To achieve this a control can be applied that lowers the speed when a noise limit is exceeded, increasing the speed again when the limit allows. This control could work on the generator and/or the pitch angle of the blades.

By changing the pitch angle while the blades rotate, the wind can flow in at an optimal angle at any position on the rotor, by which the energetic efficiency will increase on the one hand and the fluctuation strength of the sound will decrease on the other hand, even rendering the fluctuations inaudible. The total sound power will then decrease even relative to a neutral atmosphere, because the in-flow turbulence sound level will be lower due to the relative absence of atmospheric turbulence. Tilting the rotor to change the pitch angle during rotation does not appear to be a fruitful strategy: the tilt must be so great that the disadvantages will dominate.
The fluctuations near a wind farm can be stronger due to interference from the fluctuations of several turbines. This can be prevented by desynchronizing the turbines, as it happens in daytime by large scale atmospheric turbulence, by adding small and uncorrelated variations in the load of the rotors or the pitch angle of the blades of the individual turbines.

Controlling the sound production thus requires a new strategy for managing wind turbines: in daytime there is often more margin available for sound production than at night and this margin can be used in daytime in exchange for more restrictions at night.

Finally another, very different problem was addressed: the influence of wind on a microphone in or without a wind screen. When there is sufficient wind the microphone signal contains a low frequency, rumbling sound disturbing the measurement of ambient sound. This rumble is not sound from the environment, but is generated by pressure fluctuations caused by turbulent wind velocity variations. With a pressure sensitive microphone these pressure variations are not distinguishable from acoustical pressure variations. It appears that a wind screen is effective only by damping contributions of small turbulent eddies. A wind screen has no effect when eddies are bigger than the wind screen.
The strength of atmospheric turbulence does not only depend on the (average) wind velocity, but also on the local roughness of the earth surface and the stability of the atmosphere. These last two factors cause friction and thermal turbulence, respectively. The turbulence strength is

well known for an unobstructed wind flow over flat land. Turbulence is weaker in a stable and stronger in an unstable atmosphere.
The 'sound' pressure level based on atmospheric turbulence appears to agree well with measured and published levels of wind induced pressure levels. Thus the influence of wind on a sound measurement in wind can be calculated. In reverse this calculation model yields a new method to measure the strength of atmospheric turbulence.

To conclude, it can be stated that with respect to wind turbine sound an important phenomenon has been overlooked: the change in wind after sunset. This phenomenon will be more important for modern, tall wind turbines and in view of the many wind farms that are planned. If this problem is not recognized and solved it will hamper the expansion of wind energy.

SAMENVATTING

Bobby vraagt: 'Hoort u de windmolens wel eens?'
'Wat voor geluid maken ze?'
'Net als op elkaar slaand metaal, maar als er een echt harde wind staat worden de wieken vager en begint de lucht te schreeuwen van pijn.' Hij siddert.
'Waar zijn de windmolens voor ?'
'Ze zorgen dat alles 't doet. Als je je oor tegen de grond houdt kun je ze horen.'
'Wat bedoel je met alles?'
'De lichten, de fabrieken, de spoorwegen. Zonder de windmolens staat alles stil.' [1]

H. I

Dit onderzoek is tot stand gekomen na klachten van bewoners dat het geluid van een windpark luider en hinderlijker was dan voorspeld, vooral als er 's avonds of 's nachts weinig wind was. De verklaring hiervoor bleek het optreden van een ander windprofiel dan werd gehanteerd bij de voorspelling van de geluidsbelasting (het windprofiel beschrijft hoe de windsnelheid toeneemt met de hoogte). Dat dit niet eerder is gevonden heeft waarschijnlijk meerdere redenen: 1) doordat windturbines hoger en groter worden is er een groeiende kloof tussen voorspelling en praktijk; 2) er wordt normaliter overdag gemeten wanneer het windprofiel meer lijkt op het gewoonlijk gebruikte standaardprofiel; 3) men kan zich, op grond van het overdag optredende geluid, moeilijk voorstellen dat het 's nachts zo anders kan zijn; 4) "er zijn altijd wel mensen die klagen", dus klachten zijn niet altijd een reden tot grondig onderzoek; 5) tenminste een aantal voorstanders van windenergie bagatelliseert liever de nadelen dan ze op te lossen.

