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* Contents organized for archiving by: Gigi Godwin (LRB) (August/2011)

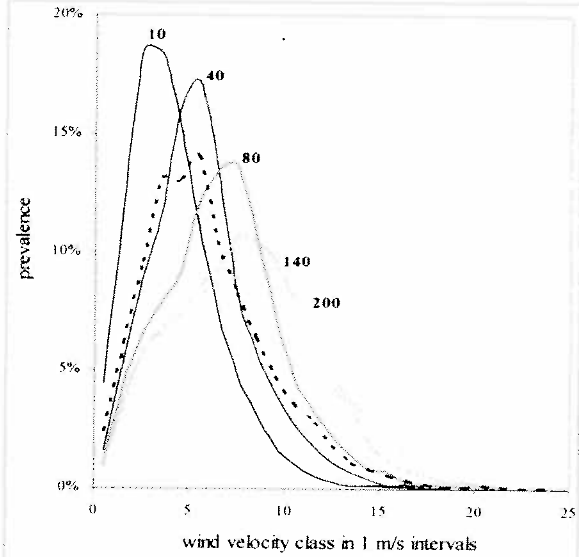

Figure VI.4: distribution of measured wind velocities at 10, 40, 80, 140 and 200 m, and of 80-m wind velocity extrapolated from 10-m wind velocity (dashed line)

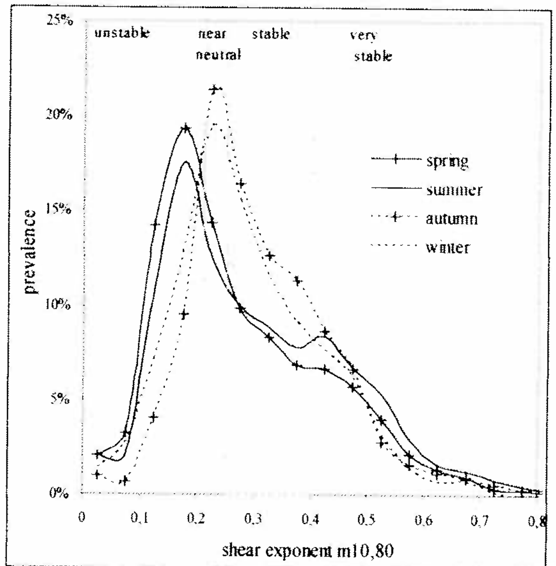

Figure VI.5: distribution of shear exponent per meteorological season, determined from 10-m and 80-m wind velocity

VI.4.2 Shear and ground heat flux

Figure VI.6 shows how the shear exponent depends on the total heat flow to the ground for two different height ranges: 10 – 80 m in the left panel, 40 – 140 m in the right panel. The heat flow at Cabauw is determined from temperature measurements at different heights, independent of wind velocity. Total heat flow is the sum of net radiation, latent and sensible heat flow, and positive when incoming flow dominates. For heat flows above approximately 200 W/m^2 the shear exponent m is between 0 and 0.21, corresponding to an unstable atmosphere, as expected. For low or negative (ground cooling) heat flows the range for m increases, extending from -1 up to +1.7. These values include conditions with very low wind velocities. If low wind velocities at 80 m height ($V_{80} < 4$ m/s, occurring for 19.7% of the time) are excluded, with very few exceptions $m_{10,80}$ varies between 0 and 0.6, and $m_{40,140}$ varies

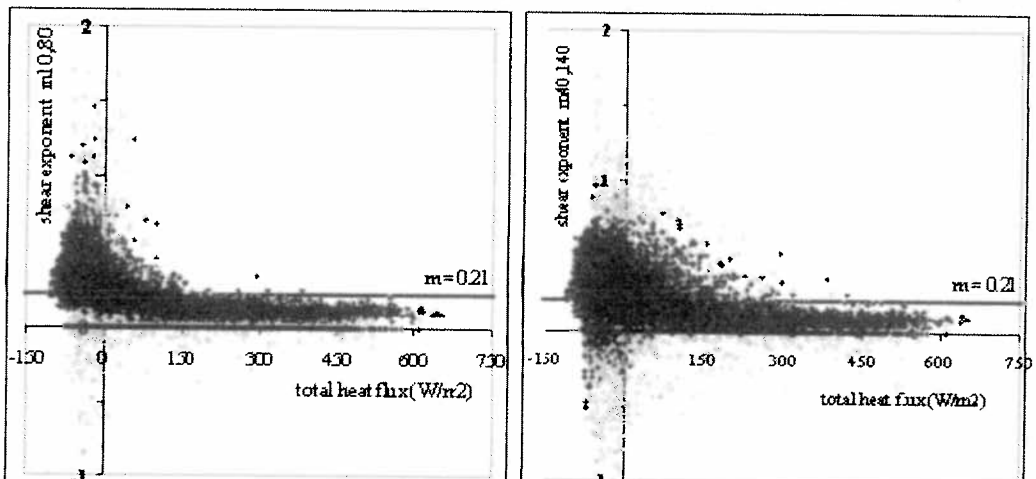

Figure VI.6: shear exponent m from wind velocity gradient between 10 and 80 m (left) and 40 and 140 m (tight) vs. total ground heat flow; grey circles: all data, black dots: V80 > 4 m/s between -0.1 and +0.8. A negative exponent means wind velocity decreases with height. The data show that below 80 m this occurs in situations with little wind ($V_{80} < 4$ m/s), but at greater heights also at higher wind velocities. In fact, V140 was lower than V_{80} for 7.5% of all hours in 1987, of which almost half (3.1%) when V_{80} was over 4 m/s. Such a decrease of wind velocity with height occurs at the top of a 'low level jet' or nocturnal maximum; it occurs at night when kinetic energy of low altitude air is transferred to higher altitudes.

For $V_{80} > 4$ m/s both shear exponents ($m_{10,80}$ and $m_{40,140}$) are fairly strongly correlated (correlation coefficient 0.85), showing that generally there is no appreciable change between 10 m and 140 m. For low wind velocities ($V_{80} < 4$ m/s) both shear exponents are less highly correlated (c.c. 0.62).

VI.4.3 Wind direction shear

When stability sets in the decoupling of layers of air also affects wind direction: the higher altitude wind more readily follows geostrophic wind and therefore changes direction while lower altitude winds are still influenced by the surface following the earth's rotation. In the left panel of figure 7 the change in wind direction at 80 m relative to 10 m is plotted as a function of the shear exponent as a measure of stability. A positive change means a clockwise

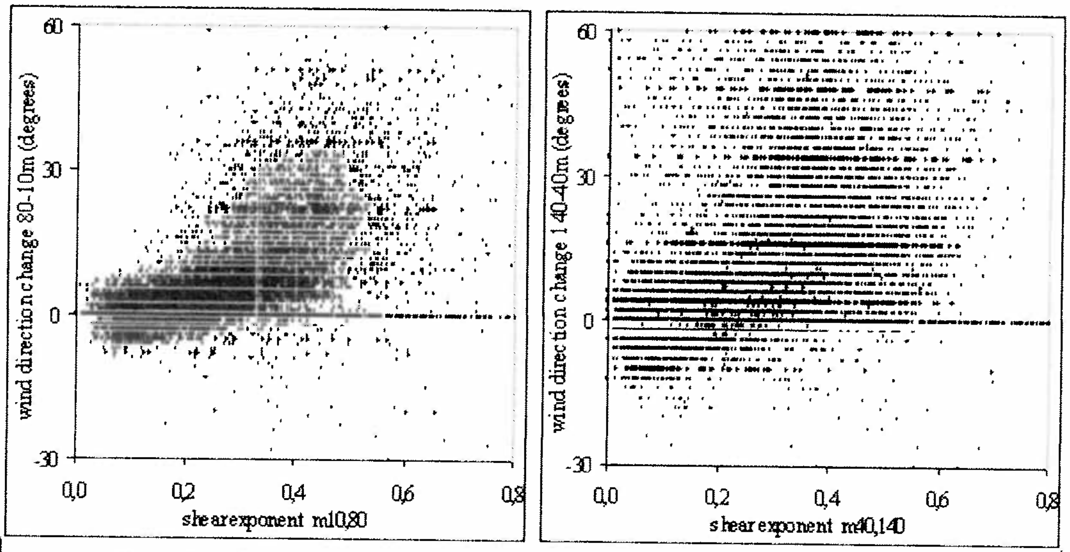

Figure VI.7: wind direction change between 10 and 80 m (left) and 40 and 140 m (right) vs. shear exponent between same heights

change (veering wind) at increasing altitude. The left panel shows the wind direction change from 40 to 140 m as a function of the shear exponent determined from the wind velocities at these heights. In both cases the average change from m=0 to m=1 is 30° (best least squares linear fit), but with a considerable variation (correlation coefficients are 0.44 and 0.29, respectively).

VI.4.4 Prevalence of stability

In figure 8 the percentages are given that the atmosphere is unstable, neutral, stable or very stable (as defined in table 1) for 1987 as a whole and per meteorological season. Prevalence is given for heights from 10 and 80 m (upper panel figure 6) and for heights from 40 to 140 m (lower panel). The upper panel is in fact a summation over the four ranges of the shear exponent in figure 5. It appears that in autumn the atmosphere is most often stable, and least often unstable. In spring the opposite is true: instability occurs more often than stability. Overall the atmosphere up to 80 m is unstable (m < 0.21) for 47% of the time and stable (m > 0.25) for 43% of the time. At higher altitudes (40 to 140 m) percentages are almost the same: 44% and 47%, respectively. This means that for most of the daytime hours the atmosphere is unstable, and for most of the night time hours stable. For the rest of the time, 9 to 10% of the time, the atmosphere is near neutral.

Climatological observations can put the Cabauw data in national perspective. In figure VI.9 the prevalence of Pasquill classes E and F (corresponding to approximately m > 0.33) are given as observed at 12 meteorological stations all over the Netherlands over the period 1940 - 1970 [14], ordered according to yearly prevalence. Three of the four lowest values are from coastal stations: Valkenburg is just behind the dunes on the Northsea coast, Vlissingen is at the Westerschelde estuarium and Den Helder is on a peninsula between the Northsea and the Waddensea. At Den Helder a stable atmosphere occurs for only 8% of the time per year, whereas at both other coastal stations this is 13% to 16% and at the other landward stations 15% to 20% of the time. At Cabauw a value of m > 0.33 occurs for 27% of the time, but this is based on measurements, not on Pasquill classification.

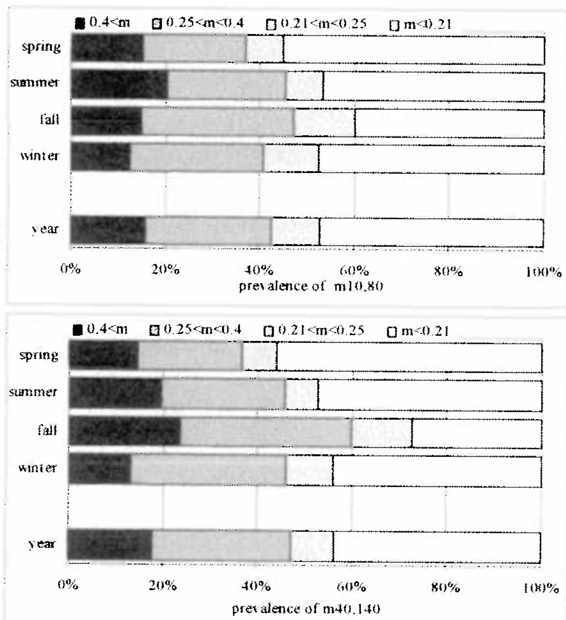

Figure VI.8: prevalence of shear exponent m between 10 and 80 m (top) and 40 and 140 m (bottom) in four seasons and year of 1987

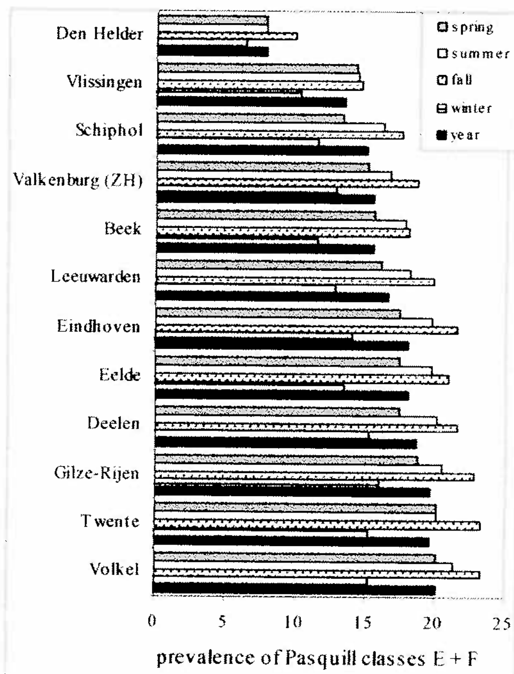

Figure VI.9: prevalence of observed stability (Pasquill classes E and F) per season and per year at 12 different Dutch stations over 30 years

VI.5. Results: effects on wind turbine performance

VI.5.1 Effect on power production

The effect of atmospheric stability can be investigated by applying the Cabauw data to a reference wind turbine, the Vestas V80-2MW [Vestas 2003, Jorgensen 2002]. To calculate the electric power P80 as a function of wind velocity V_h at hub height the factory '105.1dB(A)' highest power ('hp') curve is approximated with a fourth power polynome:

$$Ph,hp = 0.0885 \cdot V_h^4 - 8.352 \cdot V_h^3 + 185.9 \cdot V_h^2 - 1272,5 \cdot V_h + 2897 \quad \text{kW} \qquad \text{(VI.1)}$$

which is valid for $4 < V_h < 14.3$ m/s. In figure VI.10 this fitted curve is plotted as diamonds on top of the manufacturer's specification [Vestas 2003]. A fourth power relation is convenient to fit to the curvature at 12 m/s where maximum power is approached. For lower wind velocities ($V_h < 11$ m/s) the power curve can be fitted with a third power ($Ph = 1.3 \cdot V_h^3$) in agreement with the physical relation between wind power and wind velocity.

