III BASIC FACTS: wind power and the origins of modern wind turbine sound

III.1 Wind energy in the EU

Modern onshore wind turbines have peak electric power outputs up to 3 MW and tower heights of 80 to 100 meters. In 2003, 75% of the global wind power peak electric output of 40 GW was installed in the European Union. The original European target for 2010 was 40 GW, but the European Wind Energy Association have already set a new target for 2010 of 75 GW, of which 10 GW is projected off-shore, while others have forecasted a peak output of 120 GW for that year [EWEA 2004]. Whether this growth will actually occur is uncertain; with the proportional increase of wind energy in total electric power the difficulties and costs of integrating large scale windpower with respect to grid capacity and stability, reserve capacity and CO_2 emission reductions are becoming more prominent [see, *e.g.*, E.On 2004, ESB 2004]). However, further expansion of wind energy is to be expected, and as a result of this (predominantly on-shore) growth an increasing number of people may face the prospect of living near wind farms, and have reason to inquire and perhaps be worried about their environmental impact. Visual intrusion, intermittent reflections on the turbine blades, as well as intermittent shadows (caused when the rotating blades pass between the viewer and the sun), and sound, are usually considered potentially negative impacts.

III.2 Wind profiles and atmospheric stability

Atmospheric stability has a profound effect on the vertical wind profile and on atmospherical turbulence strength. Stability is determined by the net heat flux to the ground, which is a sum of incoming solar and outgoing thermal radiation, and of latent and sensible heat exchanged with the air and the subsoil. When incoming radiation dominates (clear summer days) air is heated from below and rises: the atmosphere is unstable. Thus, thermal turbulence implies vertical air movements, preventing large variations in the vertical wind velocity gradient (*i.e.* the change in time averaged wind velocity with height). When outgoing radiation dominates (clear nights) air is cooled from below; air density will increase closer to the ground, leading to a stable configuration where vertical movements are damped. The 'decoupling' of horizontal layers of air allows a higher vertical wind velocity gradient. A neutral state occurs when thermal effects are less significant, which is under heavy clouding and/or in strong winds.

Wind velocity at altitude h_2 can be deduced from wind velocity at altitude h_1 with a simple power law function:

$$V_{h2}/V_{h1} = (h_2/h_1)^m \qquad \text{(III.1)}$$

Equation III.1 is an engineering formula used to express the degree of stability in a single number (the shear exponent m), but has no physical basis. The relation is suitable where h is at least several times the roughness height (a height related to the height of vegetation or obstacles on the ground). Also, at high altitudes the wind profile will not follow (III.1), as eventually a more or less constant wind velocity (the geostrophic wind) will be attained. At higher altitudes in a stable atmosphere there may be a *de*crease in wind velocity when a nocturnal 'jet' develops. The maximum in this jet is caused by a transfer of kinetic energy from the near-ground air that decouples from higher air masses as large, thermally induced eddies vanish because of ground cooling. In fact, reversal of the usual near-ground diurnal pattern of low wind velocities at night and higher wind velocities in daytime is a common phenomenon at higher altitudes over land in clear nights as will be shown further below (Chapter VI). Over large bodies of water the phenomenon may be seasonal as atmospheric stability occurs more often when the water is relatively cold (winter, spring). This may also be accompanied by a maximum in wind velocity at a higher altitude [Smedman *et al* 1996].

In flat terrain the shear exponent m has a value of 0.1 and more. For a neutral atmosphere m has a value of approximately 1/7. In an unstable atmosphere -occurring in daytime- thermal effects caused by ground heating are dominant. Then m has a lower value, down to approximately

0.1. In a stable atmosphere vertical movements are damped because of ground cooling and *m* has a higher value. One would eventually expect a parabolic wind profile, as is found in laminar flow, corresponding to a value of *m* of 0.7 = $\sqrt{½}$. Our measurements near the Rhede wind farm yielded values of *m* up to 0.6. A sample (averages over 0:00–0:30 GMT of each first night of the month in 1973) from data from a 200 m high tower in flat, agricultural land [Van Ulden *et al* 1976] shows that the theoretical value is indeed reached: in ten out of the twelve samples there was a temperature inversion in the lower 120 m, indicating atmospheric stability. In six samples the temperature increased with more than 1 °C from 10 to 120 m height and the exponent *m* (calculated from (III.1): $m = \log(V_{80}/V_{10})/\log(8)$) was 0.43, 0.44, 0.55, 0.58, 0.67 and 0.72. More data from this site (Cabauw) and other areas will be presented in chapter VI.

