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Aerodynamic noise of wind power plants

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Aerodynamic noise of wind power plants

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Summary

The most remarkable noise source of wind power plants is their rotor blades that cause mainly broadband aerodynamic noise in frequency range 60 – 4 000 Hz. The angle of attack plays an important role in the action of a wind turbine and in broadband wind turbine noise generation. When the angle of attack increases from its optimal value, the power performance decreases and the sound level increases. The strong wind shear in a stable atmosphere, occurring mainly at night time, causes that sound levels of wind turbines may be much higher than expected, especially with modern, i.e., tall and variable speed, wind turbines. Discrepancies of even 15 dB have been observed at 400 m from a wind farm at quiet nights. Also the propagation attenuation is reduced in a stable atmosphere. These aspects lead to an implication that noise measurements of wind power plants should also contain night time results.

In the noise caused by the rotor blades there exists an amplitude modulation of ± 2–3 dB typically at a modulation frequency of about 1 Hz. It seems that there affect two separate mechanisms in the generation of the amplitude modulation: swishing, which originates from the rotation of the strongly directive sound radiating blades, and thumping, which originates from the motion of the blades through unevenly distributed flows. The uneven flows are mainly due to wind shear in stable atmosphere. The amplitude modulation is one of the most important explanatory factors for the annoyance of the aerodynamic noise of wind power plants and the main reason of the extraordinary annoying properties of the noise.

The aerodynamic optimization of the blade reduces the aerodynamic noise. It seems that totally new approaches may be needed for efficient sound reduction furthermore. The thumping type amplitude modulation can be minimized by keeping the angle of attack as constant as possible during the rotation of the blades, by cyclically varied blade pitch angle (individual pitch control). This also optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.

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Preface

The work described in report has been carried out at VTT Industrial Systems, in Smart Machines knowledge centre as a part of the VTT funded research project “Wind power plants – knowledge increase of noise and control issues” (WPPNoCo). The results of the report have been obtained mainly through a critical literary survey summarising results of recent studies and drawing conclusions adaptable to Finnish circumstances.

The work in this report is related to aerodynamic noise from wind power plants. According to the study the most remarkable noise source of wind power plants is the rotor blades that cause mainly broadband aerodynamic noise in frequency range 60 – 4 000 Hz. In the noise there exists an amplitude modulation of ± 2–3 dB typically at a modulation frequency of about 1 Hz. The amplitude modulation is one of the most important explanatory factors for the annoyance of the aerodynamic noise of wind power plants and the main reason of the extraordinary annoying properties of the noise. The thumping type amplitude modulation can be minimized by keeping the angle of attack as constant as possible during the rotation of the blades, by cyclically varied blade pitch angle. This also optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.

Espoo, January 2011

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Contents

1 Introduction

This work is part of the work done in the VTT funded research project “Wind power plants – knowledge increase of noise and control issues” (WPPNoCo). The main goal of the project is to increase the basic knowledge of the noise annoyance and control issues related to wind power plants.

2 Goal

The first goal of this work is to determine the generation mechanisms of the aerodynamic noise in wind power plants, and especially specify the main factors in the mechanisms affecting the noise annoyance. The second goal of this work is to find out means to reduce the noise and the annoyance caused by it.

Based on the results of an earlier research, it is obvious that the amplitude modulation of the aerodynamic noise of wind power plants is one of the most important explanatory factors for the annoyance and the main reason of the extraordinary annoying properties of the noise [1], so this is taken as the starting point for this work.

3 Generation mechanisms of aerodynamic noise

In Figure 1 are presented the sound power levels and associated transmission paths of various parts of a typical 2 MW wind turbine. The most remarkable noise source of wind power plants is their rotor blades that cause mainly aerodynamic noise. Other noise sources are the individual parts of the equipment of the electricity production, as the gearbox, the generator, the transformers, the cooling system and the inverter, causing mainly mechanical noise [2, 3, 4]. The aerodynamic noise is typically the most remarkable noise source of the wind power plants today, as manufacturers have been able to reduce the mechanical noise to a level clearly below the aerodynamic noise [2, 3]. The dominant role of the aerodynamic noise can be recognized especially with large turbine dimensions [5]. The aerodynamic noise will become even more dominant as the size of the wind turbine increase, because the mechanical noise does not increase with the dimensions of a turbine as rapidly as the aerodynamic noise [2, 3]. In Figure 2 is presented the frequency spectra of two upwind three-blade wind turbines.