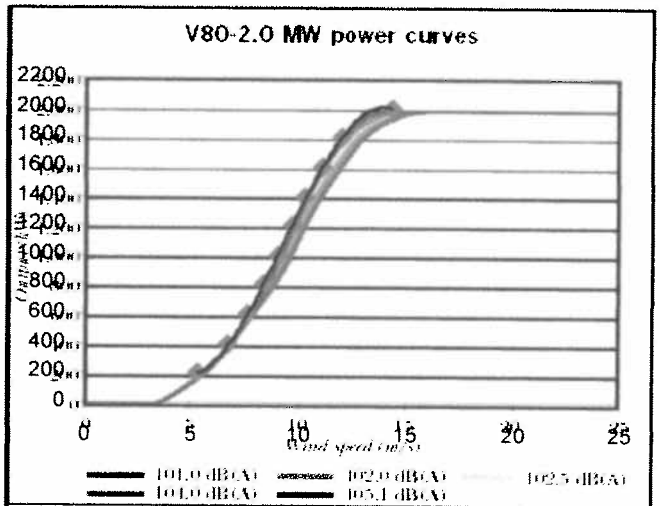

Figure VI.10: Vestas V80 power curves (lines) vs. hub height wind speed, and best fit to 105.1dB(A) curve (diamonds)

For high wind velocities (>14.3 m/s; 2% of time) electric power is constant at 2000 kW, for low wind velocities (< 4 m/s; 20% of time) electric power is set to zero. Electric power can thus be calculated from real wind velocities as measured each half hour at 80 m height, or from 80-m wind velocities logarithmically extrapolated from wind velocity at 10 m height. The result is plotted in figure VI.11 as an average power versus time of day P80,hp (averages are over all hours in 1987 at each clock hour). Actual power production appears to be more constant than estimated with extrapolations from 10-m wind velocities. When using a logarithmic extrapolation, daytime power production is overestimated, while night time power production is underestimated. The all year average is plotted with large symbols at the right side of the graph in figure VI.11: 598 kW when based on measured wind velocity or a 30% annual load factor, 495 kW when based on extrapolated wind velocity or a 25% load factor.

In figure 11 also the wind power is plotted when the turbine operates in the lowest '101.0dB(A)' power curve (best fit $Ph,lp = 0.089 \cdot V_h^4 + 0.265 \cdot V_h^3 + 43.1 \cdot V_h^2 - 326.4 \cdot V_h + 749$ kW). The year average is now 569 kW, corresponding to a 28% annual load factor. The 4 dB lower sound level setting thus means that yearly power production has decreased to a factor 0.94.

In the calculations it was implicitly assumed that the wind velocity gradient over the rotor was the same as at the time the power production was determined as a function of hub height wind

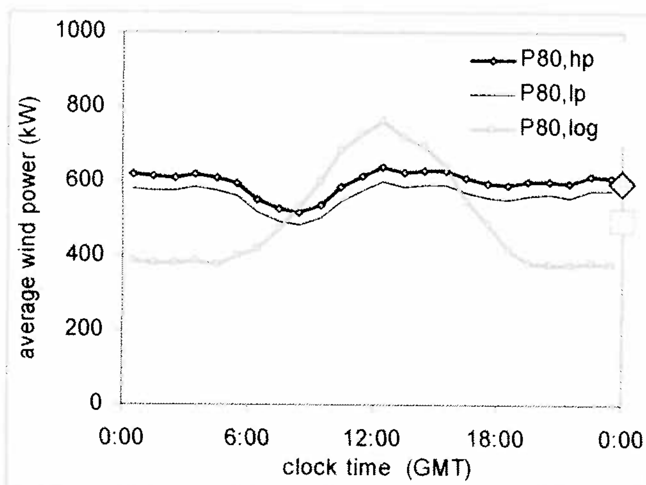

Figure VI.11: hourly averaged real and estimated wind power at 80 m height per clock hour in 1987 velocity. In stable conditions however, the higher wind gradient causes a non-optimal angle of attack at the blade tips when the tips travel far below and above the hub. This will involve some loss, which is not determined here.

VI.5.2 Effect on sound production

Figure VI.12 shows 'theoretical' sound power levels for the Vestas turbine [Vestas 2003, Jorgensen 2002]; in fact for $V_h > 8$ m/s measured levels are somewhat less, for $V_h > 8$ m/s somewhat higher [Jorgensen 2002]. To calculate the sound power level L_W as a function of hub height wind velocity V_h the factory '105.1dB(A)' power curve is approximated with a fourth power polynome:

$$L_W = -0.0023 \cdot V_h^4 + 0.146 \cdot V_h^3 - 2.82 \cdot V_h^2 + 22.6 \cdot V_h + 39.5 \quad \text{dB(A)} \qquad \text{(VI.2)}$$

for $4 < V_h < 12$ m/s and 107 dB(A) for $V_h > 12$ m/s. In figure VI.13 the result per clock hour is plotted when using actual and extrapolated (from 10 m) wind velocities. Averaged over the same hours over all 1987 sound power level in daytime is overestimated by appr. 0.5 dB, but at night underestimated by appr. 1.5 dB. In the '101.0dB(A)' low power curve setting (with a best fourth power polynomal fit $L_W = -0.022 \cdot V_h^4 + 0.781 \cdot V_h^3 - 9.98 \cdot V_h^2 + 55.3 \cdot V_h - 12.3$ dB(A)) sound power levels are 3 dB lower.

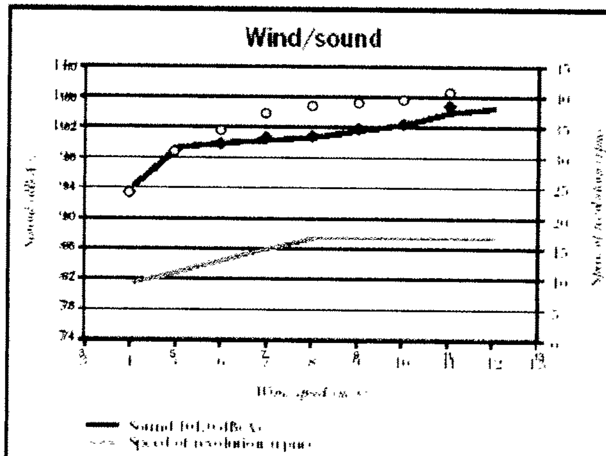

Figure VI.12: Vestas V80 sound power level at '101.0dB(A)' power curve (diamonds and upper line) and '105.1dB(A)' power curve (circles), and speed of rotation (lower line) vs. hub height wind

The year averages do not show the hourly differences between actual and logarithmically predicted sound power levels. This is shown in figure VI.14 for two days each in January and July 1987 (also shown in figure VI.2) where actual and predicted half-hour sound power levels are plotted as a function of 10-m wind velocity. On both winter days and at wind velocities $V_{10} > 5.5$ m/s actual sound power agree within 1 dB with the predicted sound power, but at lower 10-m wind velocities actual levels are rather higher for most of the time. On both summer days 10-m wind velocities are lower than in winter, but sound power level is more often higher than predicted and can reach near maximum levels even at very low (2.5 m/s) 10-m wind velocities (when at ground level people will probably feel no wind at all). In these conditions residents in a quiet area will perceive the highest contrast: hardly or no

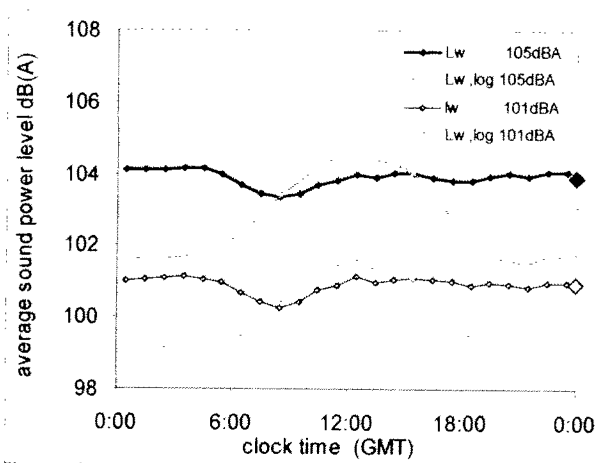

Figure VI.13: hourly averaged real and estimated (log) sound power level at '105.1dB(A)' and '101.0dB(A)' power curve settings wind induced sound in vegetation, while the turbine(s) are rotating at almost top speed. In these conditions also an increased fluctuation strength (strong 'blade swish') of the turbine sound will occur (see chapter V), making the sound more conspicuous.

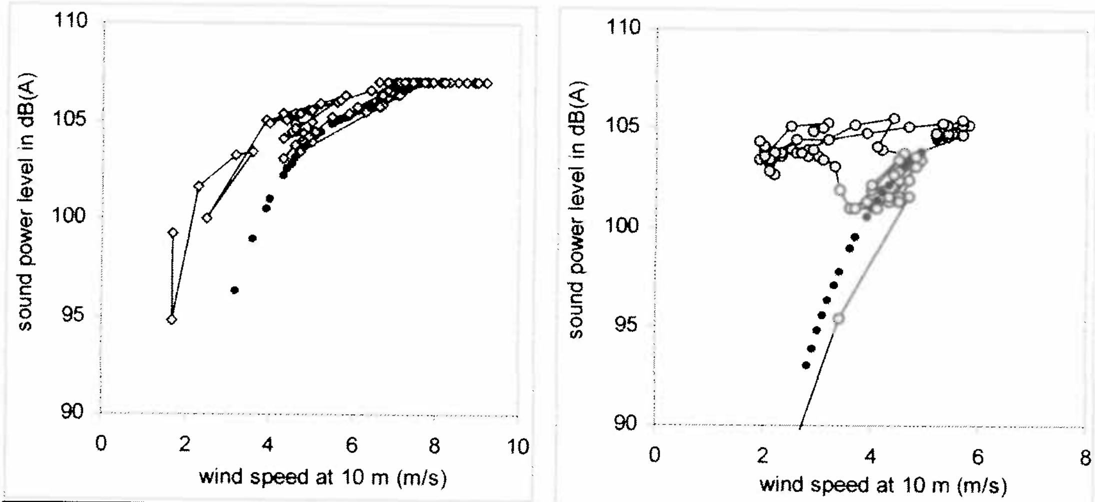

Figure VI.14: half-hourly progress of actual (grey diamonds) and logaritmically predicted (black dots) sound power level plotted vs. 10-m wind speed over 498 hours; left: January 13-14; right: July 2-3

VI.6 Other onshore results

Values of wind shear have been reported by various authors, and show similar results. Pérez *et al* [2005] measured wind velocities up to 500 m above an 840 m altitude plateau north of Valladolid, Spain, for every hour over sixteen months. The shear exponent, calculated from the wind velocity at 40 m and 220 m, varied from 0.05 to 0.95, but was more usual between 0.1 and 0.7. High shear exponents occurred more often than in Cabauw: m > 0.48 for 50% of the time. This is likely the result of the more southern position: insolation is higher, causing bigger temperature differences between day and night, and the atmosphere above the plateau is probably drier causing less reflection of infrared radiation at night. There was a distinct seasonal pattern, with little day-night differences in January, and very pronounced differences in July.

Smith *et al* [2002] used data from wind turbine sites in the US Midwest over periods of 1.5 to 2.5 years and calculated shear exponents for wind velocities between a low altitude of 25 - 40 m and a high altitude of 40 – 123 m. At four sites the hourly averaged night time (22:00 – 6:00) shear exponent ranged from 0.26 to 0.44, in daytime from 0.09 to 0.19. The fifth station was exceptional with a day and night time wind shear below 0.17.

Archer *et al* [2003] investigated wind velocities at 10 m and 80 m from over 1300 meteorological stations in the continental USA. No shear statistics are given, but for 10 stations the ratio V_{80}/V_{10} is plotted versus time of day. At all these stations the ratio is 1.4 ± 0.2 in most of the daytime and 2.1 ± 0.3 in most of the night time. Using equation 1, it follows that the shear exponent varies between 0.15 ± 0.07 and 0.35 ± 0.07, respectively.