A physical model to calculate wind velocity V_h at height h is ([Garrat 1992], p. 53):

$$V_h = (u_*/\kappa)\cdot[\ln(h/z_o) - \Psi] \qquad \text{(III.2)}$$

where $\kappa = 0.4$ is von Karman's constant, z_o is roughness height and u_* is friction velocity, defined by $u_*^2 = \sqrt{(\langle uw\rangle^2 + \langle vw\rangle^2)} = \tau/\rho$, where τ equals the momentum flux due to turbulent friction across a horizontal plane, ρ is air density and u, v and w are the time-varying components of in-wind, cross-wind and vertical wind velocity, with $\langle x\rangle$ the time average of x. The stability function $\Psi = \Psi(\zeta)$ (with $\zeta = h/L$) corrects for atmospheric stability. Here 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; the atmosphere at heights $0 < h < L$ (if L is positive and not very large) is the stable boundary layer. The following approximations for Ψ, mentioned in many text books on atmospheric physics (*e.g.* [Garrat 1992]), are used:

- in a stable atmosphere ($L > 0$) $\Psi(\zeta) = -5\zeta < 0$.
- in a neutral atmosphere ($|L|$ large $\rightarrow 1/L \approx 0$) $\Psi(0) = 0$.
- in an unstable atmosphere ($L < 0$) $\Psi(\zeta) = 2\cdot\ln[(1+x)/2] + \ln[(1+x^2)/2] - 2/\tan(x) + \pi/2 > 0$, where $x = (1-16\cdot\zeta)^{1/4}$.

For $\Psi = 0$ equation (III.2) reduces to $V_{h,log} = (u_*/\kappa)\cdot\ln(h/z_o)$, the widely used logarithmic wind profile. With this profile the ratio of wind velocities at two heights can be written as:

$$V_{h2,log}/V_{h1} = \log(h_2/z_o)/\log(h_1/z_o) \qquad \text{(III.3)}$$

For a roughness length of z_o = 2 cm (pasture) and m = 0,14, the wind profiles according to equations III.1 and III.3 coincide within 2% for h < 100 m. In figure III.1 wind profiles are given as measured by Holtslag [1984], as well as wind profiles according to formulae (III.1) and (III.3).

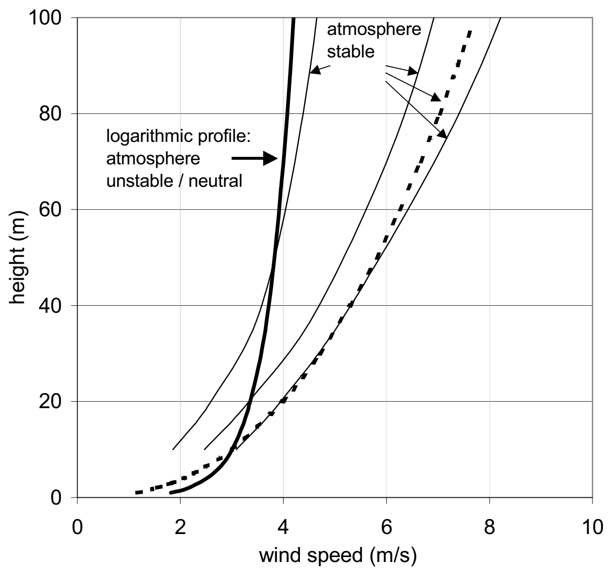

Figure III.1: wind profiles

Formula III.3 is an approximation of the wind profile in the turbulent boundary layer of a neutral atmosphere, when the air is mixed by turbulence resulting from friction with the surface of the earth. In daytime thermal turbulence is added, especially when there is strong insolation. At night time a neutral atmosphere, characterized by the adiabatic temperature gradient of -1 ºC per 100 m, occurs under heavy clouding and/or at relatively high wind velocities. When there is some clear sky and in the absence of strong winds the atmosphere becomes stable because of radiative cooling of the surface: the wind profile changes and can no longer be adequately described by (III.3). The effect of the change to a stable atmosphere is that, relative to a given wind velocity at 10 m height in daytime, at night there is a higher wind velocity at hub height and thus a higher turbine sound power level; also there is a lower wind velocity below 10 m and thus less wind-induced sound in vegetation.

With regard to wind *power* some attention is being paid to stability effects and thus to other wind profile models such as the diabatic wind velocity model (III.2) [see, *e.g.*, Archer *et al* 2003, Baidya Roy *et al* 2004, Pérez *et al* 2004, Smedman *et al* 1996, Smith *et al* 2002]. In relation to wind turbine *sound*, much less attention has been given to atmospheric stability (see section II.3).