H. II

Volgens de Nederlandse wetgeving en internationale richtlijnen kan de geluidsproductie van een windpark alleen door metingen gecontroleerd worden als de exploitant meewerkt. Het gevolg is een impliciete partijdigheid ten gunste van de exploitant en ten nadele van onafhankelijke

[1] 'The suspect', door Michael Robotham, Time Warner Paperbacks, 2003 (p. 151), vertaling G.P. van den Berg

controle. Ook door de gedetailleerdheid van voorschriften worden metingen en beoordelingen bemoeilijkt en is er geen ruimte meer voor de eigen deskundigheid van een onderzoeker. De burger kan het jargon al helemaal niet meer volgen en moet een dure deskundige inhuren om zijn zaak te beargumenteren.

Bij dit onderzoek kan men constateren dat deskundigen door het gebruik van een beperkt model van de werkelijkheid, namelijk een eeuwig neutrale atmosfeer, (tijdelijk) het zicht hebben verloren op de echte werkelijkheid waarin die neutrale atmosfeer niet zo vaak voorkomt. Juist klachten kunnen helpen om dergelijke dwalingen aan te wijzen.

H. III

Het geluid van moderne windturbines wordt vooral opgewekt door de stroming van de wind langs de wieken. Daarbij ontwikkelt zich een turbulente grenslaag aan de achterkant van de wiek waarin relatief hoogfrequent achterrandgeluid ('trailing edge sound') ontstaat dat wordt uitgestraald naar de omgeving. Deze turbulente grenslaag wordt dikker en produceert meer geluid als de wind onder een grotere hoek instroomt.
De instromende wind is zelf ook turbulent. De wiek snijdt door deze turbulente bewegingen heen waarbij weer geluid ontstaat: instromings-turbulentiegeluid ('in-flow turbulent sound'). Hierin domineren lagere frequenties. Tenslotte straalt een wiek ook geluid af als de krachten op de wiek veranderen doordat de windsnelheid lokaal varieert. Dit gebeurt telkens als de wiek de mast passeert omdat daar de wind is afgeremd door de mast. Enerzijds ontstaat daarbij meer achterrandgeluid omdat de instromingshoek verandert, anderzijds ontstaat er ook infrageluid door de plotselinge zijwaartse beweging in het tempo van de wiekpasseerfrequentie.

Bij al deze geluiden neemt de sterkte ervan toe naarmate de snelheid groter is. Omdat de tip de hoogste snelheid heeft is het geluid van een windturbine vooral van de wiektips afkomstig. Voor het menselijk gehoor is bovendien het achterrandgeluid het belangrijkst omdat dat in een frequentiegebied ligt dat wij goed kunnen waarnemen.

Vaak wordt aangenomen dat er een vaste relatie is tussen de wind op ashoogte en op een referentiehoogte van 10 meter. Dit is de relatie die geldig is in een neutrale of 'standaard' atmosfeer. Er worden geen andere relaties gegeven in de wetgeving en in internationale richtlijnen die gelden bij andere toestanden van de atmosfeer, namelijk de stabiele en instabiele toestand.