At the 2005 Berlin Conference on Wind Turbine Noise two presentations added to these wind shear data, now (also) from a noise perspective. Harders *et al* [2005] showed hourly wind velocity averaged over the year 2000 at altitudes between 10 and 98 m from the Lindenberg Observatory near Berlin. The results are very much like those in figure VI.1, with a wind

velocity ratio $V_{80}/V_{10} = 1.9$ in night time hours, decreasing to 1.3 at noon. Using equation 1, this corresponds to an avarage shear exponent of 0,30 and 0.13, respectively.
Botha [2005] presented results from 8 to 12 months measurements at sites in two flat Australian areas and two sites in more complex (non flat) New Zealand terrain. On the Australian sites the average nighttime wind velocity ratio V_{80}/V_{10} was 1.7 and 1.8, in daytime 1.5. This corresponds to shear exponents of to 0.26 to 0.28 and 0,19, respectively. In the hilly New Zealand areas the average wind velocity ratio was between 1.2 and 1.25 in day as well as night time, so the shear exponent is 0.1.

From the measurements in Bellingwolde at the Rhede wind farm the shear exponent could be calculated from the 10-m and 100-m wind velocity, the latter determined from the sound level and the relation between sound power level and hub height (100 m) wind velocity. This was done for all (892) five minute periods when wind turbine sound was dominant between 23:00 and 04:00 hours within the measurement period (May and June; location A in figure IV.1). From the Cabauw data the same period and time was selected and all values of the half-hour shear exponent $m_{10,80}$ were determined. For both locations the resulting frequency distributions of the shear exponent are plotted in figure VI.15. The distributions are rather similar, though at Cabauw very high wind shear occurred more often than at Bellingwolde.

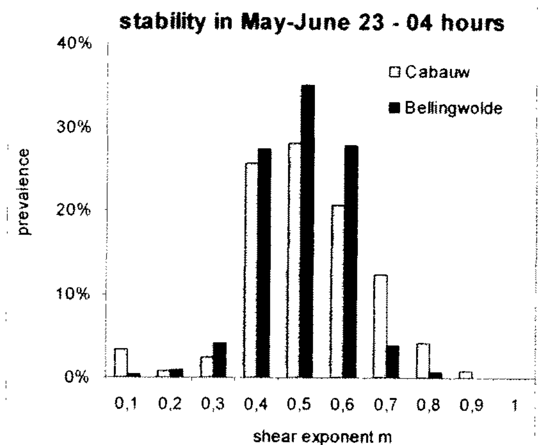

Figure VI.15: frequency distribution of the shear exponent at Cabauw and in the measurement period near the Rhede wind farm in the same period of time

VI.7 Conclusion

High altitude night time wind velocities have been underestimated by neglecting the influence of atmospheric stability. In recent years more attention is being paid to stability as it has a large impact on wind power production, especially at the height of modern, tall turbines.
Results from various landward areas show that the shear exponent in the lower atmospheric boundary layer (< 200 m) in daytime is 0.1 to 0.2, corresponding to a wind velocity ratio V_{80}/V_{10} of 1.25 to 1.5. This wind profile is comparable to the profile predicted by the well-known logarithmic wind profile for low roughness lengths (low vegetation).
At night the situation is quite different and in various landward areas the shear exponent has a much wider range with values up to 1, but more usually between 0.25 and 0.7. Near the Rhede wind farm, where long term measurements have been performed [7, 8], the same range of wind shear occurred, showing that the site indeed was suitable to study the effect of atmospheric stability on wind turbine performance and representative for many other locations.
A shear exponent $0.25 < m < 0.7$ means that the ratio V_{80}/V_{10} varies between 1.7 and 4.3. High altitude wind velocities are thus (much) higher than expected from logarithmic extrapolation of 10-m wind velocities.

The underestimate of high altitude night time wind velocity has been compensated partly by the overestimate of high altitude daytime wind velocity, which may partly explain why, until recently, atmospheric stability was not recognized as an important determinant for wind power.

To assess wind turbine electrical and sound power production the use of a neutral wind profile should be abandoned as it yields data that are not consistent with reality.

VII THINKING OF SOLUTIONS: Mitigation measures for nighttime wind turbine noise

VII.1 Meeting noise limits

In a neutral and unstable atmosphere wind turbine sound is the result of induced (and also atmospheric) turbulence on he blades; reduction of this source is the topic of dedicated research, such as the SIROCCO (*Si*lent *ro*tors by a*co*ustic *o*ptimisation) program which seeks to improve the design of the wind turbine blade; in the near future a reduction of approximately 2 dB will be probably [Schepers *et al* 2005]. Sound reduction by reducing blade speed is an option already available in modern turbines.
In this chapter we will deal with the ('added') sound produced by a wind turbine due to increasing atmospheric stability. To address this problem two types of mitigation measures can be explored:
1: reduce the sound level down to to the pertinent (legal) limit for environmental noise;
2: reduce the level variations due to blade swish/beating.

The first measure of course must be pursued as it is a legal obligation. The need for reduction depends on the type of limit. *E.g.*, in Germany the limit applies to the maximum sound immission level (the level produced at nominal maximum power), regardless of wind velocity as such. In many countries the limit is based on the wind velocity related background ambient sound level (L_{95} or L_{90}). In the UK and elsewhere the limit is a constant at low 10-m wind velocities and 5 dB above background ambient level (L_{90} + 5 dB) at higher 10-m wind velocities. In the Netherlands the standard limit is a reference curve constructed from a constant value at low 10-m wind velocities and a wind velocity dependent part at higher 10-m wind velocities (see figure VII.1). For wind farms over 15 MW other limit values may apply, and local authorities may enforce other limits in 'non-standard' local conditions.
As until now the effect of stability has usually been disregarded and the 10-m wind velocity was erroneously used for all atmospheric conditions, these limits are not always met. In stable atmospheric conditions, when hub height wind velocity exceeds the cut-in wind velocity, this implies that an extra effort to reduce the immission level may be necessary.

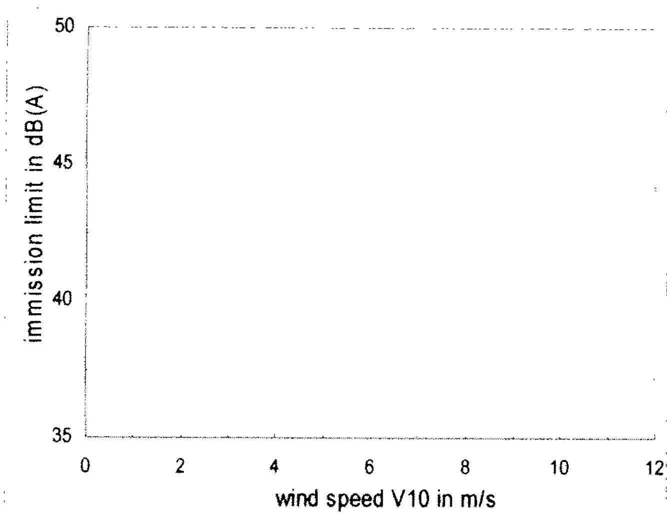

Figure VII.1: standard limit for night time wind turbine immission sound level in the Netherlands

In undulating and certainly in mountainous terrain this change in wind profile may be influenced or even overridden by relief related changes. For example: in a valley a downflowing (decelerating) wind may enhance the effect of stability, whereas an upflowing (accelerating) wind may compensate the effect of stability. Furthermore the wind profile as well as the temperature profile will simultaneously influence the propagation paths of sound. Combined effects are therefore complex and, though readily understood qualitatively, not easily predicted quantitavely.

The second measure is worth considering when the noise limit incorporates a penalty for a sound having a distinctive (impulsive or fluctuating) character. In that case either the sound immission level should be reduced by a value equal to the penalty (usually 5 dB) or the sound character must change. Many press reports as well as some scientific investigations clearly indicate that the character of wind turbine sound is important in its perception (see chapeter V and as an illustration the press article excerpt on this page –about a wind farm in a hilly countryside). Still, turbine manufacturers and consultants seem to be reluctant to acknowledge any added annoyance due to the sound character. In the long term this may feed opposition to wind energy and thus prove to be counterproductive.

VII.2 Reduction of sound level

When the sound immission level is limited to a value depending on the 10-m wind velocity or the (supposedly 10-m wind velocity dependent) ambient sound level, the problem is that hub height wind velocity is not uniquely related to 10-m wind velocity and the sound emission as well as immission level can have a range of levels depending on atmospheric stability. The turbine thus operates at hub height wind velocity, but must be controlled by a 10-m based wind velocity. To achieve a lower sound level the speed of rotation can be decreased.

VII.2.1 Wind velocity controlled sound emission

As a result of opposition to wind farm proposals in the relatively densely populated central province of Utrecht in the Netherlands all proposals were cancelled but one. The exception is in Houten (incidentally 8 km east of Cabauw; see previous chapter), where the local authorities want to stimulate wind energy by allowing the constructing of several 3 MW turbines, at the same time ensuring that residents will not be seriously annoyed. Atmospheric stability is taken into account by not accepting the usual logarithmic relation between 10-m and hub height wind velocity. The official permission will require that the immission sound level at specified locations must not exceed the background level of all existing ambient sound. Of course ambient sound level depends on wind velocity if the wind is sufficiently strong, but in this area it also depends on wind direction as that determines audibility of distant sources: a motorway to the west, the town to the north-east and relatively quiet agricultural land to the south-east. So the background ambient level, measured as L_{95}, must be measured in a number of conditions: as a function of wind velocity (1 m/s classes), wind direction (4 quadrants) and time of day (day, evening, night). These values equal the limit values for the immission level L_{imm}, and from this it can be calculated what the maximum allowable sound power level L_{Wmax} per turbine is at every condition, presuming all (or perhaps a selection of) turbines produce. It is advisable to determine wind characteristics and turbine performance over a period of at least five minutes, as wind velocity variations are relatively strong at frequencies above approximately 3 mHz (inverse of 5 min) and weak at lower frequencies down to the order of 0.1 mHz (inverse of several hours) [Wagner *et al* 1996]. On the other hand rapid control is desirable to adapt to changing conditions, so averaging over 5 minutes seems a good choice.

Control will thus be achieved in a number of steps:

a) measure wind direction and wind velocity at 10 m height in open land over a (probably) 5-minute period;
b) determine the limit value for the sound power level L_{Wmax} from the previously established relation $L_{imm}(L_W)$
c) determine the actual sound power level $L_{W,5min}$ from wind turbine performance (electric power or speed);
d) if actual $L_{W,5min}$ exceeds L_{Wmax} (equivalent to $L_{imm} > L_{95}$) the control system must decrease sound power level for the next period; if $L_{W,5min} < L_{Wmax}$ the reverse applies (until maximum speed is attained).
Changing the sound power level can be effected by increasing blade pitch (slowing the blades down).

The pro's of this control system are that it is straightforward, simple, easy to implement and directly related to existing Dutch noise limits. However, it is based on the assumption that L_{95} depends on three parameters only: wind velocity, wind direction and diurnal period. In reality background level will also depend on the hour (*e.g.* traffic: nights are very quiet at around 4am and most busy just before 7am), day of the week (*e.g.* Sunday mornings are quieter than weekday mornings), season (vegetation, holidays), atmospheric stability (no wind in low vegetation in stable conditions, even when 10-m wind velocity is several m/s) and other weather conditions such as rain. Also sound immission from distant sources will differ with weather conditions.

Measurements show that indeed 10-m wind velocity is not a precise predictor of ambient sound level. These measurements were performed from June 9 through June 20, 2005 at two locations: wind velocity was measured at 10-m height in open terrain, at least 250 m from any obstacles over 1 m height (trees lining the busy and broad Amsterdam-Rhine Canal to the northeast) and over 1000 m from obstacles in any other direction; the sound level was measured close to a farm next to the canal (see figure VII.2). Total measurement time was 220 hours.