Stability can also be categorized in Pasquill classes that depend on observations of wind velocity and cloud cover (see, *e.g.*, [LLNL 2004]). They are usually referred to as classes A (very unstable) through F (very stable). In a German guideline [TA-Luft 1986] a closely related classification is given (again closely related to the international Turner classification [Kühner 1998]). An overview of stability classes with the appropriate value of m is given in table III.1.

Table III.1: stability classes and shear exponent *m*

Pasquill class	name	comparable stability class [TA-Luft 1986]	*m*
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	IV2	0.22
D	slightly stable	IV1	0.28
E	moderately stable	II	0.37
F	(very) stable	I	0.41

According to long-term data from Eelde and Leeuwarden [KNMI 1972], two meteorological measurement sites of the KNMI (Royal Netherlands Meteorological Institute) in the northern part of the Netherlands, a stable atmosphere (Pasquill classes E and F) at night occurs for a considerable proportion of night time: 34% and 32% respectively.

From formula (III.3) the ratio of wind velocities at hub height (98 m) and reference height, over land with low vegetation (z_o = 3 cm), is $f_{log} = V_{98}/V_{10} = 1.4$. According to formula (III.1) and table III.1 this ratio would be $f_{unstable} = 1.2 = 0.85 \cdot f_{log}$ in a very unstable atmosphere and $f_{stable} = 2.5 = 1.8 \cdot f_{log}$ in a (very) stable atmosphere.

The shear exponent *m* can be determined from the measured ratio of wind velocities at two heights (V_{h2}/V_{h1}) using equation III.1:

$$m_{h1,h2} = \ln(V_{h2}/V_{h1})/\ln(h_2/h_1) \qquad \text{(III.4)}$$

III.3 Air flow on the blade

As is the case for aircraft wings, the air flow around a wind turbine blade generates lift. An air foil performs best when lift is maximised and drag (flow resistance) is minimised. Both are determined by the angle of attack: the angle (α) between the incoming flow and the blade chord (line between front and rear edge; see figure III.2). The optimum angle of attack for turbine blades is usually between 0 and 4º, depending on the blade profile.

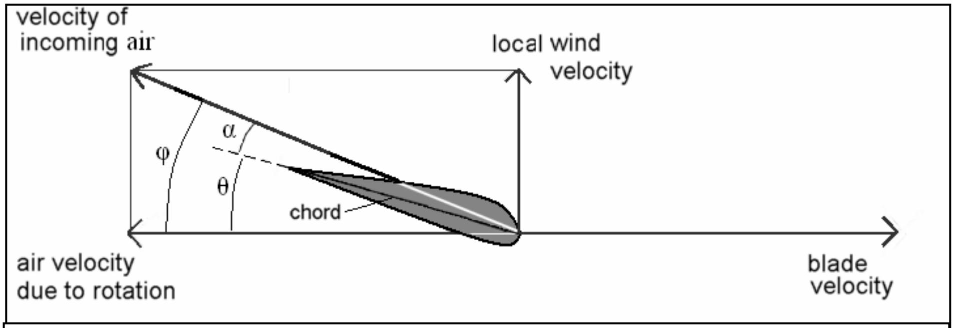

Figure III.2: flow impinging on a turbine blade with flow angle φ, blade pitch angle θ and angle of attack on blade α = φ - θ

The local wind at the blade is not the unobstructed wind velocity. The rotor extracts energy from the air at the cost of the kinetic energy of the wind. The velocity of the air passing through the rotor is thus reduced to $V_b = (1 – a)V_h$, where a is the induction factor. The highest efficiency of a wind turbine is reached at the Betz limit: at this theoretical limit the induction factor is 1/3 and the efficiency is 16/27 (≈ 60%) [Hansen 2000]. The wind velocity at the blade is thus:

$$V_b = V_h \cdot 2/3 \qquad \text{(III.5)}$$

III.4 Main sources of wind turbine sound

There are many publications on the nature and power of turbine sound: original studies [*e.g.* Lowson 1985, Grosveld 1985] and reviews [*e.g.* Hubbard *et al* 2004, Wagner *et al* 1996]. A short introduction on wind aeroacoustics will be given to elucidate the most important sound producing mechanisms.

If an air flow is smooth around a (streamlined) body, it will generate very little sound. For high velocities and/or over longer lengths the flow in the boundary layer between the body and the main flow becomes turbulent. The rapid turbulent velocity changes at the surface cause sound with frequencies related to the rate of the velocity changes. The turbulent boundary layer at the downstream end of an airfoil produces *trailing edge sound*, which is the dominant audible sound from modern turbines. When the angle of attack increases from its optimal value the turbulent boundary layer on the suction (low pressure) side grows in thickness, thereby decreasing power performance and increasing sound level. For high angles of attack this eventually leads to stall, that is: a dramatic increase of drag on the blades. Apart from this turbulence inherent to an airfoil, the atmosphere itself is turbulent over a wide range of frequencies and sizes.