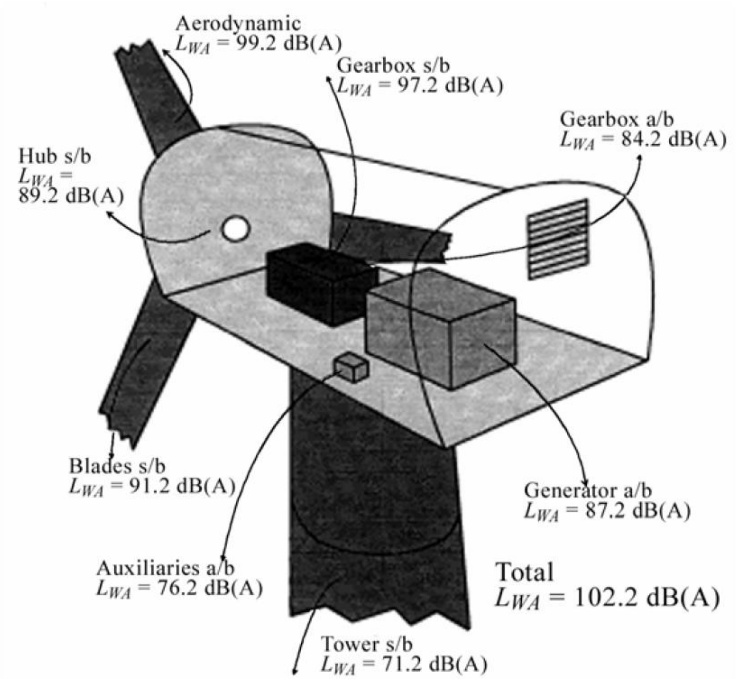

Figure 1. Sound power levels of wind turbine parts; transmission paths: a/b airborne, s/b structure-borne [6].

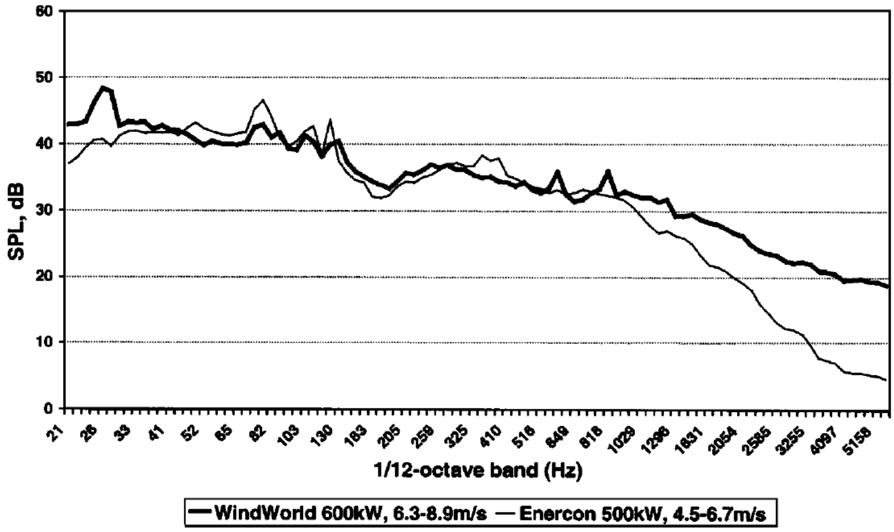

Figure 2. Frequency spectra of two upwind three-bladed wind turbines at down wind conditions [2].

The noise caused by the rotor blades is the most remarkable part of the noise of wind power plants, with respect to both the sound level and the annoyance.

3.1 Broadband aerodynamic noise

The broadband aerodynamic sound of rotor blades is composed of four major components caused by flow turbulence: the trailing edge sound (turbulent boundary layer – trailing edge interaction), blunt trailing edge sound, the tip vortex sound and the in-flow turbulent sound, the trailing edge sound being the most remarkable [7, 8]. The turbulence generates broadband aerodynamic noise in frequency range 60 – 4 000 Hz [9, 4].

