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Do wind turbines produce significant low frequency sound levels?

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Summary

Wind turbines produce low frequency sounds, but it has not been shown this is a major factor contributing to annoyance. Sound from wind turbines involves several sound production mechanisms related to different interactions between the turbine blades and the air. Low frequency sound is predominantly the result of the displacement of air by a blade and of turbulence at the blade surface.

An important contribution to the low frequency part of the sound spectrum may be the result of the sudden variation in air flow the blade encounters when it passes the tower: the angle of attack of the incoming air suddenly deviates from the angle that is optimized for the mean flow.

This effect probably has not been considered important as the blade passing frequency is of the order of one hertz where human hearing is very insensitive. This argument however obscures a very relevant effect: the low blade passing frequency modulates well audible, higher frequency sounds and thus creates periodic sound. This effect is stronger at night because in a stable atmosphere there is a greater difference between rotor averaged and near-tower wind speed. Measurements have shown that more turbines can interact to further amplify this effect.

The effect is confirmed by residents near wind turbines who mention the same common observation: often late in the afternoon or in the evening the turbine sound changes to a more 'clapping' or 'beating' sound, the rhythm in agreement with the blade passing frequency. It is clear from the observations that this is associated to a change to a higher atmospheric stability. The increased annoyance has not been investigated as such, although there are indications from literature this effect is relevant. It is of increasing relevance as the effect is stronger for modern (that is: tall) wind turbines.

Introduction

Modern wind turbines have electric power outputs up to 2 MW (increasing now to 5 MW) and have turbine heights of 80 to 100 meters (increasing to 120 m). In the European Union, producing 74% of the wind power in the world, by the end of 2002 23 GW has been installed, and this should increase to the European target of 40 GW for 2010, but already a capacity of 90 GW has been forecasted for that year [1]. As a result of this growth an increasing number of people are living near (projected) wind parks and have reason to inquire and perhaps be worried about their environmental impact. Visual impact, intermittent reflections on the turbine blades as well as intermittent shadows (sun behind rotating blades), and sound are usually considered potentially negative impacts.

Wind turbines are also suspected to be a cause of low frequency noise, affecting people living nearby. This has been brought forward in the United Kingdom where opponents of wind parks state “current recommendations for noise evaluation near wind turbine sites completely exclude the measurement of low frequency sound” [2]. In a reaction the British Wind Energy Association denies this and accuses the other party “to misunderstand technical information, but be happy to use the material in inappropriate ways. One example of this is their persistent misuse of material on noise”. [3].

Yet, a recent review for the British Department for Environment, Food and Rural Affairs states: “Infrasound exposure is ubiquitous in modern life (…..) common in
urban environments, and as an emission from (…..) air movement machinery including wind turbines (….). The effects of infrasound or low frequency noise are of particular concern because of its pervasiveness (…..) compared with other noise.” [4]. Also, according to a project proposal from the Swedish Kungl Technical Highschool “there is a risk for low frequency sound from the large wind turbine farms that are planned both in Sweden and in other European countries” [5]. So, those who link wind turbines with low frequency sound are in expert company. But, does it affect nearby residents?

This paper explores the nature of (low frequency) wind turbine sound and explains why low frequencies may be relevant and not relevant at the same time, depending on perspective.

Sources of wind turbine sound

There is a wealth of information on the nature, cause and power of turbine sound. A review resulting from a research programme of the European Union is given by Wagner *et al* [6]. A concise overview of the three sound source mechanisms relevant to this paper will be given here, preceded by an introduction on wind aeroacoustics.

If an air flow is smooth around a (streamlined) body, it will generate little sound. For high speeds and/or over longer lengths the flow in the boundary layer (between body and main flow) becomes turbulent. As this leads to rapid velocity *changes* this will cause more sound with frequencies related to the rate of the velocity changes. A typical size for this turbulence is the boundary layer thickness.

As is the case for aircraft wings or propellor blades, a wind turbine blade is driven by lift generated by the air flow and performs best when lift is maximized and at the same time drag (flow resistance) is minimized. Both are determined by the angle of attack: the angle between the incoming flow and the chord (line between front and rear edge) of the blade. When the angle of attack increases from its optimal value the turbulent boundary layer grows in thickness and turbulence strength, decreasing power performance and increasing sound level. For an increasing angle of attack this eventually leads to stall: a dramatic reduction in lift.