Figure III.3: 15 m blades for Altamont Pass, Ca (photo: Alex Haag)

Turbulence can be defined as changes over time and space in wind velocity and direction, resulting in velocity components normal to the airfoil varying with the turbulence frequency causing *in-flow turbulent sound*. Atmospheric turbulence energy has a maximum at a frequency that depends on altitude and on atmospheric stability. For wind turbine altitudes this peak frequency is of an order of magnitude of once per minute (0.017 Hz). The associated eddy (whirl) scale is of the order of magnitude of several hundreds of meters [Petersen *et al* 1998] in an unstable atmosphere, less in a stable atmosphere. Eddy size and turbulence strength decrease at higher frequency, and vanish due to viscous friction when the eddies have reached a size of approximately one millimetre.[1]

A third sound producing mechanism is the response of the blade to the change in lift when it passes the tower. The wind is slowed down by the tower which changes the angle of attack on the blade; as a result the lift and drag forces on the blade suddenly change. The resulting sideways movement of the blade causes *thickness sound* at the blade passing frequency and its harmonics.[2] Thickness sound is also mentioned as sound originating from the (free) rotating blade pushing the air sideways. However, the associated air movement is relatively smooth and is not a relevant source of sound.

A more thorough review of these three sound production mechanisms is given in appendix B, where frequency ranges and sound levels are quantified in so far as relevant for this book.

Sound originating from the generator or the transmission gear has decreased in level in the past decades and has become all but irrelevant if considering annoyance for residents.

To summarize, a modern wind turbine sound spectrum can be divided in (overlapping) regions corresponding to the three mechanisms mentioned:

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[1] for more information on atmospheric turbulence: see chapter VIII

[2] a thickness sound pulse has a length t_{pulse} with an order of magnitude of (tower diameter/tip speed ≈) 0,1 s, so its spectrum has a maximum at $1/t_{pulse} \approx 10$ Hz. The spectrum of a periodic series of Dirac pulses (unit energy 'spikes' with, here, a period of T_{blade}) is a series of spikes at frequencies n/T_{blade} (n = 1, 2, 3, 4, ...). When periodic thickness sound is considered as a convolution of the single sound pulse with a series of Dirac pulses, the Fourier transform is the product of the transforms of both, that is: the product of the sound pulse spectrum centered at $1/t_{pulse}$ and spikes at n/T_{blade}. The result is a series of spikes with the single sound pulse spectrum as an envelope, determining each spike level. In practice $1/T_{pulse}$ usually has a value of 4 to 8 Hz (see *e.g.* [Wagner 1996]) and the harmonic closest to this frequency carries most energy.

- High frequency: *trailing edge (TE) sound* is noise with a maximum level at 500–1000 Hz for the central octave band, decreasing with 11 dB for neighbouring octave bands and more for further octave bands.
- Low frequency: *in-flow turbulent sound* is broad band noise with a maximum level of approximately 10 Hz and a slope of 3–6 dB per octave.
- Infrasound frequency (f < 30 Hz): the *thickness sound* is tonal, the spectrum containing peaks at the blade passing frequency f_B and its harmonics.

As thickness sound is not relevant for direct perception, turbulent flow is the dominant cause of (audible) sound for modern wind turbines. It is broad band noise with no tonal components and only a little variation, known as blade swish. Trailing edge sound level is proportional to 50·logM (see equation B.4 in appendix B), where M is the Mach number of the air impinging on the blade. TE sound level, the dominant audible sound source in a modern turbine, therefore increases steeply with blade speed and is highest at the high velocity blade tips. Writing Mach number at the blade tip as $M = V_{tip}/c$, wind turbine sound level strongly depends on blade tip speed V_{tip}:

$$L_{TE} \sim 50 \cdot \log(V_{tip}/c) \qquad \text{(III.6)}$$

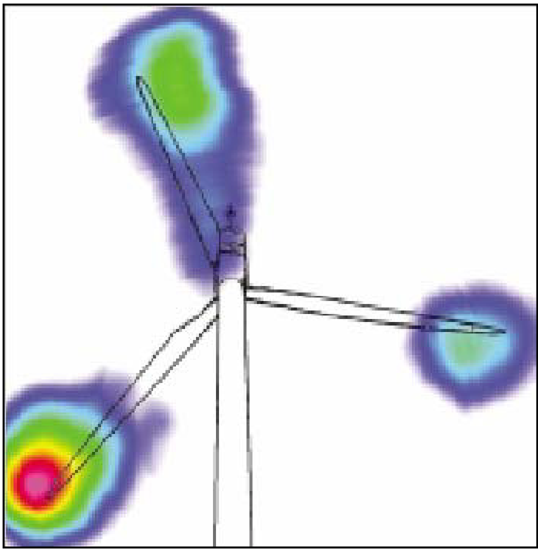

Figure III.1: an 'acoustic photograph' showing the high speed tips of a wind turbine radiate most sound; colors from centre to outside contour indicate an decreasing sound level (photo: Acoustic Camera, GFaI, Berlin)