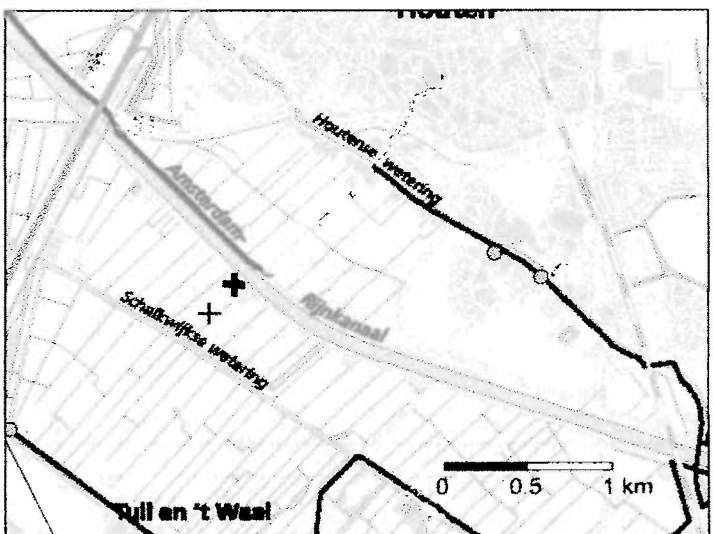

Figure VII.2: measurement locations for wind speed and direction (light cross) and ambient sound level (heavy cross) close to Houten (in upper part of map); top is north

Some results are plotted in figure VII.3: L_{95} per 5-minute period as a function of wind velocity (averaged per 5 minutes), separately for two wind directions and two periods. The periods are night (23pm – 7am) and day (7am – 7 pm), the wind directions southeast (90° - 180° relative to north) and northwest (270° - 360°), where respectively the lowest and highest ambient levels were expected. The northwest data total 675 5-minute periods or 26% of all measurement time, the southeast data cover 511 periods or 19% of the measurement time. The 5-minute L_{95} values are calculated from all (300) 1-second samples within that period. To determine a long-term background level an appropriate selection (wind direction, period) of all measured 1-second sound levels can be aggregated in 1 m/s wind velocity classes (0-1 m/s, 1-2 m/s, etc.). In figure 2 these aggregated values (connected by lines to assist visibility) are plotted for day and night separately. It is clear that in many cases the 5-minute period values of L_{95} are higher, in less cases lower than the long-term value. This means that if the immission limit is based on the measured long-term background sound level, then in a significant amount of time the actual background level will not be equal to the previously established long-term level. This is important for 10-m wind velocities as low as 2 m/s, as even then 100-m wind may be strong enough to drive a turbine at high speed.

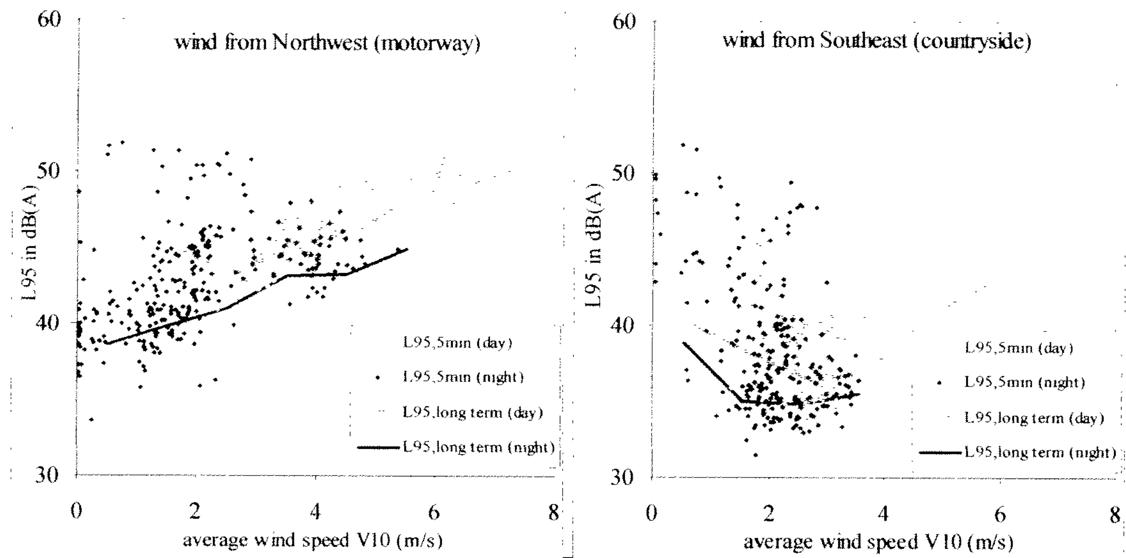

Figure VII.3: 5-minute $L_{95,5min}$ in day (open, grey diamonds) and night time (solid, black dots) and long-term L_{95} (lines) as a function of 10-m wind velocity in open terrain for two different wind directions (implying different sound sources)

VII.3.2 Ambient sound level controlled sound emission

An alternative to a wind velocity controlled emission level is to measure the ambient sound level itself and thus determine the limit value directly. To achieve this the background ambient sound level can be determined by measurement (*e.g.* in 5-minute intervals) and compared to the immission level calculated from the actual turbine performance. If the immission level L_{imm} is exactly equal to the ambient background level L_{95} without turbine sound (so $L_{imm} = L_{95} = L_{imm,max}$), then background sound level including turbine sound is $L_{95+wt} = \log.\text{sum}(L_{imm,max} + L_{95}) = L_{imm,max} + 3$ dB or $L_{imm,max} = L_{95+wt} - 3$ dB. If the calculated immission level is equal to measured ambient L_{95+wt}, turbine sound apparently dominates the background level and the turbine should slow down.
This type of control can also be achieved in several steps. Again assuming 5-minute measurement periods, these are:
a) determine the actual sound power level $L_{W,5min}$ (integrated over 5 minutes) from turbine power production or speed;
b) measure actual background level $L_{95+wt,5min}$ at a location where the limit applies;
c) if $L_{imm} > L_{95+wt,5min} - 3$ dB then $L_{W,5min} > L_{Wmax}$ and the control system must decrease sound power level for the next 5-minute period, if $L_{W,5min} < L_{Wmax}$ the reverse must happen (until maximum speed is attained).

Here it is assumed that the microphone is on a location where the background ambient level L_{95} (without any turbine) equals the limit value. If a measurement location is chosen further away from the turbine(s), the immission sound level will decrease with a factor ΔL_{imm} at constant L_W, whereas L_{95} will not change (assuming that ambient sound does not depend on location). In this case a correction must be applied to the measured L_{95} ($L_{imm,max} = L_{95+wt} - \Delta L_{imm}$) to determine what sound power level is acceptable. A similar approach may be used if the limit is not L_{95} itself, but L_{95} + 5 dB. In that case, is it not possible to determine L_{95} from measurements at a location where this limit applies, as the turbine sound is allowed to be twice as intense as background sound itself. In that case a measurement location may be chosen where ΔL_{imm} is 5 dB.

An apparent drawback of this sound based control is that measured ambient sound may be contaminated by local sounds, that is: from a source close to the microphone, but not as loud as a turbine. Also, figure 2 suggests that there are significant variations in $L_{95,5min}$, which could imply large control imposed power excursions if these variations occur in short time. The first drawback can be solved by using two or more microphones far enough apart not to be *both* influenced by a local source. The limit value is then either $L_{95,5min}$ determined from all measured sound levels within the previous 5-minute period, or the lowest value of $L_{95,5min}$ from each microphone location.
Secondly, large variations in either wind velocity or background sound level are rare, as is shown in figure 3 where the difference is plotted between consecutive 5-minute and 15-minute values of L_{95} and average free 10-m wind velocity. For 99% of the time the change in wind velocity averaged over consecutive periods of 5 or 15 minutes is less than 1.5 m/s (in 72% less than 0.5 m/s). For 94% of the time the change in background sound level over consecutive periods of 15 minutes is less than 3.5 dB (96% for 15 minute periods) and in 88% (89%) of the time the change is less than 2.5 dB. So if the adjustment of sound power level is in steps no larger than 3 dB, most changes can be dealt with in a single step.

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 less likely a similar change occurs within the next one or two periods.

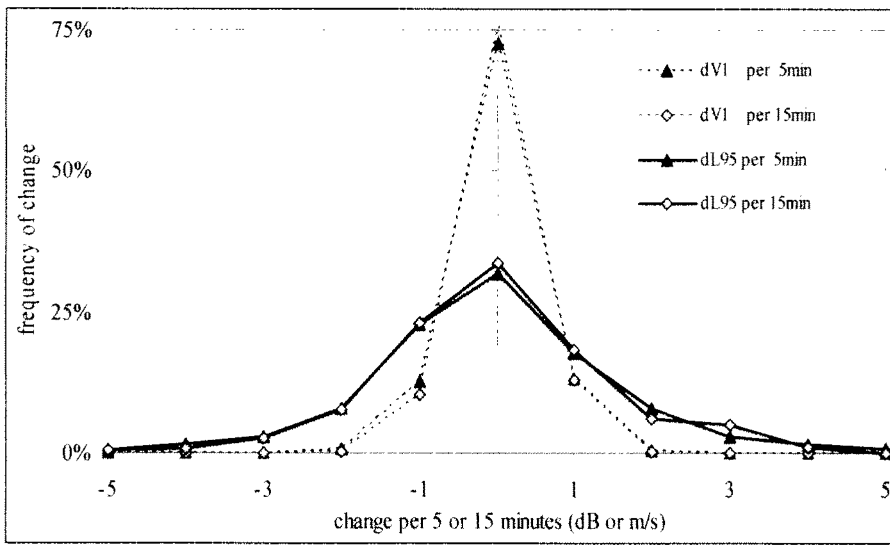

Figure VII.4: frequency distributions of changes per 5 and per 15 minutes of average wind velocity and background ambient sound level in classes of one unit (dB or m/s)

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. When the blade passes the tower this angle can change from its optimum value (zero) up to 4° or 5°. 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. Both effects may lead to well audible level variations of 3 -10 dB as has been shown theoretically as well as in practice [2].
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 length blade and is lowest at the tip. At zero angle of attack, blade pitch is 10° (0.17 radians) at a typical blade tip speed of 70 m/s and wind velocity of 12 m/s. As 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 is about 0.8° at the lower tip in an unstable atmosphere, increasing to almost 3° in a very stable atmosphere [2].
In front of the tower there is a further change in angle of attack due to the fact that the tower is an obstacle slowing down air passing the tower. This change is of the order of 2° [2].

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, which also occurs in daytime, can be eliminated further 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 is not perceived as a (relatively annoying) fluctuating sound.

VII.4.2 Rotor tilt

If the rotor is tilted backwards. the angle of attack will change while the blade rotates. If the tilt angle changes from zero to θ, the angle of attack at the low tip increases from α to α', with:

$$\tan(\alpha') = (\tan[\arctan\{\sin(\alpha)/\rho\} + \theta] - \tan(\theta))\cdot\rho/\cos(\alpha) \qquad \text{(VII.1)}$$

(1)

where $\rho = r/b$ is the ratio of radius r and blade width b (at radius r). For small blade pitch angles and blade slenderness ρ between 10 and 40 the increase of angle of attack with tilt (from 0 to θ) can be approximated with:

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

(2a)

In the range $\alpha \leq 20°$, $10 \leq \rho \leq 40$ and $\theta \leq 30°$, the standard deviation of the constant 1.1 is 0.06. With angles expressed in degrees, equation 2 reads:

$$\Delta\alpha = (33 \pm 2) \cdot 10^{-5} \cdot \alpha \cdot \theta^2 \qquad \text{(angles in degrees)} \qquad \text{(VII.2b)}$$

(2b)

This means that for a tilt angle of 2°, as used in modern turbines and 10° blade pitch (tip rotational speed 70 m/s, wind velocity 12 m/s), the change in angle of attack (relative to a vertical rotor with zero tilt) is negligible (0.014°).
Rotor tilt could compensate a 1° change in angle of attack due to high stability when the tilt angle is 17°. In this case the horizontal distance between the low tip and the turbine tower increases with at least 10 m. This will also lead to a smaller change in angle of attack as at this distance the velocity deficit in front of the tower (due to the presence of the tower) is lower.
A major disadvantage of a substantial tilt is that it decreases the rotor surface normal to the wind; also it will lead to a substantial higher torque at the hub.

VII.4.3 Desynchronization of turbines

When the atmosphere turns 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 the turbines become better synchronized. This synchronization may lead to coincidence of blade beats from two or more turbines for an observer near the wind farm, and thus higher pulse levels. To desynchronize the turbines in this situation, the random variation induced by atmospheric turbulence 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 $n = fz/U \approx 0.01$, where U 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 $U = 10$ m/s this corresponds to a physical frequency $f = nU/z = 1$ 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 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 emiision 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 the near future 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 nothing further 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 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 probably 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.

VIII RUMBLING WIND: Wind induced sound in a screened microphone

VIII.1 A history of wind induced 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 $Sr = fD/V$, Reynolds number $Re = DV/\nu$ and Mach number $M = V/c$ (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: $p_f/\rho V^2 = \mathit{function}(Sr, Re, M)$. 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:

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

where f_m is the middle frequency of the 1/3 octave band. The data points agreed within appr. 3 dB with (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 1 can also be written in acoustical terms by expressing the rms pressure as a sound pressure level relative to 20 μPa:

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

Here V_o is a reference velocity of 1 m/s and $\rho = 1.23$ kg/m^3 is used (air density at 1 bar and 10 °C). (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 screenand 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 also depend on meteorological parameters. 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 $\overline{u} = 0$, to obtain the rms pressure fluctuation $p = \rho V u$ [2] (italics are used to denote the rms value x of a variable x: $x = \sqrt{\overline{x^2}}$). 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:

$$p = \alpha \cdot \rho (V u)^k$$

(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 & Raspet 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 then predicted by (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 $p(0) = -\frac{1}{2} \cdot \rho V u$ or:

$$p(0) = \tfrac{1}{2}\rho V u \qquad \text{(VIII.4)}$$

Comparison with equation (VIII.3) shows that now $\alpha = 0.5$ and $k = 1$.