When the rotor blade rotates, the air flow impinges to the surface of the blade profile and continues propagating over the blade to the trailing edge, where it separates, see Figure 3. The flow at the forward end of the surface of the blade is laminar but its turbulence grows towards the trailing edge close to the blade surface in the so called boundary layer. The turbulent flows coming from different sides of the blade strike at the trailing edge generating a turbulent flow wake [4]. The turbulence in the boundary layer generates sound, particularly when it interacts with the trailing edge [8]. The increase in the turbulence over the blade is the higher the larger the change in the blade profile is. The turbulence can be increased by the geometry of the trailing edge (blunt), the roughness (dirtiness, icing) of the blade surface, and turbulence and the flow speed of the oncoming flow [4]. The turbulence grows with growing blade tip speed, the trailing edge sound level being proportional to $50 \cdot \log_{10}(M)$, where M is the Mach number of the air impinging on the blade [7]. In modern blade profiles the area of the blade narrows towards the blade tip in which case most of the noise is not generated at the blade tip but in region situating in the blade 0.75 – 0.95 from the base of the blade [9, 4]. The source region moves outwards with increasing frequency and it is larger with rough blades. The roughness of the blade surface raises the radiated sound level especially at low frequencies. The bluntness of the trailing edge causes a clear maximum (narrow band) in the sound spectrum [10].

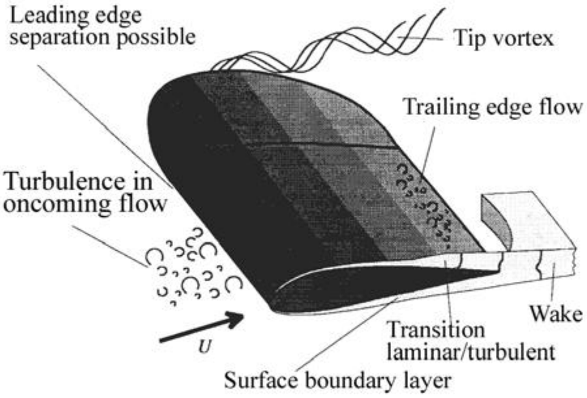

Figure 3. Schematic of flow around a rotor blade [6].

At the tip of the blade the air flows strike from three different directions causing a tip vortex which generates sound [8, 4], especially when the vortex is interacting with the trailing edge [11].

Turbulence can be defined as temporal and spatial changes in wind velocity and direction, resulting velocity components normal to the airfoil causing in-flow turbulent sound. The maximum of its spectrum is typically in the infrasound region [7].

In Figure 4 is presented Grosveld’s view [12] to relative contributions of broadband noise sources to the total noise spectrum for one wind turbine.

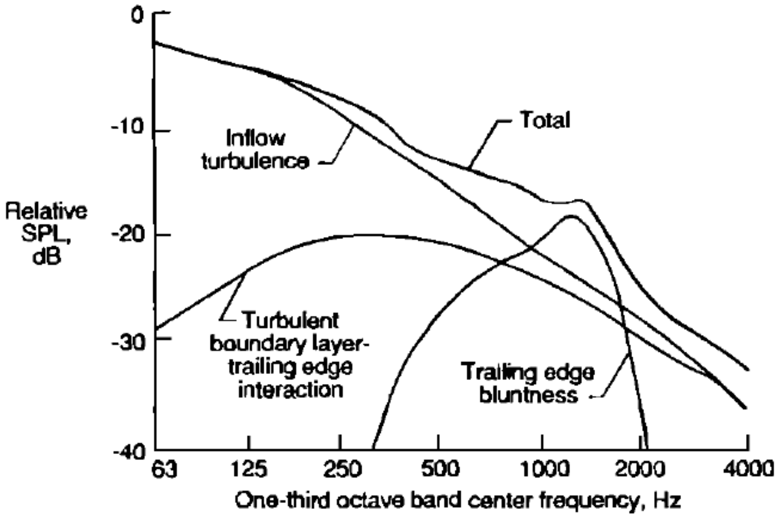

Figure 4. Relative contributions of broadband noise sources to the total noise spectrum calculated for one wind turbine [12, 5].

Noise increases may be associated with localized aerodynamic flow separation during large deflections of flaps, used for speed control [5]. With stall controlled plants the noise grows remarkably in the stalling situation [4].

The angle of attack (the angle between the incoming air flow and the blade chord, see Figure 5) plays an important role in the action of a wind turbine and in broadband wind turbine noise generation [7, 13]. The air flow around a wind turbine blade generates lift. An air foil performs best when lift is maximized and drag is minimized. Both of them are determined by the angle of attack. The optimum angle of attack is usually between 0 – 4°, depending of the blade profile. When the angle of attack increases from its optimal value, the turbulent boundary layer on the low pressure side of the blade grows in thickness, decreasing power performance and increasing sound level. High angles of attack may lead to stall, i.e., dramatic increase of drag on the blades and radiated sound [7]. In Figure 6 is presented the increase of trailing edge sound as a function of the angle of attack.