De atmosfeer wordt *instabiel* als overdag de lucht nabij de grond relatief warm is door contact met het door zoninstraling verwarmde aardoppervlak. Er ontstaan dan verticale luchtbewegingen en het windprofiel is niet meer gelijk aan dat in een neutrale atmosfeer, maar wijkt daar niet sterk vanaf. Een *stabiele* atmosfeer kent echter een duidelijk afwijkend windprofiel. De atmosfeer is stabiel als de lucht nabij de grond relatief koud is door contact met het door warmte-uitstraling afkoelende aardoppervlak 's nachts. Een stabiele atmosfeer treedt vooral op tijdens niet gedeeltelijk of geheel onbewolkte nachten met niet teveel wind (aan de grond). In een stabiele atmosfeer is de turbulentie sterk verminderd met als gevolg dat luchtlagen minder sterk gekoppeld zijn. De onderste luchtlaag wordt daardoor minder meegenomen door de wind die op grotere hoogte gewoon blijft doorwaaien, waardoor er grotere verschillen zijn tussen windsnelheden op verschillende hoogten.

Het hier beschreven onderzoek is grotendeels uitgevoerd bij windpark Rhede vlakbij de Duits-Nederlandse grens. Het park telt 17 1,8 MW turbines met een ashoogte van 98 m en drie wieken van 35 m lengte. Op een aantal punten is het niveau van het invallende geluid langdurig gemeten. Het geluid kon tot op 2 km afstand worden gemeten. Bij een zwakke wind (op 10 m hoogte) bleken de turbines, anders dan voorspeld, al op vrijwel topsnelheid te kunnen draaien en dientengevolge veel geluid te produceren.

Een windprofiel dat bij stabiele omstandigheden past bleek de gemeten geluidsniveaus uitstekend te kunnen verklaren. Bij een gelijke windsnelheid op een referentiehoogte van 10 meter, produceren windturbines in een stabiele atmosfeer meer geluid dan in een neutrale atmosfeer, terwijl dan tegelijkertijd de windsnelheid nabij de grond zo laag is dat het natuurlijke omgevingsgeluid van ruisende vegetatie zwakker is.

Het contrast tussen windturbinegeluid en natuurlijk omgevingsgeluid is daardoor bij stabiele omstandigheden groter dan bij instabiele.

H. V

Als het windprofiel na zonsondergang verandert door een stabieler wordende atmosfeer, wordt het verschil in windsnelheid over de rotor groter. Dit veroorzaakt een verandering in de sterkte van het achterrandgeluid. Bij de lage tip wordt dit nog versterkt doordat de instromingshoek al ongunstiger was vanwege de door de mast verlaagde windsnelheid. De verschillen in windsnelheid leiden tot variaties in het door de tips afgestraalde geluid die het grootst zijn als een tip de mast passeert. Voor een moderne, hoge windturbine bedraagt de berekende variatie ongeveer 5 dB 's nachts, terwijl dit overdag ca. 2 dB is. Dit wordt ervaren als een duidelijker fluctuatie van het geluid.
Een stabielere atmosferische grenslaag betekent bovendien dat er minder atmosferische turbulentie is waardoor windturbines in een park een meer gelijke en meer constante wind ervaren. In een stabiele atmosfeer kunnen windturbines daardoor, méér dan overdag, een tijd nagenoeg gelijk lopen en weer langzaam uiteenlopen. Bij meerdere turbines kunnen de fluctuaties in het geluid elkaar versterken als ze het gehoor van een waarnemer gelijktijdig bereiken. Bij twee turbines (op gelijke afstand) leidt dit tot een 3 dB hoger niveau van de fluctuaties, bij drie turbines tot een 5 dB hoger niveau.
Bij metingen bleek dit beredeneerde effect daadwerkelijk voor te komen. Bij een enkele windturbine van 45 m ashoogte werden op een afstand van 280 m 's nachts variaties gevonden van 6 dB. Bij het windpark bedroegen de variaties meestal 5 dB, maar ze konden oplopen tot ongeveer 9 dB, zoals verwacht wordt bij het samenvallen van de fluctuaties van meerdere turbines.
Uit onderzoek elders en uit beschrijvingen van omwonenden kan men constateren dat het geluid van een windturbine of windpark vooral na zonsondergang hinderlijker wordt door het 'zoeven' of 'klotsen', 'klappen', 'slaan' of 'bonken'. De omschrijvingen vermelden steeds een periodieke variatie bovenop een constant ruisachtig geluid. Dit correspondeert met de berekende en gemeten modulatie van het achterrandgeluid. Uit psycho-akoestisch onderzoek is veel eerder al

gebleken dat de menselijke gevoeligheid voor geluidsfluctuaties hoog is bij frequenties die juist voorkomen in het nachtelijke geluid van moderne turbines. Als dit fluctuerende geluid voldoende luid doordringt in een slaapkamer kan het tot slaapverstoring leiden.