Finally, in this introduction, Boersma showed that sound spectra due to wind measured at 1.5 m above flat, open grassland were in good agreement with Strasberg's results [Boersma 1997]. 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 study 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 (Section 2). Then we will turn to measured spectra related to wind, obtained by the author as well as by others (Section 3). Finally the results will be discussed (Section 4).

VIII.2 Atmospheric turbulence

A wind borne eddy that is large relative to the microphone wind screen, so 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 Introduction, 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 $\alpha = 0.5$. 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 [3], and $\alpha \leq 0.5$; Morgan & Raspet found $\alpha = 0.16 - 0.26$ [2]. The pressure level due to atmospheric turbulence can be expressed as a sound pressure level L_{at} (with reference pressure $p_{ref} = 20$ μPa):

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

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 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 [Zheng *et al*2003].

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 ([Kaimal *et al* 1972], p. 53):

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

Here $\kappa = 0.4$ is von Karman's constant, z_o is the roughness height and u_* is the friction velocity, defined by $u_*^2 = \sqrt{(\overline{uw}^2 + (\overline{vw}^2)} = \tau/\rho$, where τ equals the momentum flux due to turbulent friction across a horizontal plane.
$\Psi = \Psi(\zeta)$ is a function (of $\zeta = z/L$) correcting for atmospheric stability. Monin Obukhov length L is an important length scale for stability and can be thought of as the height above which thermal turbulence dominates over friction turbulence. Garratt [1992] gives the following approximations:

- In a stable atmosphere $L > 0$ and $\Psi(\zeta) = -5\zeta < 0$.
- In a neutral atmosphere $|L|$ is large or $1/L \approx 0$, $\Psi(0) = 0$, and (6) reduces to the well known logarithmic wind profile.
- In an unstable atmosphere $L < 0$ and $\Psi(\zeta) = 2 \cdot \ln[(1+x)/2] + \ln[(1+x^2)/2] - 2/\tan(x) + \pi/2 > 0$ where $x = (1-16 \cdot \zeta)^{1/4}$.

For $-1 < \zeta < 1$, $\Psi(\zeta)$ is of the same order of magnitude as the logarithmic term in (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 rms longitudinal velocity fluctuation u_f per unit frequency in a neutral atmosphere depends on frequency as [Kaimal *et al* 1972]:

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

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 (6), leads to $u_f^2 = 105 \cdot u_*^2 \cdot z/V = 105\kappa^2 zV \cdot [\ln(z/z_o) - \Psi]^{-2}$. 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 (7) reduces to $3.2 \cdot (33n)^{-2/3}$, leading to $u_f^2 = 0.3 \cdot u_*^2 \cdot (V/z)^{2/3} \cdot f^{-5/3}$, which describes the inertial subrange. The frequency where (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 ≈ 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 $u_f^2 = 0.3 \cdot u_*^2 \cdot (V/z)^{2/3} \cdot f^{-5/3}$. It is convenient to integrate this over a frequency range f_1 - f_2 to obtain a

1/3-octave band level ($f_m = 2^{-1/6} \cdot f_2 = 2^{1/6} \cdot f_1$) with centre frequency f_m: $u_{1/3}{}^2 = 0.046 \cdot u_*{}^2 \cdot (f_m \cdot z/V)^{-2/3} = [0.215 \cdot u_* \cdot (f_m \cdot z/V)^{-1/3}]^2$. Substituting u_* from (6) and applying the result to equation (5) for 1/3 octave band levels $L_{at,1/3}(f_m) = 20 \cdot \log(\alpha \rho V u_{1/3}/p_{ref})$, yields:

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

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 (VIII.8) $C = 20 \cdot \log(0.215 \kappa \alpha \rho V_o{}^2/p_{ref}) = 62.4$ dB for $\kappa = 0.4$, $\alpha = 0{,}25$, $\rho = 1{,}23$ kg/m^3 and pressure level is taken re $p_{ref} = 20$ 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 $f = V/\ell$) 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 $(\ell^2/D^2) \cdot \sqrt{(D^2/\ell^2)} = \ell/D = V/fD$. 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 $D/\ell \approx 0.3$ ([Morgan 1993], see also [Zheng *et al* 2003]). We therefore expect at sufficiently high frequencies the pressure at the microphone to decrease proportional to $20 \cdot \log(D/\ell)$ relative to (8), and this decrease must vanish when $D/\ell = Df/V < 0.3$, *i.e.* below the cut-off frequency $f_c = 0.3V/D$. As the change will be gradual, a smooth transition can be added to (VIII.7):

$$L_{at,1/3}(f) = 40 \cdot \log(V/V_o) - 6.67 \cdot \log(zf/V) - 20 \cdot \log[\ln(z/z_o) - \Psi] - 10 \cdot \log(1 + (f/f_c)^2) + C \qquad \text{(VIII.9a)}$$

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 $Sr = fD/V$ as independent variable of a 'meteorologically reduced' 1/3 octave band level L_{red}:

$$L_{red,1/3} = L_{at,1/3} - 40 \cdot \log(V/V_o) + 20 \cdot \log[(z/D)^{1/3} \cdot (\ln(z/z_o) - \Psi)] = - 6.67 \cdot \log(Sr) - 10 \cdot \log[1 + (3Sr)^2] + C \qquad \text{(VIII.9b)}$$

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

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

This can be rewritten in a aerodynamic terms as:

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

where $C_p = 20\cdot\log(0.215\kappa\alpha) - 9.5 = -43$ dB. For F(z) = -20 dB (*e.g.* a 10 cm diameter wind screen at a z = 2 m, z_0 = 5 cm and $\Psi = 0$) the right hand side of (VIII.10b) is $-26.67\cdot\log(Sr) - 63$. 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 & Morgan (see Introduction). The change in slope, visible at Strouhal number Df_c/V= 0.3 in figure 1, is a feature not explained by the earlier authors.

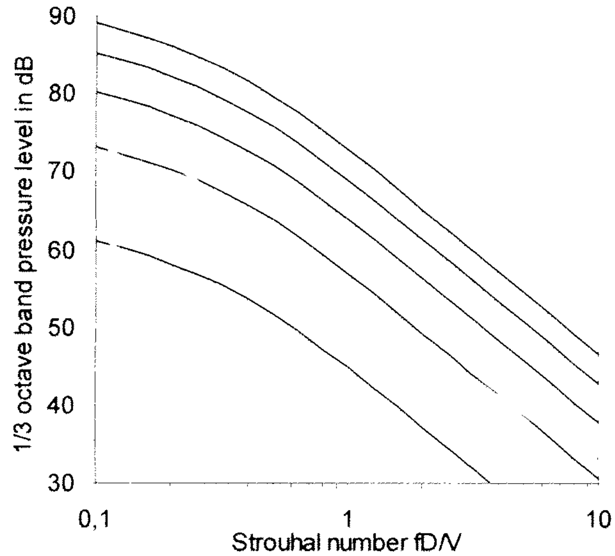

Figure VIII.1: black lines: 1/3 octave band levels Lat,1/3 due to atmospheric turbulence at wind velocities of (bottom to top) 2, 4, 6, 8 and 10 m/s; F(z) = -18 dB, C=64 dB; gray lines: levels at same wind velocities according to Strasberg

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, $L_{at,1/3} \sim 46.7\cdot\log V$ and $\sim -6.7\cdot\log f$;

iii- at higher frequencies, but still in the inertial subrange, eddies average out over the wind screen more effectively at increasing frequency ($L_{at,1/3} \sim -26.7\cdot\log f$), but pressure level increases faster with wind velocity ($L_{at,1/3} \sim 66.7\cdot\log V$) ;

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 $Sr = fD/V > 0.1D/\eta_s \approx 100\cdot[D/\text{m}] = D/\text{cm}$.

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

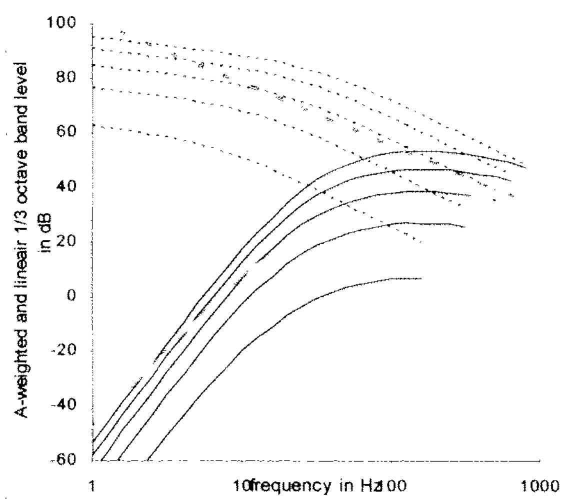

Figure VIII.2: lineair (dashed) and A-weighted (solid lines) 1/3-octave pressure levels due to atmospheric turbulence on a screened microphone with F(z)+C=42 dB, D = 0.1m, for wind speeds 2, 4, 6, 8 and 10 m/s (black, bottom to top); bold grey dashed line: 1/3 octave band levels according to Strasberg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

VIII.2.4 Wind induced broad band A-weighted level

In figure VIII.2 1/3-octave band levels according to equation (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 $\Psi = 0$). 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:

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

where $\ell_o = 1$ m is a reference length. (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 $5 < D/\text{cm} < 50$. 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, (VIII.11a) becomes:

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

Now for $z_o = 2{,}5 - 6$ cm and $\Psi = 0$, 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 3 is a plot of (11) with G(z) = 0, C = 62 dB. Also plotted in figure 3 is the relation according to Strasberg, obtained by A-weighting and integrating equation (2) over f.

VIII.3 Comparison with experimental results

VIII.3.1 Measured spectral pressure levels due to wind turbulence

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

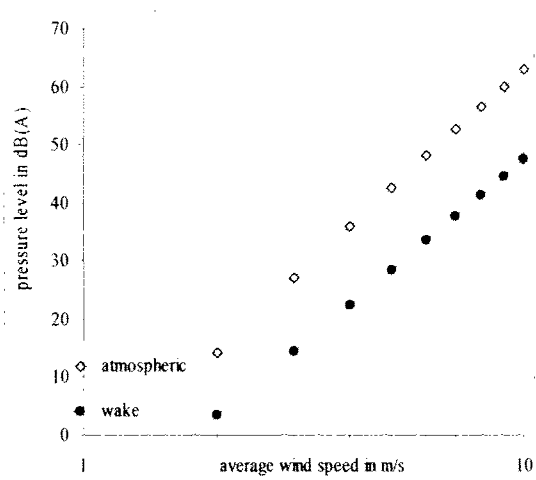

Figure VIII.3: A-weighted broad band pressure level caused by atmospheric or wake turbulence with G(z)+C=62.4 dB, D = 0.1m location (a golf course), Boersma grass height (≈ 10 cm), Larsson only mentions measurement height over grass at either 1.25 or 4 m, without specifying which height applies to a 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 that however 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 [13] 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 (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 $\Psi = 0$) 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

Table VIII.1: measurement characteristics

author	period	location	zo (cm)	Hwind (m)	Hmic (m)	Vmic (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] 9.5	6 obs. [5]	9 9	63 – 8k	1/1
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	Grassland	3 [2]	2	1.5	3 – 7	no [4]	160	9	6 – 16k	1/3
						2 – 9	9	430	7	6 – 16k	
this study:											
Horsterwold	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	grassland	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

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 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 $\Psi = 0$ 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 $Sr = fD/V$. The approach taken here is to

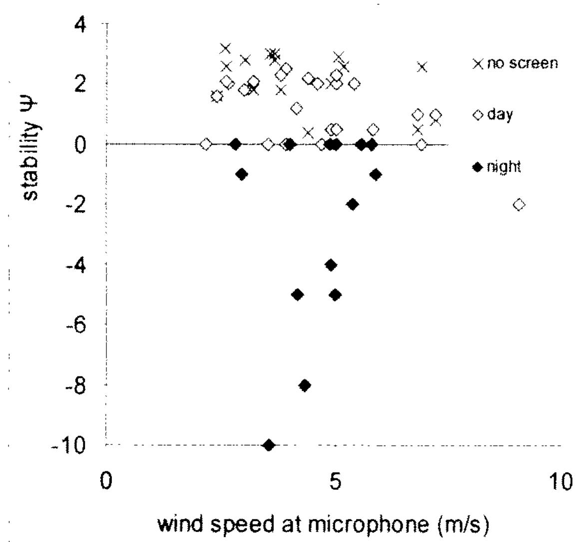

Figure VIII.6: values of the stability function after fitting reduced spectral levels Lred with theoretical spectrum, for measurements in day or night time, and for unscreened microphones in vary Ψ to obtain a best fit to the theoretical value of the L_{red} levels at non-dimensional frequencies in the 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 $\Psi \leq 0$ and $\Psi \geq 0$, 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 $\Psi \leq 0$.