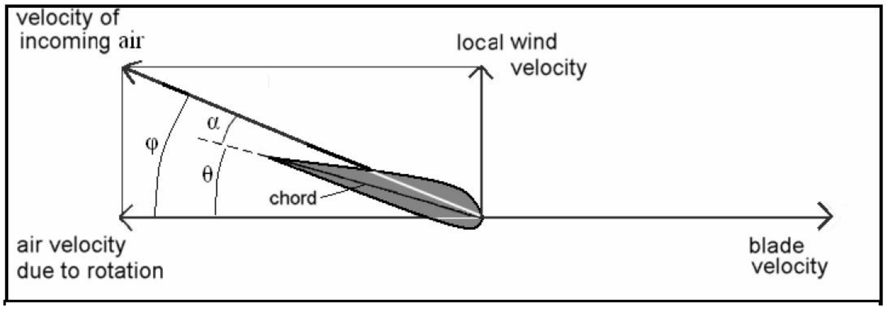

Figure 5. Flow impinging on a turbine blade with flow angle φ, blade pitch angle θ and angle of attack $\alpha = \varphi - \theta$ [7].

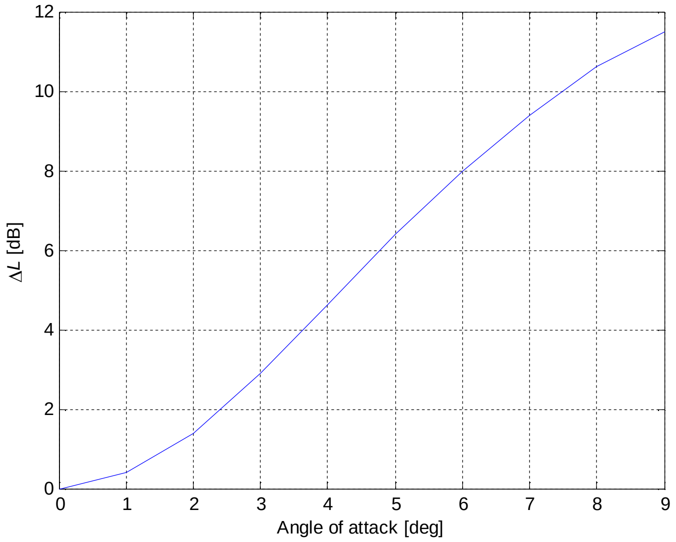

Figure 6. Increase of trailing edge sound as a function of angle of attack [7, 13].

Before going further, the concept of atmospheric stability needs to be explained. A direct citation of van den Berg [7] is given below:

“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.”

Based on the former, there is the strong change in the wind profile at blade heights in a stable atmosphere occurring mainly in night time, see Figure 7. Atmospheric stability leads to a situation where close to the ground the wind can be weak while higher up there is a strong wind. The strong wind shear causes that sound levels of wind turbines may be much higher at night time than expected, based, e.g., on wind velocity measurements at the height of 10 m calibrated for the neutral atmosphere. This is especially relevant for modern, i.e., tall and variable speed, wind turbines. Discrepancies of even 15 dB have been observed at 400 m from a wind farm at quiet nights [7]. The reverse is true for an unstable atmosphere, though to a lesser degree [7, 14]. Also the scattering of sound from turbulences caused by rising warm air lacks in stable atmosphere causing the turbine noise to carry much farther at night time than expected [15]. The strong wind profile in a stable atmosphere and the temperature inversion in an extremely stable atmosphere cause also the refraction of sound downwards reducing the propagation attenuation (the former to downwind direction). These aspects lead to a conclusion that noise measurements of wind power plants should be done also at night time, to get the worst case data [7]. The lack of scattering at night time may also lead to situations where the sound of several turbines increase in some directions due to constructive interference [15].