In de gematigde klimaatzone kan men tussen zonsondergang en zonsopgang boven land een stabiele atmosfeer verwachten als er een -gedeeltelijk- onbewolkte hemel is (bewolking verhindert de warmte-uitstraling) en een niet te harde wind (veel wind bevordert de verticale warmtevereffening). Uit een analyse van metingen van het KNMI bij Cabauw, in het midden van Nederland, tot op 200 m hoogte blijkt dat er een dagelijkse en jaarlijkse gang is in het windprofiel die samenhangt met de dagelijkse en seizoensvariatie in de warmte-uitwisseling tussen aardoppervlak en atmosfeer. Dat bij zonsondergang de wind vaak gaat liggen is een gevolg van de toenemende atmosferische stabiliteit, en deze windsnelheidsafname nabij de grond gaat gepaard met een toename van de windsnelheid op grotere hoogte.
Dit heeft belangrijke gevolgen voor de energieproductie van een windturbine, waarbij bovendien de rotorhoogte een rol speelt. Als wordt uitgegaan van de gemeten windsnelheden bij Cabauw op 10 m hoogte en een altijd neutrale atmosfeer, dan zou het over een jaar gemiddelde opgewekte elektrische vermogen van een 80 m hoge 2 MW windturbine bijna 500 kW bedragen. Gebaseerd op de werkelijke, gemeten windsnelheid op 80 m hoogte bedraagt het over een jaar gemiddelde vermogen echter 600 kW. Door atmosferische stabiliteit is er dus, ten opzichte van een neutrale atmosfeer, een aanmerkelijk hogere opbrengst in de nachturen, waardoor zelfs de lagere opbrengst overdag ruim wordt gecompenseerd.

De hogere windsnelheid 's nachts op de rotor veroorzaakt echter ook een hogere geluidsproductie. Als weer wordt uitgegaan van windsnelheden op 10 m hoogte en een neutraal veronderstelde atmosfeer, dan bedraagt het geluidsvermogen van de turbine 's nachts gemiddeld ca. 102 dB(A). In werkelijkheid is het ruim 2 dB hoger. Ook dit is een gemiddelde over een heel jaar; in afzonderlijke nachten kan het verschil veel groter zijn, bijvoorbeeld als een windturbine op (vrijwel) topsnelheid draait, terwijl verwacht was dat deze, gezien de lage windsnelheid op 10 m hoogte, helemaal niet zou produceren. Dit gebeurt vooral in het zomerhalfjaar.

De mate waarin atmosferische stabiliteit optreedt bij Cabauw blijkt nauwelijks te verschillen van wat bij windpark Rhede is waargenomen. Op andere locaties in landen in de gematigde zone blijkt stabiliteit in vergelijkbare mate voor te komen. De beschreven gevolgen van atmosferische stabiliteit zullen dus bij veel windparken optreden die in de gematigde zone staan of nog gebouwd worden. Echter, boven grote wateroppervlakken is stabiliteit eerder een seizoens- dan een dagelijks verschijnsel, en in bergachtig gebied kunnen de gevolgen van stabiliteit op het windprofiel zowel versterkt als verzwakt worden door veranderingen tengevolge van hoogteverschillen in het gebied.