Also, the atmosphere itself is turbulent over a wide range of frequencies and sizes. Atmospheric turbulence energy has a maximum at a frequency that depends on height and atmospheric stability; for wind turbine altitudes this frequency is of an order of magnitude of once per minute (≈ 0.01 Hz), and the associated eddy (whirl) ‘diameter’ is of the order of magnitude of a several hundreds of meters [7]. Eddy diameter and turbulence strength decrease at increasing frequency and vanish because of viscous friction when they have reached the size of a millimeter.

Turbulent flow is the dominant cause of (audible) sound for modern wind turbines. There are several mechanisms whereby the sound actually is produced.

1. When a blade moves through the air, the air on the forward edge is moved sideways moving back again at the rear edge. So for a periodically moving blade the air is periodically forced, leading to ‘thickness noise’. Normally this will not lead to a significant sound production.

However, when a blade passes in front of the turbine tower, it encounters a wind that is influenced by the tower: the wind is slowed down and is forced to move sideways around the tower. This means that quite suddenly the angle of attack changes and lift and drag change abruptly. The change in mechanical load will increase thickness sound at the rate of the blade passing frequency f_B (f_B is the turbine rotation frequency multiplied by the number of blades). As the movement is not purely sinusoidal, there are harmonics with frequencies $k \cdot f_B$ where k is a (small) integer. As f_B typically has a value of approximately 1 Hz and harmonics may occur up to 10 - 20 Hz, this sound is in the infrasound region. Another consequence is that high frequency sound will also increase abruptly because of increased turbulence due to the sub-optimal angle of attack, creating the typical swishes superimposed on the constant noisy sound of a wind turbine.

2. Because of atmospheric turbulence there is a random movement of air superimposed on the average wind speed. The contribution of atmospheric turbulence to wind turbine sound is named ‘in-flow turbulence noise’ 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 1., but changes will usually be 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.
3. High frequency sound is due to several flow phenomena at the blade itself or in the turbulent wake behind a blade (‘airfoil self-noise’). It increases when induced turbulence increases, *e.g.* because of higher speed or of irregularities (scratches, dirt, insects) on the blade surface. It is essentially broad band sound, but if the turbulence can lock into a fixed length (such as a slit or cut parallel to the trailing edge), a specific frequency can become prominent, resulting in tonal sound.

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

Measured wind turbine sound spectra

In the summer of 2002 wind turbine sound has been recorded in and near wind park Rhede on the German-Dutch border. The park has a straight row of ten ca. 300 m spaced turbines parallel to the border and a less regular, somewhat uneven spaced row of seven turbines appr. 400 m behind the first row. Each turbine is 100 m high (hub heigth) with a blade length of 35 m, and produces nominally 2 MW electricity. It proved that the sound level, determined by the rotation speed of the turbines, depended on atmospheric stability and was not well predicted at evening and night hours by the usual reference wind speed measured at 10 meter altitude [8].

In figure 1 1/3 octave band spectra of the recorded sound have been plotted. The sound was recorded on a TASCAM DA-1 DAT-recorder with a precision Sennheiser microphone. The sound was then sampled in 1-second intervals on a Larson Davis 2800 frequency analyzer. The frequency response of the measurement chain is within 3 dB for frequencies above 4 Hz. From 1 to 4 Hz the frequency response is not accurately known (this has never been a necessity in our work). The spectra were determined from recordings (appr. 5 minutes each) taken with the microphone just above a hard surface at ground level at 100 m from two different turbines (plotted levels are measured Leq minus 6 dB correction for coherent reflection against the surface), and from a recording 1.5 m above a paved terrace and 2 m in