Swish, which is the variation in TE sound, thus also originates predominantly at the tips.

This book deals with modern variable speed turbines where the angle of attack is constant over a wide range of wind speeds. Keeping blade pitch (the angle between the blade chord and the rotor plane) constant, the rotational speed increases with wind speed usually up to a rated wind speed of some 14 m/s. At higher wind speeds the pitch angle is decreased at constant rotational speed to keep a constant angle of attack until for safety reasons the rotor is stopped. The effect on sound production is that first the sound power level increases up to the rated wind speed, then remains almost constant at higher wind speeds.
In a constant speed turbine the rotational speed has a fixed value, though usually a turbine then has two speeds to accommodate for low and high wind speeds. Here the blade pitch is set to optimize the angle of attack up to the rated power. Above rated power, a situation that will not occur very often, the pitch angle is kept constant, so the angle of attack increases with wind speed and the turbine becomes less efficient. The result is that the sound power at low speed is almost constant, then increases sharply at the change to the higher speed. After that it is again almost constant, increasing again above the rated power when the angle of attack drifts away from the optimum value.

Sound from downwind rotors, *i.e.* with the rotor downwind from the tower, was considered problematic as it was perceived as a pulsating sound (see appendix B). For modern upwind rotors this variation in sound level is weaker. It is not thought to be relevant for annoyance and considered to become less pronounced with increasing distance due to loss of the effect of directivity, due to relatively high absorption at swish frequencies, and because of the increased masking effect of background noise [ETSU 1996]. However, an increase in the level of the swishing sound related to increasing atmospheric stability has not been taken into account as yet. In this context the periodic change in angle of attack near the tower proves to be important, not in relation to thickness sound but as a modulation period.

So, what's the sound like...?

(.....) Our experience is that mechanical noise is insignificant compared to the aerodynamic noise, or 'blade thump' as we call it. At "our" windfarm the mechanical noise is usually only audible when within about 100 metres of the turbine, but the blade thump can be heard at distances of up to 1.5 Km away.
(.....)
Some residents describe this noise as an old boot in a tumble dryer, others as a Whumph! Whumph! Whumph! Either way its not particularly loud at 1.5 km distance but closer than that and it can be extremely irritating when exposed to it for any period of time. Some residents have even resorted to stuffing chimney stacks with newspaper as the sound reverberates down the stack.
Because it is generally rhythmic, it's not the kind of noise that you can shut out of your mind, like, say, distant road noise - this is why we think the noise level stipulation on the planning conditions of such a windfarm development is woefully inadequate for protecting local residents from the noise effects of a windfarm.
All of us agree that the most disturbing aspect of the noise is the beat that we think is caused by the blades passing the tower of the turbine. As the rotational speed of the 3 bladed turbines is about 28 rpm "on full song" this results in a sound of about 84 beats per minute from each turbine.
The sound rises and falls in volume due to slight changes in wind direction but the end result for those in the affected area is a feeling of anxiety, and sometimes nausea, as the rate continually speeds and slows - we think that is maybe because this frequency of the pulses is close to the human heart rate and some residents feel that their own pulse rate is trying to match that of the turbines. (.....)

When does it strike?
The windfarm makes a noise all the time it is operating, however there are times when it becomes less of a nuisance.
When the wind is very strong, the background noise created by the wind whistling around trees etc. drowns out the noise of the turbines and the problem is reduced. (.....)
In this area we all agree that the worst conditions are when the wind is blowing lightly and the background noise is minimal. Under these conditions residents up to 1 kilometre have complained to the Environmental Health department about the drone from the turbines. Unfortunately these are just the sort of weather conditions that you would wish to be outside enjoying your garden. (.....)
During the summer nights it is not possible for some residents, even as far away as 1000 metres, to sleep with the window open due to the blade thump. (......)

Excerpts describing wind turbine sound and its effects, from a page of the website of MAIWAG (consulted December 3, 2005), a group of residents in three villages in the south of Cumbria (UK)