Geluid van een windturbine of windpark wordt dus om twee redenen na zonsondergang hinderlijker: het wordt luider en het geluid vertoont sterkere fluctuaties. Bij een gegeven rotordiameter kan een wiek alleen stiller worden door een ander ontwerp of door de snelheid te verlagen. Snelheidsverlaging gaat echter ten koste van het opgewekte elektrische vermogen en moet daarom liefst alleen worden toegepast wanneer dat nodig is. Daartoe kan een regeling worden toegepast die de snelheid verlaagt wanneer een geluidslimiet wordt overschreden, en deze weer verhoogt wanneer de limiet dat toelaat. De regeling zou kunnen ingrijpen op de generator en/of de vaanstand van de wieken.
Door de vaanstand tijdens de rotatie van de wieken te variëren kan op elke positie de wind onder een optimale hoek de rotor instromen, waardoor enerzijds het energetisch rendement toeneemt en anderzijds de fluctuatiesterkte van het geluid afneemt en de fluctuaties zelfs onhoorbaar kunnen worden. Het totale geluidsvermogen zal afnemen, zelfs ten opzichte van een neutrale atmosfeer, omdat het instromingsturbulentie-geluid zal verminderen door de relatieve afwezigheid van atmosferische turbulentie. Het kantelen van de rotor waardoor tijdens een rotatie de vaanstand verandert lijkt geen vruchtbare strategie: de kanteling moet zo groot zijn dat de nadelen overheersen.

Bij een windpark kunnen de fluctuaties sterker zijn door interferentie van de fluctuaties van meerdere turbines. Dit kan worden voorkomen door de turbines te desynchroniseren, zoals dat overdag gebeurt door grootschalige atmosferische turbulentie, door kleine en ongecorreleerde variaties in de belasting van de rotors of in de vaanstand van de wieken van de afzonderlijke turbines.

Het beheersen van de geluidsproductie vergt derhalve een nieuwe strategie bij de regeling van windturbines: overdag is er vaak meer geluidsruimte beschikbaar dan 's nachts en die ruimte kan overdag gebruikt worden als er 's nachts beperkingen worden opgelegd.

Als laatste is nog een geheel ander probleem onderzocht: de invloed van wind op een microfoon, al of niet in een windbol. Bij voldoende wind bevat het microfoonsignaal een laagfrequent, rommelend geluid waardoor de meting van omgevingsgeluid wordt verstoord. Deze 'rumble' is geen geluid uit de omgeving, maar ontstaat door drukvariaties tengevolge van turbulente windsnelheidsvariaties. Met een drukgevoelige microfoon zijn deze drukvariaties niet te onderscheiden van akoestische drukvariaties. Het blijkt dat een windbol alleen effectief is doordat de bijdragen van kleine turbulente wervels worden gedempt. Een windbol heeft geen effect bij wervels die groter zijn dan de windbol.
De sterkte van atmosferische turbulentie hangt niet alleen af van de (gemiddelde) wind snelheid, maar ook van de lokale ruwheid van het aardoppervlak en de stabiliteit van de atmosfeer. De twee laatste factoren veroorzaken respectievelijk wrijvingsturbulentie en thermische turbulentie. De turbulentiesterkte is in de literatuur goed bekend bij een vrije aanstroming van wind over vlak land. De turbulentie is zwakker in een stabiele, sterker in een instabiele atmosfeer.
Het op atmosferische turbulentie gebaseerde 'geluids'drukniveau blijkt goed overeen te komen met gemeten en gepubliceerde niveaus van door wind geïnduceerde drukniveaus. De invloed van wind op een geluidsmeting in wind kan dus worden berekend. Omgekeerd levert het rekenmodel een nieuwe methode om de sterkte van de atmosferische turbulentie te meten.

Tot slot kunnen we concluderen dat er bij het geluid van windturbines een belangrijk fenomeen over het hoofd is gezien: de verandering van de wind na zonsondergang. Dit fenomeen zal belangrijker worden voor moderne, hoge windturbines en met het oog op de vele windparken die worden gepland. Als dit probleem niet wordt onderkend en opgelost zal het de uitbreiding van windenergie bemoeilijken.