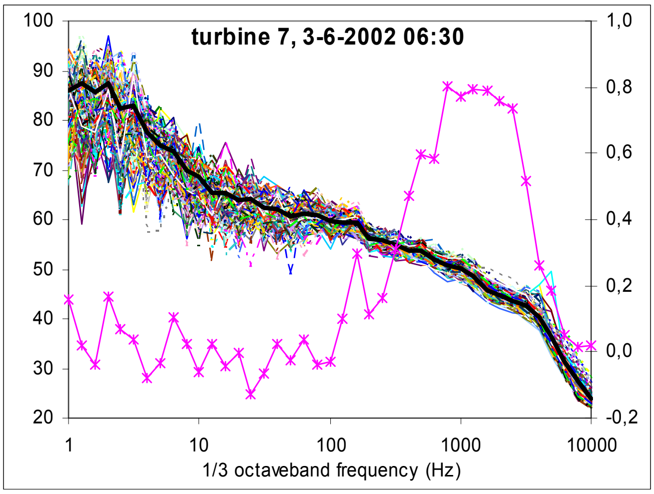
front of the façade of a dwelling at 750 m distance from the nearest row of turbines (measured Leq minus 3 dB correction for incoherent reflection at the façade).
In each part of figure 1 200 spectra (spaced 1 sec) as well as the energy averaged spectrum have been plotted. Also the correlation coefficient σ between all unweighted 1/3 octave band levels and the overall A-weighted sound levels has been plotted for each 1/3 octave band frequency. It is clear from the spectra that most energy is found at lower frequencies. This does not imply it is relevant for hearing as human hearing however is relatively insensitive at low frequencies. Indeed, the correlations show that most audible energy near the turbines is contained in the 1/3 octave band levels with frequencies from 400 through 3150 Hz (where σ > 0.4). For the sound at the façade this is one octave lower (200 - 1600 Hz) because higher frequencies were better absorbed and now contribute less to the sound energy as they do near the turbines.

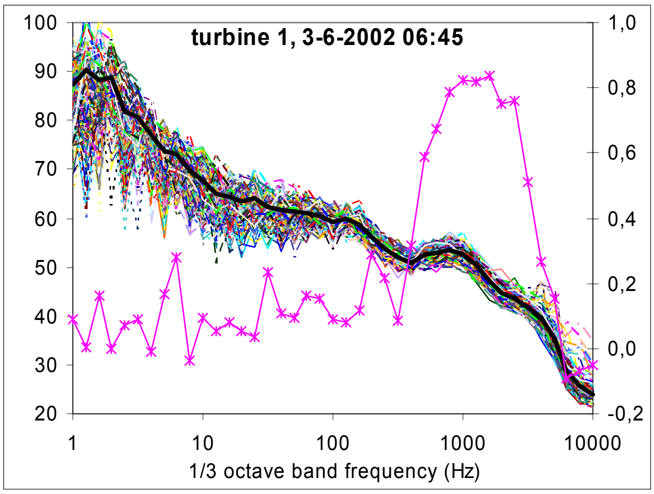
In figure 2 thirteen more detailed 1-second 1/3 octave band spectra have been plotted from the sound on the façade (see figure 1). Although the bandwidth should be taken smaller to detect the harmonics of the blade passing frequency f_B = 1 Hz, the first harmonic at 2 Hz is clearly visible. A more detailed spectrum form a single turbine is given by Betke *et al* [9].

In figure 3 the three average spectra from figure 1 have been repeated, and the median hearing threshold for otologically selected young adults (according to ISO 226 [10]) has been added as well as the hearing threshold for the best hearing 10% of this group (10 percentile) which is 7 to 8 dB below the median level. It is clear that the sound below appr. 20 Hz must be considered inaudible for even well hearing people, even when one stands close to the turbine. Sound levels above the low frequency range but below appr. 1000 Hz are dominant with respect to audibility.
From figure 3 it is clear that sound levels at 100 m from a turbine (the two upper spectra) and at a location 750 km away from the first row of turbines are of comparable level at infrasonic frequencies; in fact the level differs only 4 dB. Although at the larger distance the sound level of a single turbine decreases, this is counterbalanced by the fact that more turbines contribute. At higher frequencies the same is true, but at increasing distance more sound energy is lost because of absorption.
The spectra in figure 3 are divided in three regions. For frequencies below 10 Hz the sound is dominated by thickness noise associated with the blade passing frequency (and harmonics). Then, in the higher infrasound region and upwards, where the level falls less steeply, in-flow turbulence is the dominant sound producing mechanism. Gradually, at frequencies above 100 Hz, airfoil self-noise is becoming the most dominant source, declining only at high frequencies of several kHz.