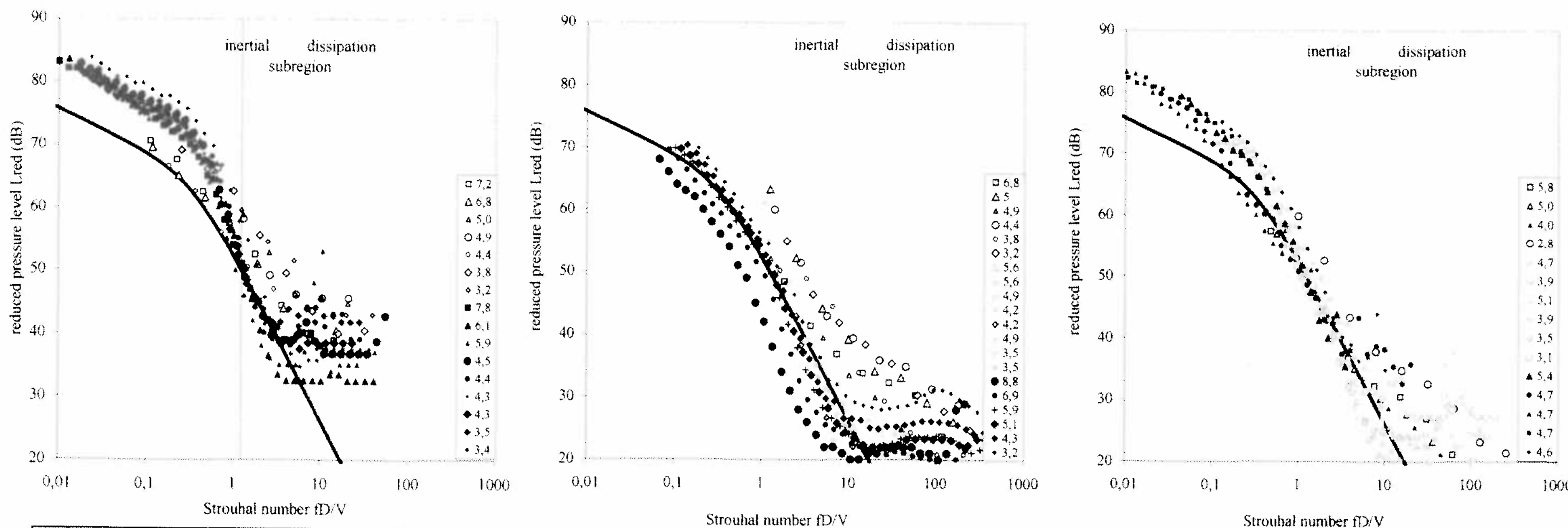

Figure VIII.4: reduced 1/3 octave band pressure levels at different wind velocities (in legend: m/s), bold line is predicted spectrum; left: unscreened microphone, from Larsson (open symbols) and Boersma (black symbols; middle: screened microphone, from Larsson (open symbols), Jakobsen (grey) and Boersma (black symbols); right: screened microphone, measurements in Horsterwold (open symbols), Kwelder (grey) and Zernike (black symbols).

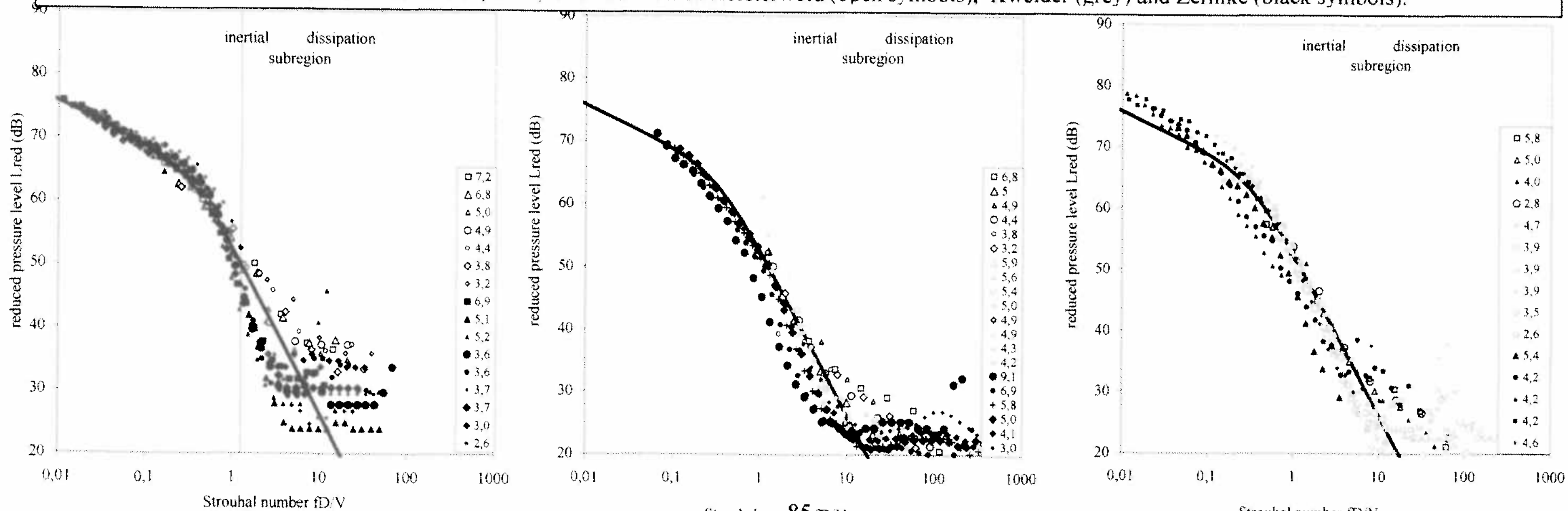

Figure VIII.5: same as figure 4, but after fitting with stability function

VIII.3.2 Measured broad band pressure levels due to wind turbulence

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 $L_A = 4.4 \cdot v + 27.5$ (v and L_A measured at the same height), to Jakobsen $L_A = 6.8 \cdot v - 2.6$ (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

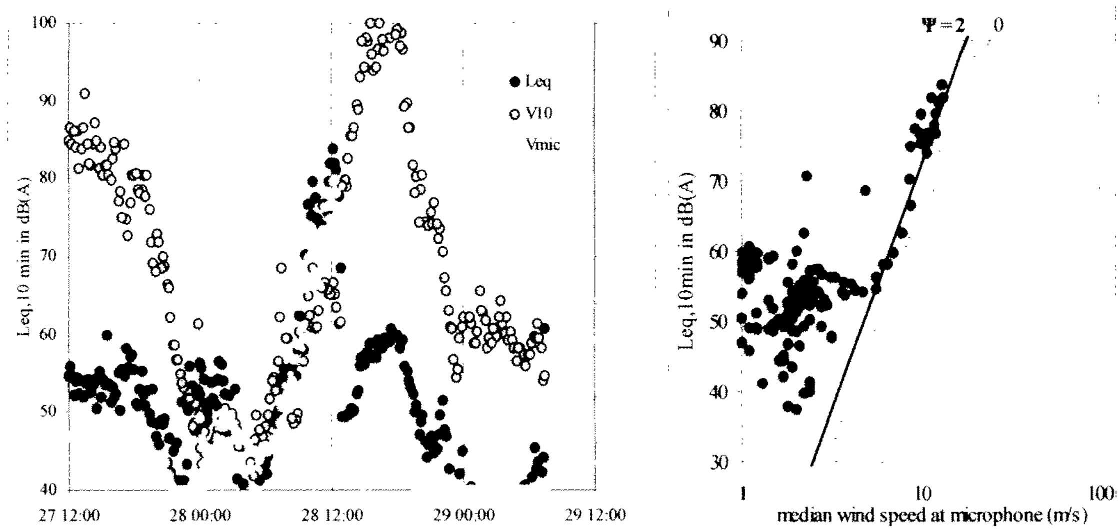

Figure VIII.7: measurements during a storm in front of a big shed; left: 10 minute averages of wind speed at microphone and at 10 m height and sound pressure level Leq; right: Leq as a function of microphone wind speed and predicted sound pressure level (G(4.6) = 8.2 dB) measure sound pressure level 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 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 lower wind velocities. Again, the stability factor Ψ is not known , but in daytime and in strong winds it must be small and positive. In figure 7 results are shown for two values of Ψ (with zo = 20 cm) encompassing the measured values.

VIII.3.3 Screen reduction

For two of our Zernike summer measurements (see table 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 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 (1.8 cm < D < 2.4 cm) wind screen the average screening effect would agree better with the calculated effect.

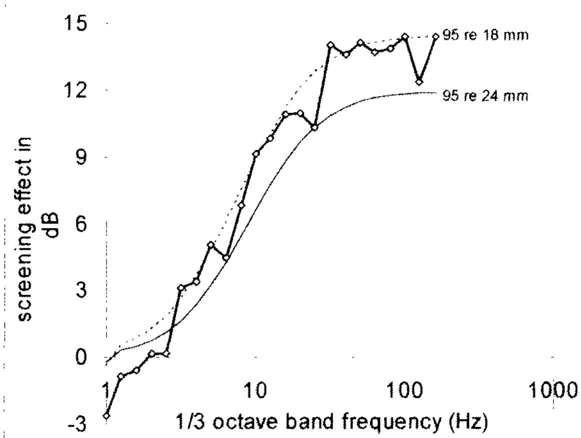

Figure VIII.8: measured (line with markers) and calculated screening effect of a 9.5 cm relative to a 2.4 or 1.8 cm wind screen

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, 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*). 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 $\zeta = z/L$ 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.

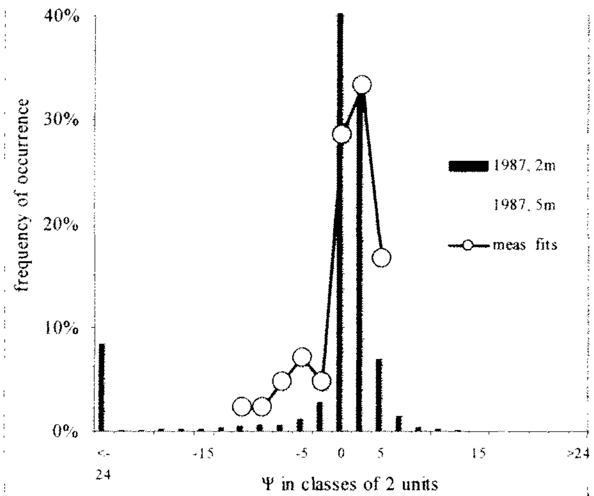

Figure VIII.9: frequency distributions of stability factor Ψ at 2m and 5 m height, based on ½ hour observa-tions over 1987 and resulting from fitted spectra

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 slopes are as in eq. 9b, the best fit of all data points in figure 5 at $Sr < 2.5$ is a line $L_{red,1/3} = -6.7 \cdot \log(Sr) - 10 \cdot \log[1 + (3.8 \cdot Sr)^2] + 62.0$. So the ratio ℓ/D (3.8) where screen averaging over eddies sets in may be greater than assumed (3); 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). The fit is within 2.2 dB of the calculated value (eq. 9b); for $2.5 < Sr < 16$ this 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 $\Psi = 0$). 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 $z_o = 10$ 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: $\Delta L_A = 20 \cdot \log(D_2/D_1)$ (from equation (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 (1) or (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 (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 (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 1.6) have been addressed separately in the previous chapters. In tThis chapter, we present gives 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 usingby 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, at the same wind velocity v_{10}, be significantly higher in a stable atmosphere at the same wind 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 non-neutral, 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 wind park in Rhede 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 4 to 6 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

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[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.

turbines may arrive simultaneously for a period of time and increase the fluctuation level further at the observer's position. 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 the distances to the observer.

Blade passing frequency is the parameter determining the modulation frequency of wind turbine sound. Human perception is most sensitive to modulation frequencies close to 4 Hz in the region of~~of~~ sound with 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 for~~causes~~ 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~~degree~~ 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. Also, the low near-ground wind velocity creates less wind noise on the microphone. As a result, sound measurements during~~in~~ a stable night are much less influenced by wind induced microphone noise (and other sounds as well, since ~~as~~ nights are usually more quiet) than in a neutral or unstable atmosphere.

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]

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 (at night), as both

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

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, which is much lower than atmospheric turbulence is in non-stable conditions. 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.

IX.4 Occurrence 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~~that~~ determine the magnitude and evolution over time of the heat balance in the atmospheric boundary layer. Most important are differences in heat transfer on~~in~~ 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.

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.
Near the Rhede wind farm the same range of night time wind shear occurred, showing that thi~~s~~e site is representative of~~for~~ many other locations and suitable for~~to~~ studying the effect of atmospheric stability on wind turbine performance.