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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:

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

G(z): turbulence related function:

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

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 $\Omega R/c$) [-]
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 ($\Omega R/2\pi$) [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 $\Omega RC/\nu$); 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·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: instantaneous 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 $\approx 2V/3$ $[m \cdot s^{1}]$

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

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

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 Ω $2\pi f_B/3$ 2 rad·s^{1} (20 rpm), $f_{\mathrm{peak,if}}$ 11 Hz which is in the infrasound region. Measured fall-off from $f_{\mathrm{peak,if}}$ 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

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

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

$$\delta^* \quad b \cdot 0.37 \cdot C \cdot Re^{\,0.2}/8 \tag{B.3}$$

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]:

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

and total trailing edge immission sound level as:

$$SPL_{TE} \quad 10\cdot\log(\Sigma_i\, 10^{SPLi/10}) \tag{B.5}$$

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 δ_α^* δ_s^*, f_α 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_α K_2-K_1+3) are plotted in figure B.1 and these can be approximated by:

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

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

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

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

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:

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

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

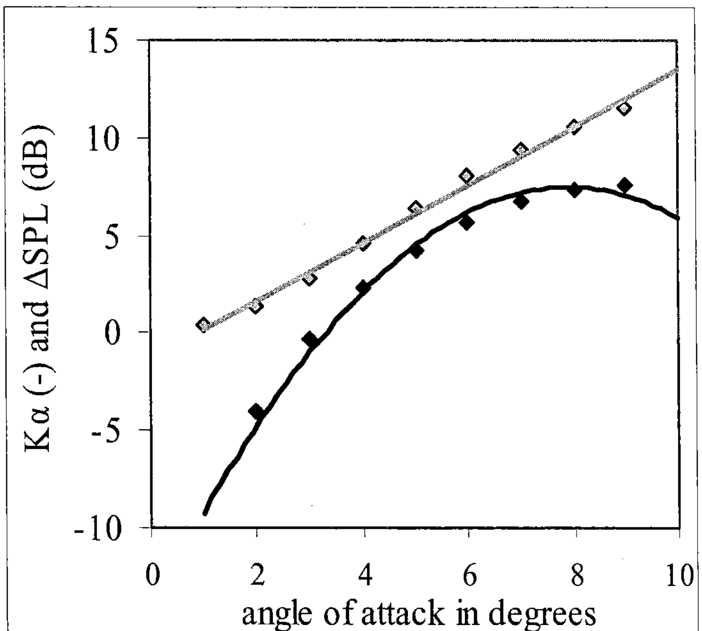


Figure B.1: non-zero angle of attack correction K_α (black diamonds) and resulting added sound pressure level ΔSPL (gray diamonds) with best fits in range $1° < \alpha < 10°$

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 1.8° ± 1.1°. 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.