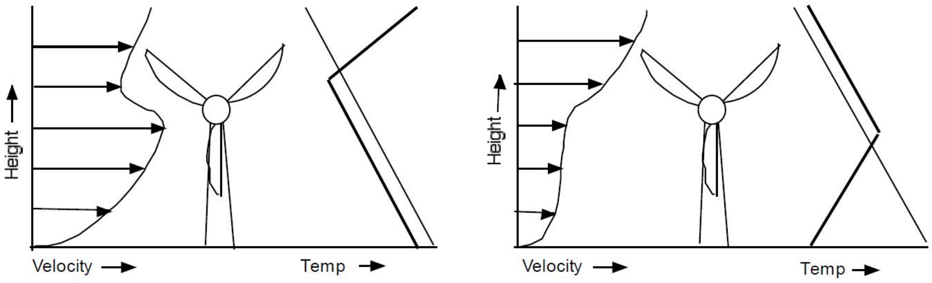

Figure 7. Neutral atmosphere near the ground with stable above (left); stable atmosphere near the ground with neutral above [13].

Highest broadband sound levels have been measured in the upwind and downwind directions, and lowest ones in the crosswind directions. According to Hubbard et al. [5], levels measured at night time are generally lower, particularly in the crosswind directions, and the lower night time levels are believed to be associated with less intense inflow turbulence. According to van den Berg [16], the above is only valid for small wind turbines, tall wind turbines produce on average more sound in night time than in day time. This is due to the atmospheric conditions presented above. In near field most of the noise is produced when the blades are moving downwards [10].

3.2 Amplitude modulation in aerodynamic noise

In Figure 8 is presented the A-weighted sound level within a period of 3 minutes near one wind power farm. The slow level variation is caused by variations in wind speed and atmospheric sound transmission. The amplitude modulation of about 1 Hz in the sound is due to the amplitude modulation of the aerodynamic noise of the rotor blades. The variation in the depth of the modulation is due to changes in the mutual phases of the rotor sounds of several turbines because the rotors do not rotate at exactly the same speeds. [17]

The amplitude modulation appears most generally at the octave bands of 500 Hz, 1 kHz and 2 kHz typically with an amplitude of ± 2 – 3 dB [18, 19]. Also higher modulation amplitudes have been observed [8]. The modulation frequency is the same as the blade passing frequency

$$f = \frac{n\omega}{60}[\mathrm{Hz}],$$

where n is the number of blades and ω is the rotation speed of the rotor [rpm]. The modulation frequency in the noise of a three blade turbine rotating at 26 rpm is thus 1.3 Hz.

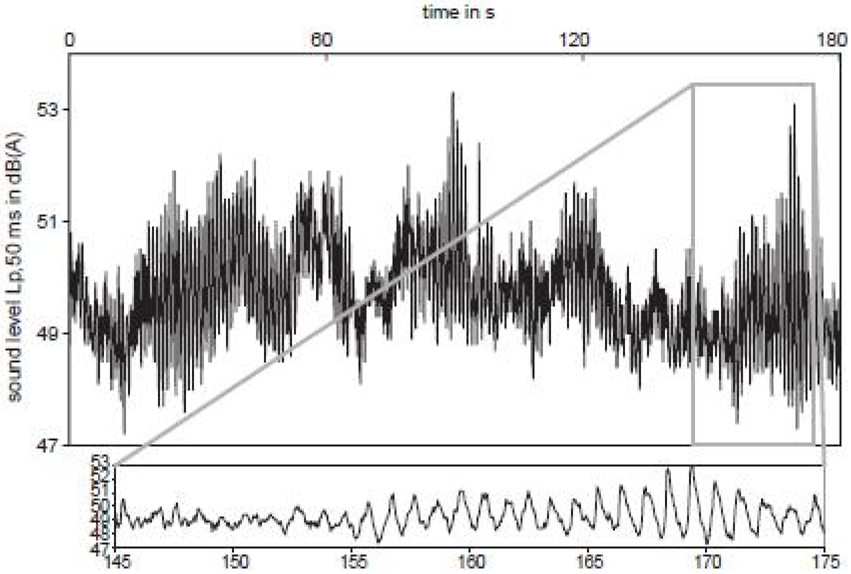

Figure 8. A-weighted sound level caused by one wind power park at a distance of 750 m from the nearest turbine measured within a period of 3 minutes; part of the sound level fluctuation is zoomed below the figure [17].

It has also been argued that the amplitude modulation frequency is not quite exactly related to the blade passing frequency at least at long observation distances and that the modulation of different frequency components does not happen in equal phases [19].

Trailing edge noise is the most likely source of the amplitude modulated sound according to van den Berg [7]. The process of the generation of the amplitude modulation has not been discovered quite unambiguously [3]. The most obvious explanation has been given by Bowdler [19], who states that there affect two separate mechanisms in the generation of the amplitude modulation. One is swishing, which originates from the rotation of the strongly directive sound radiating blades. The other is thumping, which originates from the motion of the blades through unevenly distributed flows. The swish is described as benign modulation of sound and the thump as “impulsive sound with a rapid rise time” by Bowdler.