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 a~~l~~lways 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~~-room~~ for sound (and energy) production in daytime, but less during~~in~~ quiet nights. A strategy for onshore wind farms might be~~is~~ 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 controlling~~ed~~ 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. 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, 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 ~~relation to~~ 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 reference height via a (possibly implicit) neutral or 'standard' wind profile. A correct, stability dependent, wind profile should be used. In mountainous terrain one should determine the relationship between hub height wind velocity on the one hand and ambient background sound at an immission location on~~at~~ the other hand directly, 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 conditions, the difference in sound power as well as in sound limits can lead to new control strategies and onshore wind farm concepts. Presently~~Now~~ only distance is a factor used to minimize noise impact. When daytime immission levels do but nighttime immission levels do not (always) comply with~~to~~ the noise limits, a control system can be implemented to reduce the turbine speed when necessary.

In new turbine designs continuous blade pitch control can 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, only driven only by wind with a constant profile. This may motivate researchers and consultants to put more effort into better predictions of wind turbine noise, and considering again noise exposure to local residents.

This period has begaun with publishing the results of the measurements at the Rhede wind farm and at it the end, ed, it seeminglys almost symbolically, coincided 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. A delegate assured me the 'Vandenberg-effect' was a name that would stick to my contribution (it is used in at least Australia, Great Britain and New Zealand). Now I feel I can be proud of this, but earlier I had protested to the name: stability was the correct meteorological term to use, and it is universal, not something onlyjust I had measured in an obscure part of the world. 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. ThusSo, it becomesis also 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 sensiblesound 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 a better insight into 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 dichotomy with such significant consequences?

Several technical possibilities to minimize the noise have been outlinedshown 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 WARAYDU 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)*

ACKNOWLEDGMENTS

Bobby asks: 'Do you ever hear the windmills?'
'What sound do they make?'
'It's a clanking metal noise, but when the wind is really strong the blades blur and the air starts screaming in pain.' He shudders.
'What are the windmills for ?'
'They keep everything running. If you put your ear to the ground you can hear them.'
'What do you mean by everything?'
'The lights, the factories, the railways. Without the windmills it all stops.' [1]

SUMMARY

[1] 'The suspect', by Michael Robotham, Time Warner Paperbacks, 2003 (p. 151)

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 begintde 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 't allemaal stil.' [1]

SAMENVATTING

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

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Appendix A: List of symbols

Symbol:	definition [unit]
α:	angle of attack [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 (here: between (1/3) octave band level and L_A); also: air density [kg/m^3]
$\Psi(\zeta)$:	stability function
ζ:	dimensionless height (h/L)
Ω:	turbine rotor angular velocity [$rad \cdot s^{-1}$]
a:	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: 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]
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
f_B:	blade passing frequency [Hz]
f_c:	screen size related corner frequency ($f_c = 0.3V/D$)
f_i:	α-dependent factor for boundary layer thickness [-]
f_{log}:	ratio v_{98}/v_{10} valid in a neutral atmosphere [-]
f_{stable}:	ratio v_{98}/v_{10} valid in a stable atmosphere [-]
F_{bb}:	fluctuation strength [vacil]
F(z):	turbulence related function: $F(z) = -20 \cdot \log[(z/D)^{1/3} \cdot (\ln(z/z_o) - \Psi)]$ [dB]
G(z):	turbulence related function: $G(z) = -20 \cdot \log[0.2 \cdot (z/\ell_o)^{1/3} \cdot (\ln(z/z_o - \Psi)]$ [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 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 sound level [dB(A)]
L_{A5}:	5-percentile of broad band sound levels over a time period [dB(A)]
L_{A95}:	95-percentile of broad band sound levels over a time period [dB(A)]
$L_{at}(u)$:	pressure level due to atmospheric turbulence [dB]
$L_{at,1/1}(f)$:	pressure level due to atmospheric turbulence per frequency octave band [dB]
$L_{at,1/3}(f)$:	pressure level due to atmospheric turbulence per frequency 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 frequency 1/3 octave band [dB]
$L_{red,1/3}$:	'meteorologically reduced' 1/3 octave band level [dB]
$L_{red,1/1}$:	'meteorologically reduced' octave band level [dB]
L_W:	sound power level; L_{Wj}: j-th octave band sound power level [dB(A)]
M:	Mach number = air flow velocity/c (at radius R: M = ΩR/c) [-]
m:	stability exponent [-]
$m_{h1,h2}$:	*m* determined between heights h_1 and h_2 [-]
mf:	modulation factor [-]
n:	dimensionless frequency (n = fz/V) [-]
N:	number of blades [-]; rotational speed (ΩR/2π) [s^{-1}]
Ph:	Power at height h; Ph,lpp; Ph,hp [W]
p:	(sound) pressure
p_f:	rms pressure in narrow frequency band centered at frequency f
$p_{f1/3}$:	rms pressure in 1/3 octave band
p_{ref}:	reference (sound) pressure [20 μPa]
p(0):	rms pressure at center of wind screen
r:	distance [m]
R:	rotor radius = blade length [m]
ΔR:	increment in R [m]
R_X:	range between maximum and minimum sound levels (X= bb or f) [dB]
$R_{X,90}$:	range between 5- and 95-percentile of sound levels (X= bb or f) [dB]
Re:	chord based Reynolds number (Re = ΩRC/v); wind screen diameter based Reynolds number [-]
V:	air flow velocity or wind velocity [m/s]
V_o:	reference velocity [1 m/s]
v_h:	wind velocity at height h [$m \cdot s^{-1}$]
v_{ref}:	wind velocity at reference height [$m \cdot s^{-1}$]
v_{xx}:	wind velocity at height xx m [$m \cdot s^{-1}$]
Sp_i:	1/3 octave band weighing function for TE sound[dB]
SPL_i:	sound pressure level [dB]
Sr:	Strouhal number [-]
u:	longitudinal (along wind) component of wind turbulence velocity [m/s]
u_f :	rms longitudinal component of wind turbulence velocity per unit frequency [m/s]
u*:	friction velocity [m/s]
<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
i:	component of TE sound (i = p, s, α)
if:	in-flow
p:	pressure, pressure side
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 sound power level at the 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 blade–tower wake interaction is weaker 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 lower, near downwind turbines 10 to 30 dB higher, where 95 dB(G) corresponds to the average infrasound hearing threshold [Jakobsen 2004]. Infrasound from (upwind) wind turbines thus 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 in *A*, but changes will be random (not periodic) and less abrupt. For turbulent eddies the size of the chord length and less, effects are local and do not occur coherently over the blade. When the blade cuts through the eddies, the movement normal to the wind surface is reduced or stopped, given rise to high accelerations and thus sound.
In-flow turbulence sound has a maximum level in the 1/3 octave band with frequency:

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

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

B.3 High frequencies: trailing edge sound.

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

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

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

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

for a zero angle of attack. Re is the chord based Reynolds number [29]. The experimental factor a 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*), $f_{peak,TE}$ = 1700/a Hz. With a = 2 to 4, $f_{peak,TE}$ is 450 – 900 Hz. The spectrum (see Sp_i below) is symmetrical around $f_{peak,TE}$ and decreases with 3 dB for the first octave, 11 dB for the next; the contribution from further octave bands is negligible [Brooks *et al* 1989].

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

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

and total trailing edge immission sound level as:

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

where the index i refers to the pressure side, suction side or angle of attack part (i = p, s, α). The directivity function D_h equals unity at the front of the blade (θ = 180°) and falls off with $\sin^2(\theta/2)$. Because of the strong dependence on M (~ M^5) 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 $8\cdot 10^5$ 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 $i = \alpha$.

For small non-zero angles of attack ($\alpha < 5°$) the boundary layer thickness shrinks δ^* with a factor $f_p = 10^{-0.042\alpha}$ at the pressure-side and grows with a factor $f_s = 10^{0.068\alpha}$ at the suction-side; $\delta_\alpha^* = \delta_s^*$, so $f_\alpha = f_s$.
K_α has a large negative value for $\alpha = 0$. For $1° < \alpha < 5°$ and $M = 0.2$ it can be approximated by $K_\alpha = 3.6\alpha - 12.1$ ([Brooks *et al* 1989], formula 49 with $K_\alpha = K_2 - K_1 + 3$).
With equation B.4, equation B.5 can be rewritten as:

$$SPL_{TE} = 10\cdot\log(\delta^*\cdot M^5\cdot\Delta R\cdot D_h/r^2) + K_1 - 3 + 10\cdot\log(\Sigma_i\, 10^{(10\cdot\log(fi)+Spi + Ki)/10}) \qquad (B.6)$$

The last term in B.6 is the α-dependent part. For the peak frequency 1/3 octave band level ($Sp_i = 0$) the last term in equation B.6 is 3 dB for $\alpha = 0$, and 4.4 dB at $\alpha = 2°$, then increasing with approx. 1.7 dB per degree to 9.4 dB at $\alpha = 5°$. The level increase relative to the level at $\alpha = 0$ is given in table A1.

Table A1: increase of trailing edge sound level with angle of attack α					
A	1	2	3	4	5
$SPL_{TE}(\alpha) - SPL_{TE}(\alpha=0)$ (dB)	0.4	1.4	2.9	4.6	6.4

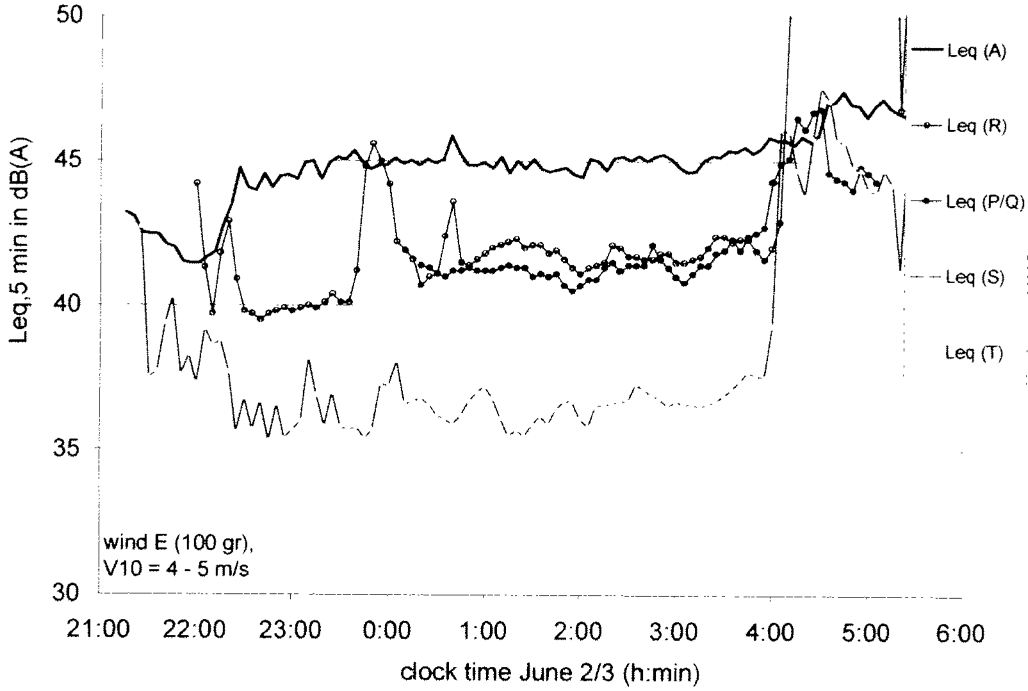
The swishing sound that one hears when a blade passes the tower is less than 3 dB (in daytime) [ETSU 1996]. It must correspond to a change in sound level of 1 dB to be heard at all. An increase of 1 dB corresponds to an increase in α from zero to a value of 1.7° (0.03 radians), an increase of 2 dB corresponds to 2.5° (0.04 radians). So we estimate the change in α at the tower passage as 2.1 ± 0.4°. Part of this is due to the lower wind velocity at the lower blade tip relative to the rotor average (0.8°, see section 3*a* of main text), the rest is due to the slowinf downb of the wind by the tower.
For small angles the change of wind velocity with angle of attack α at radius R is:

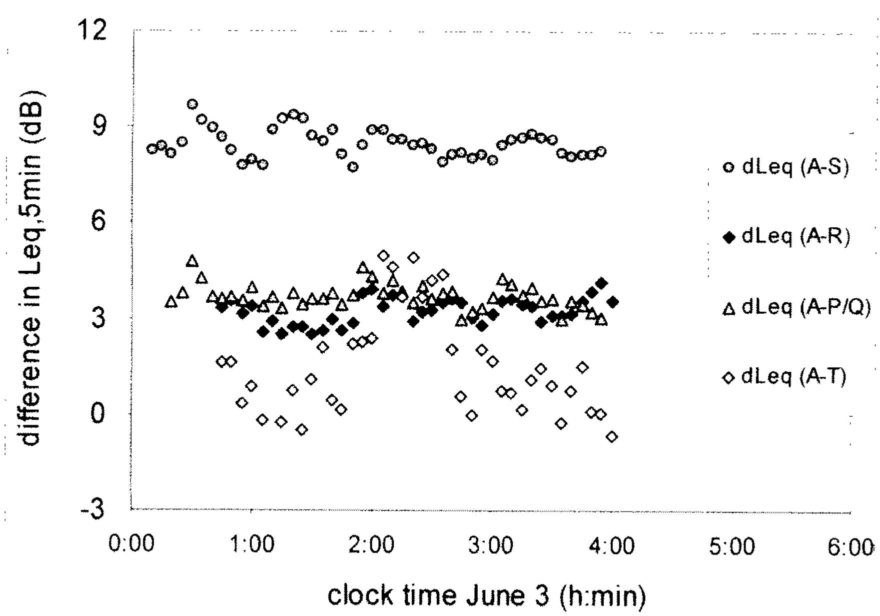
$$dV_{wind}/d\alpha = \Omega\cdot R \qquad (B.7)$$