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

$$dV_{wind} \quad 0.017 \cdot \Omega \cdot R \cdot d\alpha \tag{B.9}$$

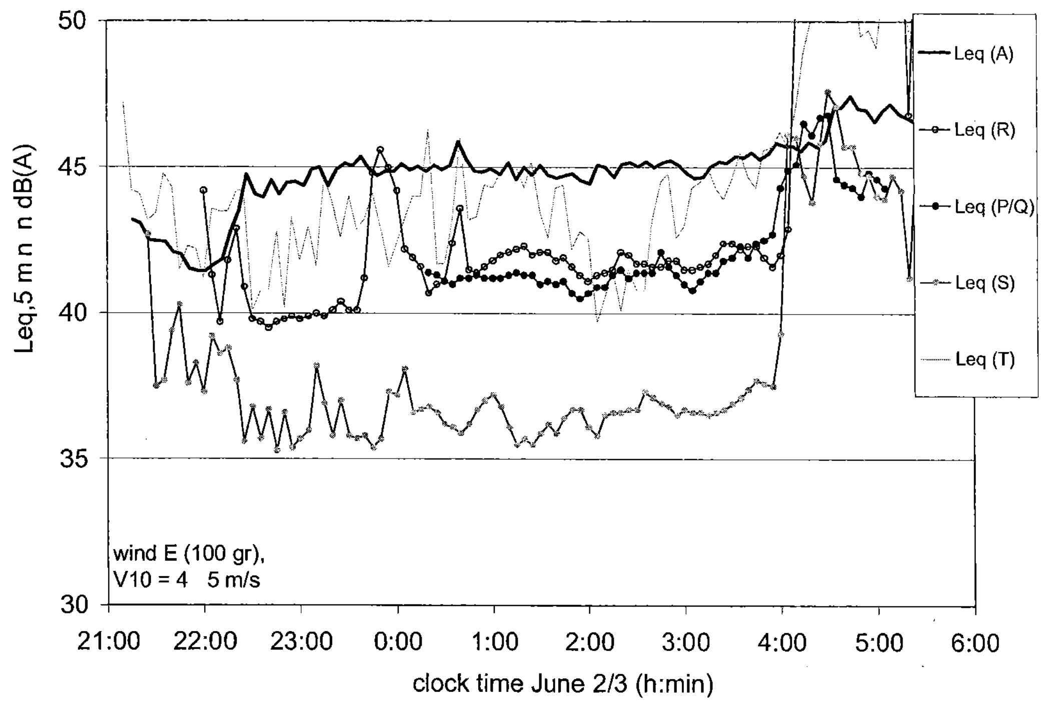
with α in degrees.

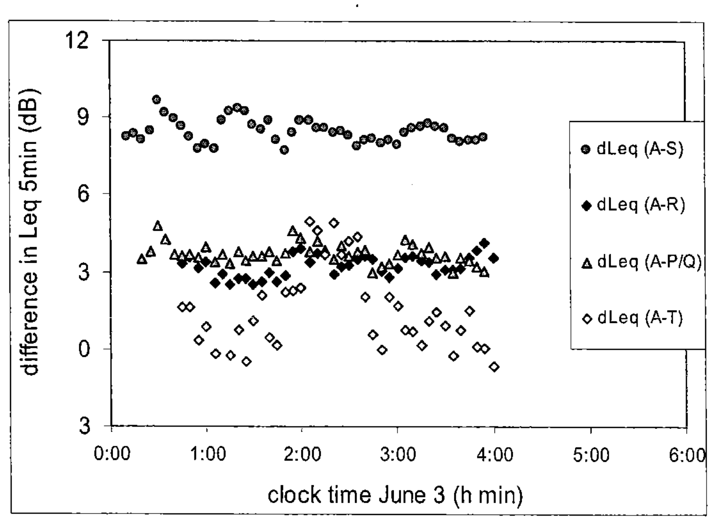
So for a modern turbine at high speed ($\Omega \cdot R \approx 70$ m/s at tip at 20 rpm) the wind velocity deficit where the blade tip passes the tower and α 1° (0.017 radians) is 1.2 m/s. In a free 14 m/s wind, *i.e.* 9.3 m/s at the rotor, this is 13%. This deficit is due to the influence of the tower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