Impulsiveness

Wind turbine sound is not usually considered to be impulsive, as it has a more or less constant level due to the essentially random nature of the sound production mechanisms. Although there are periodic audible swishes, these are no equal to ‘real impulses’ like hammering or gun shots.
However, in a stable atmosphere the periodic swishes are louder than in daytime and residents use words like clapping, beating or thumping to describe the character or the sound. In the case of the Rhede wind park, the beating can be heard clearly at distances of at least up to 1 km and at night one can use it to determine the rotational speed of the turbine. So perhaps wind turbines can produce impulsive sound, but only in specific atmospheric conditions: the atmosphere must be stable. To understand this we must understand the implications of a stable atmosphere with respect to wind, the matter driving wind turbines.





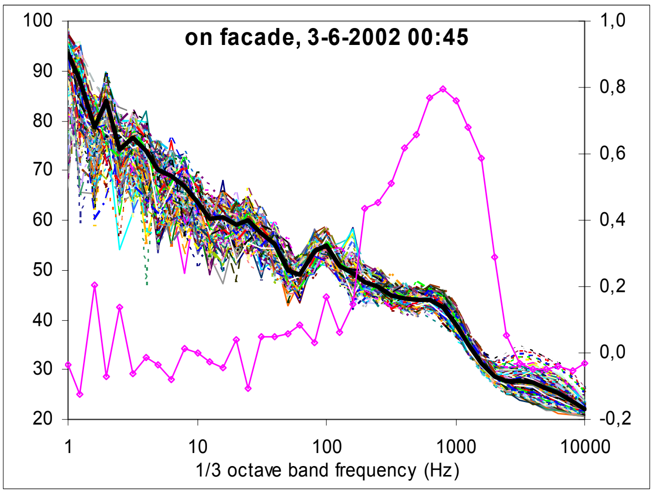


Figure 1:
left axis (in dB): 200 consecutive, unweighted and 1 second spaced 1/3 octave band levels (thin lines), and average spectral level (thick line) near two turbines and near dwelling;

right axis: coefficient of correlation (line with markers) at each 1/3 octave band frequency between all 200 1/3 octave band levels and overall A-weighted levels

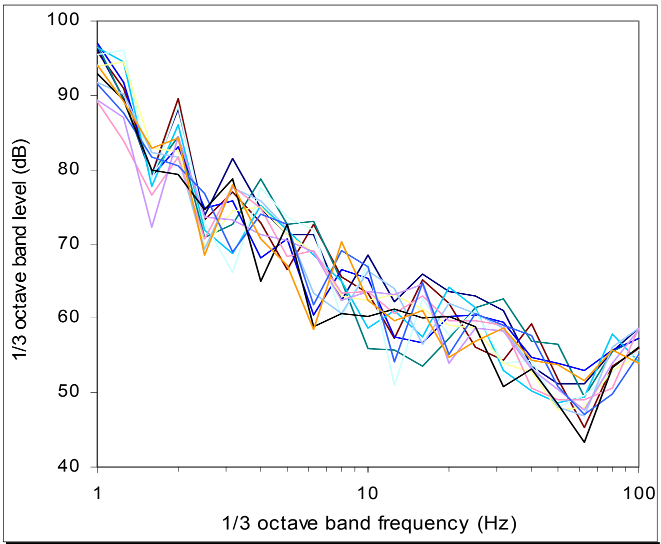


Figure 2:
13 unweighted, 1 second spaced 1/3 octave band levels near a turbine

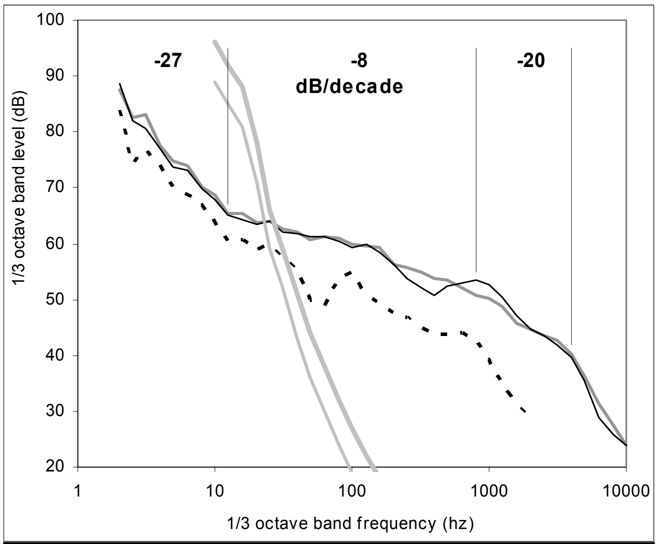


Figure 3: regions in 1/3 octave band spectra near turbines (grey and thin black line) and dwelling (dotted line) with average spectrum slope in dB/decade, and 10 and 50 percentile hearing threshold level for young adults