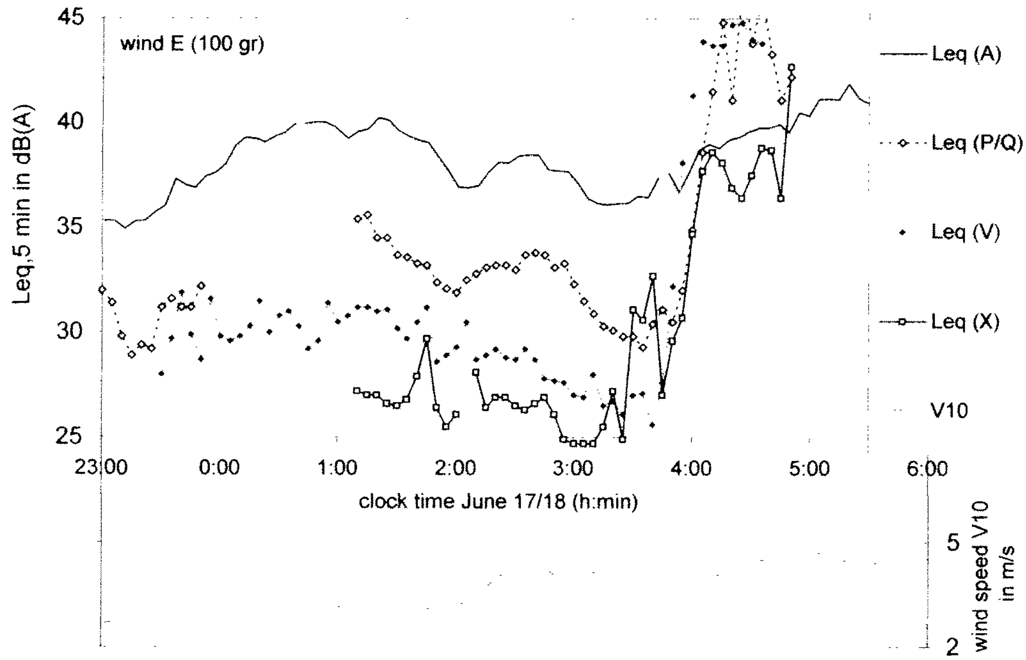
So for a modern turbine ($\Omega\cdot R \approx 70$ m/s at tip at 20 rpm) the wind velocity deficit where the blade tip passes the tower and $\alpha = 2.1°$ (0.037 radians) is 2.6 m/s. In a (rotor averaged) 14 m/s wind this is 20%. This deficit is due to the influence of the tower as well as the (daytime) wind profile.

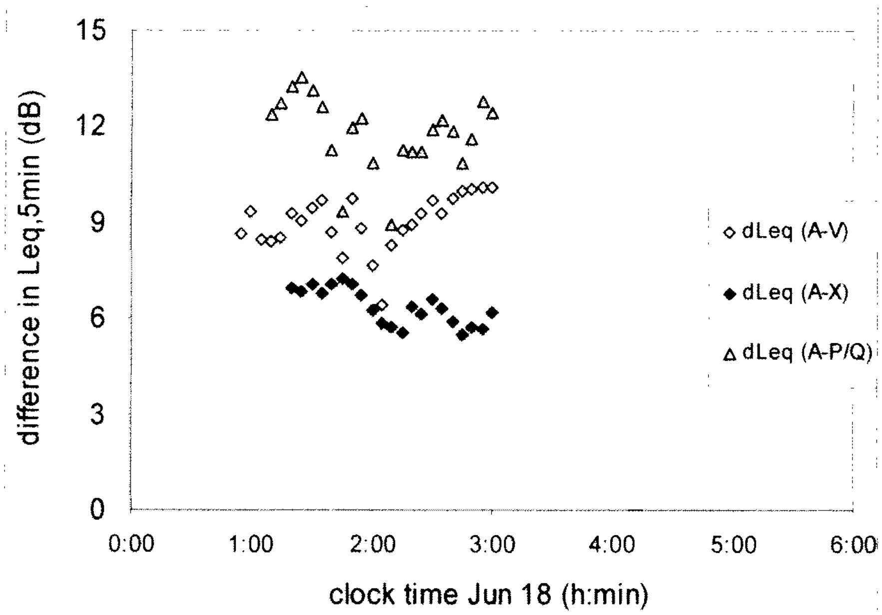
Appendix C: Simultaneous sound level registrations

Additional information to section IV.10: measurements at locations A and P through X (see map figure IV.8) 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 shown in graphs.






45
40
35
30
25
Leq,5 min in dB(A)
wind E (100 gr)
23:00
0:00
1:00
2:00
3:00
4:00
5:00
6:00
clock time June 17/18 (h:min)
5
2
wind speed V10 in m/s
Leq (A)
Leq (P/Q)
Leq (V)
Leq (X)
V10


15
12
9
6
3
0
difference in Leq,5min (dB)
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: Publications by the author

D1 Published and conference papers

D1.1 Single author

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Onduidelijke stralingsnormen leiden tot onrust, Intermediair vol. 27 nr. 35 (30 augustus 1991), pp. 27-28

Hoogspanningslijnen en overheidsbeleid, NVS-Nieuws 17e jaargang nr. 5 (december 1992), pp. 11-12

Waar of niet: mogelijk of vermeend, NVS-Nieuws 18e jaargang nr. 2 (april 1993) pp. 8-9 (reactie op artikel)

Noise from the Marnewaard shooting range; a review of sound and annoyance measurements, proc. Internoise93, Leuven 1993, pp. 1145-1148

A home kit for road traffic noise, proc. Euronoise95, Lyon 1995, pp. 163-168

Laagfrequent geluid-een onderschat probleem, Geluid mrt 1996, pp.14-18

Straling - één pot nat; Psychologische effecten van elektromagnetische straling, NVS-Nieuws, 22e jaargang nr.4, oktober 1997, pp. 11-14

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Bommen op Vlieland, Geluid dec. 1997, pp.140-142

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Wind turbines at night: acoustical practice and sound research, proceedings Euronoise2003, Naples (2003)

Effects of the wind profile at night on wind turbine sound, Journal of Sound and Vibration vol. 277 (4-5), pp 955-970 (2004)

Windturbines: een verschil van dag en nacht, Geluid, jaargang 27, nr. 1 (2004)
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D2. Science Shop reports and memoranda

D2.1 Single author, reports

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FORWARD

WHAT HAVE I DONE?

Now each morning when I awake, I pray and then ask myself, "What have I done?"

I am involved with the BlueSky/GreenField wind turbine project in N.E. Fond du Lac County. I am also a successful farmer who cherishes his land. My father taught me how to farm, to be a steward of my fields, and by doing so, produce far better crop production. As I view this year's crops, my eyes feast on a most bountiful supply of corn and soybeans. And then my eyes focus again on the trenches and road scars leading to the turbine foundations. **What have I done?**

In 2003, the wind energy company made their first contacts with us. A $2000 "incentive" started the process of winning us over, a few of us at a time. The city salesman would throw out their nets, like fishermen trawling for fish. Their incentive "gift" lured some of us in at first. Then the salesmen would leave and let us talk with other farmers. When the corporate salesmen returned, there would be more of us ready to sign up; farmers had heard about the money to be made. Perhaps because we were successful farmers, we were the leaders and their best salesman. **What have I done?**

Sometime in 2004 or 2005, we signed $4000.00 turbine contracts allowing them to "lease" our land for their needs. Our leases favored the company, but what did we know back then? Nobody knew what we were doing. Nobody realized all the changes that would occur over which we would have no control. How often my friends and I have made that statement! **What have I done?**

I watched stakes being driven in the fields and men using GPS monitors to place markers here and there. When the cats and graders started tearing 22 foot wide roads into my fields, the physical changes started to impact not only me and my family, but unfortunately, my dear friends and neighbors. Later, a 4 foot deep by 2 foot wide trench started diagonally across my field. A field already divided by their road was now being divided again by the cables running to a substation. It was now making one large field into 4 smaller, irregularly shaped plots. Other turbine hosts also complained about their fields being subdivided or multi cable trenches requiring more land. Roads were cut in using anywhere from 1000 feet to over a 1/2 mile of land to connect necessary locations. We soon realized that the company places roads and trenches where they will benefit the company most, not the land owner. One neighbor's access road is right next to some of his out buildings. Another right next to his fence line. **What have I done?**

At a wind company dinner presented for the farmers hosting the turbines, we were repeatedly told - - nicely and indirectly - - to stay away from the company work sites once they start. I watch as my friends faces showed the same concern as I had, but none of us spoke out. Months later, when I approached a crew putting in lines where they promised me they would definitely would not go, a representative told me I could not be here. He insisted that I leave. The line went in. The company had the right. I had signed the lease. **What have I done?**

Grumbling started almost immediately after we agreed to a 2% yearly increase on our 30 year lease contracts. Some felt we should have held out for 10%. What farmer would lock in the price of corn over the next 5 years, yet alone lock one in at 2% yearly for 30 years? Then rumors leaked that other farmers had received higher yearly rates, so now contracts varied. The fast talking city sales folk had successfully delivered their plan. Without regard for our land, we were allowing them to come in and spoil it. All of the rocks we labored so hard to pick in our youth were replaced in a few hours by miles of roads packed hard with 10 inches of large breaker rock. Costly tiling we installed to improve drainage has now been cut into pieces by company trenching machines. **What have I done?**

Each night, a security team rides down our roads checking the foundation sites. They are checking for vandals and thieves. Once, when I had ventured with guests to show them foundation work, security stopped us and asked me, standing on my own property, what I was doing there. **What have I done?**

Now, at social functions, we can clearly see the huge division this has created among community members. Suddenly, there are strong-sided discussions and heated words between friends and, yes, between relatives about wind turbines. Perhaps this is of greater consequence than the harm caused to my land! Life is short and my friendships precious. **What have I done?**

I tried, as did some of the other farmers, to get out of our contracts, but we had signed a binding contract and a contract is a contract. If you are considering placing wind turbines on your property, I strongly recommend that you please reconsider. Study the issues. Think of the all the harm versus benefits to your land and, in the future, to your children's land by allowing companies to lease your land for turbines.

This was written by Don Bangert of Chilton, Wisconsin after he interviewed a landowner in Northeast Fond du Lac County for two hours. Don wrote this story and then showed it to the landowner who wishes to remain anonymous. The landowner approved this for publication.

WHAT HAVE I DONE?

PLEASE DO NOT DO WHAT I HAVE DONE!


FORWARD
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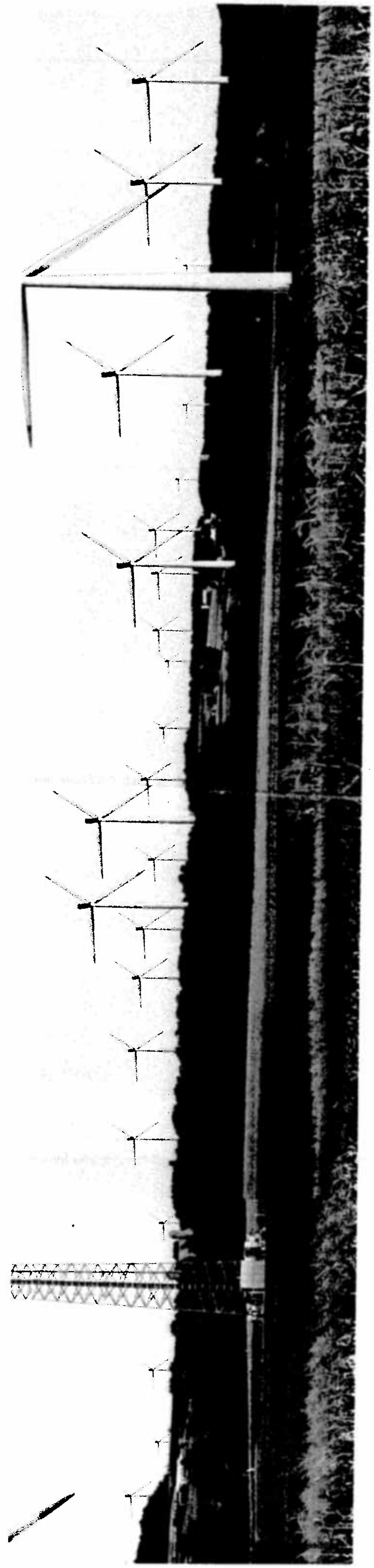


FORWARD

Added to the LRB's legal library collection.