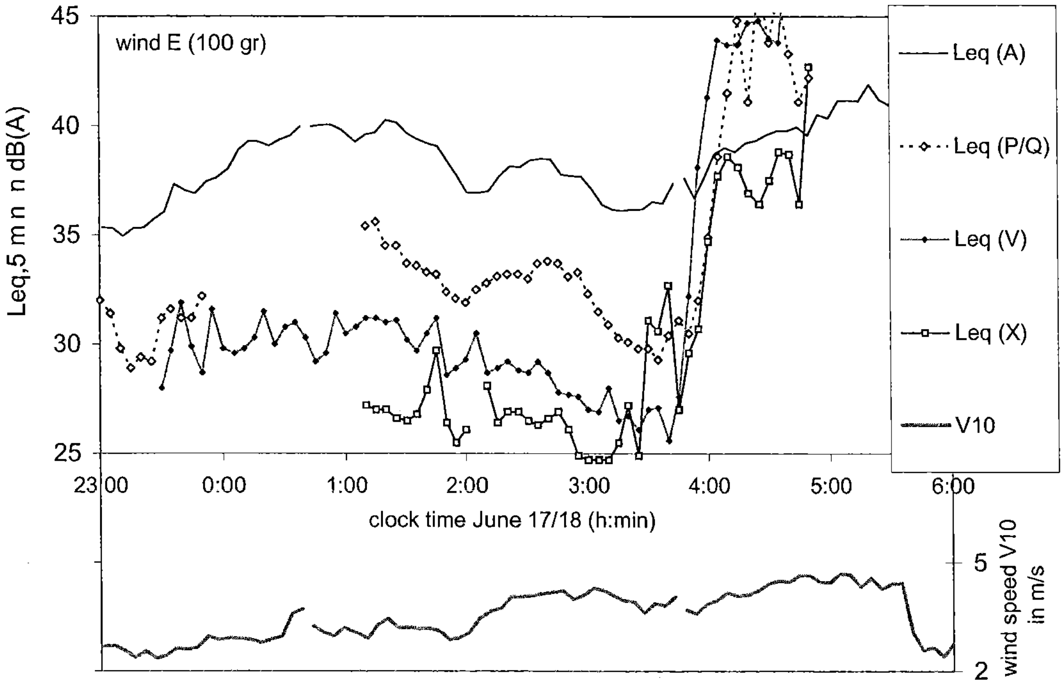
Appendix C

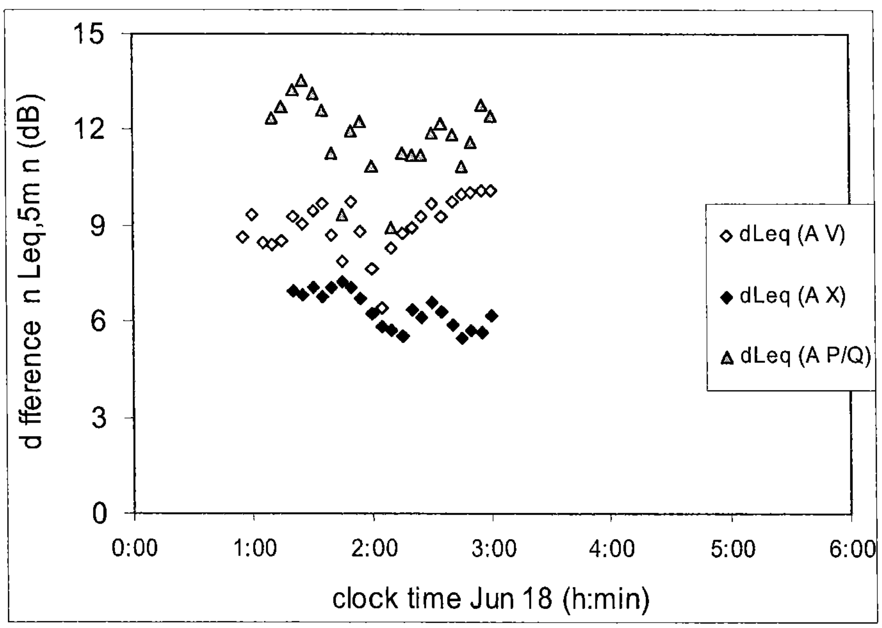
Simultaneous registrations of sound immission level

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 m n n dB(A)
45
40
35
30
25
23:00
0:00
1:00
2:00
3:00
4:00
5:00
6:00
clock time June 17/18 (h:min)
Leq (A)
Leq (P/Q)
Leq (V)
Leq (X)
V10
5
2
wind speed V10 in m/s


d fference n Leq,5m n (dB)
15
12
9
6
3
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
clock time Jun 18 (h:min)
dLeq (A V)
dLeq (A X)
dLeq (A P/Q)

Appendix D
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