The wind speed v_h at height h in the atmosphere can be written as:

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

where v_{ref} is the wind speed at a reference height h_{ref} (usually 10 m). The exponent m depends upon atmospheric stability. For a neutral atmosphere, occurring under heavy clouding an/or in strong winds, air buoyancy dominates thermal effects and m has a value of appr. 0.2. In an unstable atmosphere, as is usual in daytime (if not neutral), m has a value of appr. 0.1. In a stable atmosphere m should theoretically reach values up to a maximum of $½\cdot\sqrt{2}$, describing a parabolic wind profile corresponding to laminar flow. Our Rhede measurements yielded values of m up to 0.6 [8]. A sample from data from the Royal Dutch Meteorological Institute KNMI [11] shows that indeed this theoretical maximum can be reached: in ten out of twelve midnight half hours (averages over 0:00 – 0:30 GMT) of each first night of the month there was a temperature inversion in the lower 120 m, indicating atmospheric stability. Of these in six cases the temperature increased with more than 1 °C from 10 to 120 m height and the exponent m (calculated from (1): $m = \log(v_{80}/v_{10})/\log(8)$) was 0.43, 0.44, 0.55, 0.58, 0.67 and 0.72 (we expect to do a more thorough analysis on more data to obtain statistically relevant long-term results).
In the following text we will use a value m = 0.1 for an unstable atmosphere and m = 0.6 for a stable atmosphere. These values will be used for altitudes between 10 and 120 m. It is probable that the wind profile above 120 m will not follow formula (1), as eventually a more or less constant wind speed (the geostrophic wind) will be attained, perhaps, in a stable atmosphere, after a decrease when the top of a 'low level jet' at about 100 m height has been reached. Because of this, the optimal height for a windturbine from an energetic point of view wil probably be about 100 m.

Effects depend on wind turbine properties (such as speed, diameter and height). We will use typical dimensions of a modern 1.5-2 MW wind turbine: hub height 80 m, rotor diameter 70 m and rotational speed increasing with wind speed to a maximum value of 20 rpm.

Now there are two reasons why the periodic swishes acquire a more impulsive character in a stable atmosphere relative to an unstable or neutral atmosphere.
1- Rotational speed will be determined by a rotor averaged wind speed, but the difference in wind speed between the upper and lower part of the rotor increases. Suppose the wind speed at hub height is v_{80} = 8 m/s. Then in daytime (m = 0.1) the wind speed at the lowest point of the rotor would be v_{45} = 7.6 m/s, at the highest point v_{115} = 8.3 m. The difference in wind speed over the rotor of 0.35 m/s causes a change in angle of attack of only 0.25° (both plus or minus relative to average value). A very slight vertical tilt of the rotor can offset this. In nighttime (m = 0.6) however, at the same wind speed at hub height, v_{45} is 5.7 m/s and v_{115} 9.9 m/s, so the difference in wind speed over the rotor and the change in angle of attack are now 6 times as large: 2.1 m/s and 1.5°, respectively. As a consequence there will be more airfoil self-noise.
A further effect is that there is a greater mismatch between optimum and actual angle of attack when the blade passes the mast (where there was already a mismatch due to the tower), causing higher blade loading and more turbulence. This effect is readily audible when night falls: the blades start clapping or beating at the blade passing frequency. The effect is stronger when stability increases, and also when wind speed at hub height increases up to the point where friction turbulence overrides stability and the atmosphere becomes neutral.
2- As was shown earlier [8], in a stable atmosphere wind turbines can run almost synchronously because the relative absence of turbulence leads to less random motion