A blade directs the sound in the plane perpendicular to the axis of the blade. Furthermore, the main radiation directions in this plane occurs forwards with respect to the blade tip motion to angles about ± 45° [19, 10, 20], see Figure 9. These directions change during the rotation of the blades, causing the swishing type amplitude modulation. If the wind comes from north and the rotation happens clockwise, the blade radiates sound mainly to north-east and south-east directions when it is in its lowest position, and to north-west and south-west directions when it is in its uppermost position. At these directions the swishing type modulation is most easily detected in far field, especially at downwind directions (south-east and south-west), and it is quite minimal to directions perpendicular to the plane of rotation (north and south). The shadow effect of the tower when the blade radiates at its lowest position makes notches in the modulation (in south-east direction with up-wind machines), see Figure 10, making the modulation more noticeable [19, 10, 20]. Also other scattering effects due to the tower may have an effect to the modulation. The swishing phenomenon is further affected by the Doppler effect where the observed frequency content rises when the blade approaches the observer and the observed frequency content falls when the blade recedes from the observer, due to the proportional motion between a blade and an observer. The crowding of the wave fronts in the direction of blade motion due to the Doppler effect, and the opposite phenomenon in the opposite direction cause amplitude changes in the frequency spectrum [21]. The swishing type modulation is merely a function of the geometry (observe – turbine) and not a function of the variation of noise level created by the rotating blade [19].

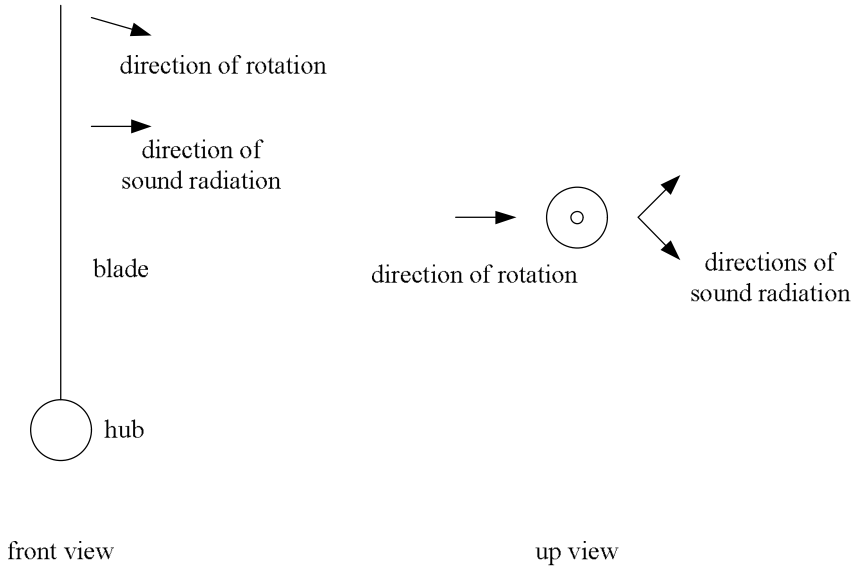

Figure 9. Sound radiation directions in swishing phenomenon.

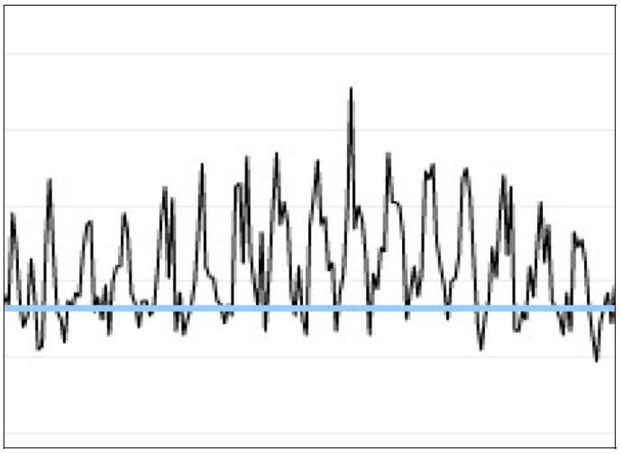

Figure 10. Example of notches in amplitude modulation [19].