superimposed on the constant (average) wind speed at each turbine. Turbines in a wind park therefore experience a wind that is more constant over greater distances. As a result they tend to react the same, that is: their turbine speeds are more nearly equal. This is confirmed by long term measurements by Nanahara *et* al who analysed coherence of wind speeds at locations at increasing distances in two coastal areas [12]. At night hours wind speeds at different locations were found to change more coherently than they did at daytime [13]. The difference between night and day hours was not very strong, probably because just time of day is a helpful, but not sufficient indicator for stability, especially not near sea and over all day lengths in an entire year.
Because of the *near*-synchronicity of several turbines, sometimes two are in phase and the blade passing pulses coincide, and then go out of phase again. The same can happen for three and perhaps more turbines. Exact synchronicity would not give the same effect, because it is improbable that an observer would hear these pulses at the same time. Because of near-synchronicity however, an observer will hear coinciding pulses for part of the time. Synchronicity here refers to the sound pulses of the different turbines at the location of the observer: pulses synchronize when they arrive simultaneously. This does not imply that the rotors are in phase: in that case the pulses would not arrive simultaneously unless the turbines would be at a distance to the observer equal to the distance sound propagates in one pulse repetition time or a multiple.

Both effects, the wind speed gradient and the near-synchronicity, increase the level of the sound heard when the blades pass the tower. The extra blade loading itself is not audible because of the high hearing threshold at the very low blade passing frequency. But the effect of added induced turbulence increases the levels at frequencies that already were dominating the best audible part of the sound, that is, at 750 m distance, at 200 – 1600 Hz (= range with high correlation in figure 1). When the pulses at the Rhede wind park synchronize, the level of the 800 Hz 1/3 octave band (best correlated to audibility: see façade spectrum in figure 1) increases with 10 dB, whereas the total A-weighted level increases with 5 dB. In general the height of the pulse will depend on the change in angle of attack and the distances of the wind turbines relative to the observer: the beat due to several turbines will reach higher pulse levels when more turbines are at approximately equal distances and contribute equal immission levels. The clapping or beating is thus at well-audible frequencies and has a repetition rate equal to the blade passing frequency.

Window rattling

Although infrasound levels from large turbines at frequencies below 20 Hz are too low to be audible, they may cause structural elements of buildings to vibrate. The vibrations may produce higher frequency, audible sound.
Windows are usually the most sensitive elements as they move relatively easy because of the low mass per area. Perceptible vibrations of windows may occur at frequencies from 1 to 10 Hz when the incoming 1/3 octave band sound pressure level is at least appr. 52 dB [14]; at higher or lower frequencies a higher level is needed to produce perceptible vibrations. As can be seen in figures 1 – 3 sound pressure levels above 60 dB at frequencies below 10 Hz occur close to a turbine as well as at 750 m distance and further.

A window vibrating at the impinging frequency transmits this frequency to the indoor air. If this does not coincide with a room resonance, the sound will not be louder than outdoors. For rooms in dwellings with a greatest dimension of 10 m, resonance frequencies are higher than appr. 15 Hz and thus cannot coincide with relevant harmonics of f_B, the blade passing frequency.

However, a window pane itself may have a resonant frequency of, *e.g.,* 40 Hz and a frequency of 10 Hz then may sustain a window pane resonance, thus transforming inaudible infrasound to audible higher frequencies. Also, a loosely fitted window may move to and fro and being stopped by the window frame vibrates at higher frequencies radiated into the room.

Conclusion

Infrasonic harmonics of the blad passing frequency from modern, tall wind turbines must be considered inaudible. Low frequency in-flow turbulence sound may be audible, but wind turbine sound is loudest at medium to high frequencies. This readily audible sound is caused by atmospheric and induced turbulence at the blade surface. The level of this medium/high frequency turbulent sound varies at the rate of the blade passing frequency, which causes the typical swishing sound of a modern wind turbine.

When the atmosphere becomes more stable, which is usual at night when there is a partial clear sky and a light to moderate wind (at ground level), there is an important change in wind profile affecting the performance of a modern, tall wind turbine. The airflow around the blade then changes tot less than optimal, resulting in added induced turbulence. This effect is strongest when the blades pass the tower, causing short lasting, higher sound levels at the rate of the blade passing frequency. In a wind park these pulses can synchronize, leading to still higher pulse levels for an observer outside the park. The resulting repetitive pulses change the character of the wind park sound and must be expected to cause added annoyance.

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