There is the strong change in the wind profile at blade heights in a stable atmosphere occurring mainly in night time, as presented earlier, see Figure 7. Because the noise from a blade grows with growing flow speed, and because the flow speed grows as a function of height in a stable atmosphere, the blade generates more sound in the highest position than in the lowest one in a stable atmosphere, causing the thumping effect. The angle of attack is changing all the time in this kind of situation, thus reinforcing the change in the amplitude of the sound, see Figure 6. This explanation for the thumping type modulation is further supported by the fact that the amplitude modulation appears most strongly during night time when the stable atmosphere near the ground is more probable than during day time [13]. Van den Berg states that the change in the aerodynamic environment seen by a wind turbine blade as it passes in front of the tower has an effect to the thumping effect [7]. According to Moorhouse et al., the effect of the tower on an upwind turbine noise modulation is not borne out by measurements in the field [8].

The uneven air velocities causing the thumping phenomenon may be due to, besides the wind shear described above, also meteorological turbulence, or turbulence created by topography or other turbines [22, 19]. If this kind of turbulent eddies are larger in size than the blade, the situation may be interpreted as a change in the direction and velocity of the incoming flow equivalent to a deviation of the optimal angle of attack [22], giving also rise to sound radiation increase.

Other explanations of the same or different kind for the generation of the amplitude modulation have also been given. According to one explanation, the modulation would be caused by the interaction between the disturbed flow around the tower, and the blade, i.e., by the blades passing the wind shadow of the tower [3, 23, 24]. This can only happen with downwind machines. On possible explanation is the small pressure drop caused by the tower on the blade when it is at the bottom of its arc [15]. A report for ETSU in the UK concludes that the modulation is due to a combination of tower shadow effects as the blades pass the tower plus the directivity properties of the sound radiation [25, 19]. Anyway it is probable that the amplitude modulation in fact originates from more than only one possible reason presented above.

The thumping effect can be most easily observed at some distance from the wind farm, close to a turbine it is normally not observed. The fact that the thumping and other wind shear effects have obtained a lot of attention with modern turbines is not due to their bad design but to that they are higher than earlier machines and they operate in heights with strong wind shear [7].

3.3 Aerodynamic periodic noise

Unstable flow over holes, slits or a blunt trailing edge may cause also tonal sound components [6]. Also unusual wind flows interacting with turbine parts may cause tonal sound with older turbines [23].

Downwind machines produce low frequency sound (20 – 100 Hz) and infrasound. These sound components are produced, e.g., when the rotating rotor blade encounters localized deficiences of the air flow passing the tower [5]. The wind is slowed down by the tower which changes the angle of attack on the blade, causing sudden changes in lift and drag forces [7]. The tower wakes are affected by details of the vegetation and terrain as well as by details of the tower structure. The turbulence level of the inflow, affecting the sound level, is typically lower at night time than at day time, so noise levels are lower at night time than at day time, particularly in the crosswind directions. The low frequency sound pulses generated in this way have highest amplitudes in the upwind and downwind directions and lowest amplitudes in the crosswind directions. Infrasound may be generated also due to the periodically compressed air between the blade and the tower. Both of these phenomena cause periodic noise at the blade passing frequency and at its harmonics, called thickness sound [7] (monopole type sound radiation). The noise at the blade passing frequency occurs at infrasound region and the higher harmonics occur partially at the audio frequencies, see Figure 11. The higher harmonics may be remarkably high, especially with the first phenomenon. [5, 6, 26]

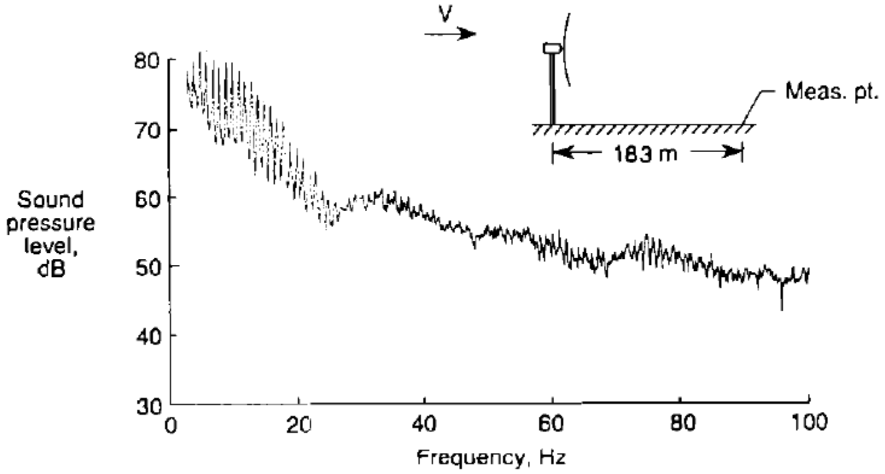

Figure 11. Example narrow-band noise spectrum at low of frequencies of a downwind machine [5].

Upwind machines do not produce as much low frequency sound and infrasound [6, 26], see Figure 12.

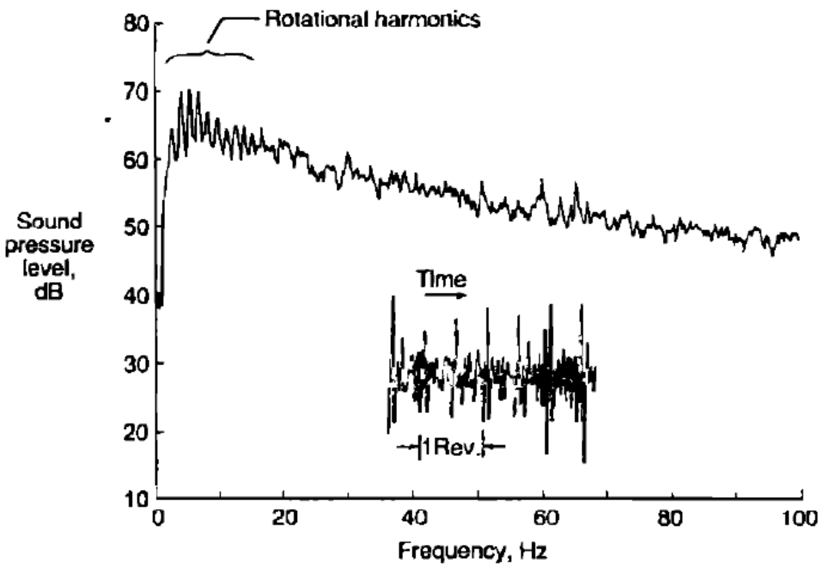

Figure 12. Example narrow-band noise spectrum at low frequencies of an upwind machine [5].

With downwind as well as upwind machines, low frequency sound and infrasound at the blade passing frequency and its harmonics can be generated also by rotor plane inflow gradients caused, e.g., by wind profiles. The wind profile may have high gradients at the rotor plane due to e.g., terrain induced distortion [5]. Gradients can also be due to wakes shed from other blades [6].

4 Noise control measures

Most new power plants are built as upwind machines, in which the low frequency noise is much lower than in the old downwind machines. The problems with downwind machines have been tried to be solved, e.g., by positioning the rotor further away from the turbine [24, 26].

The aerodynamic noise (both the broadband noise and the low-frequency periodic noise) can be reduced by limiting the speed of the blade tip to a maximum value and by changing the blade angle in plants with blade angle control [4, 5, 13], to minimize the angle of attack, see Figure 6. Variable speed wind turbines often rotate at slower speeds in low winds, and with variable speed control it is possible to programme the turbine sound levels before installation [26].

The optimization of the blade to more efficient reduces the aerodynamic noise [23]. The noise can be reduced by optimizing aerodynamically the turbulent boundary layer development along the blade sections and the turbulence properties in the vicinity of the trailing edge [27]. Especially, the modification of the blade trailing edge is important [6], using, e.g., sharp or serrated trailing edges [11]. In the aerodynamic trailing edge optimization, the outer part of the blade, where the highest flow velocities are present, should be especially considered [28]. The blades may be pitched (rotated around their long axis) and they can be designed to have a reduced sensitivity to roughness on the leading edge [26]. The tip vortex can be reduced by changing the tip geometry, e.g., by using an extended aerofoil in the tip to change the tip flow parallel to the main flow across the blade [4], see Figure 13.

Figure 13. Extended aerofoil in the tip of a blade [29].

It has been shown in SIROCCO project that it is possible to design airfoils which fully maintain their aerodynamic behaviour but which at the same time can meet additional acoustic criteria [9]. However, the noise reduction obtained in the project was of the order of only 0.5 dB(A). The project aimed only to modify existing blades which may be an indication of that totally new approaches may be needed for efficient sound reduction furthermore.

An example of a new type of a blade leading edge construction is presented in Figure 14. Fish [30] discovered that the serrated edges of humpback whale fins create a more efficient flow of water, and he adapted the design to create a new approach to fan and wind turbine blades. There is an increase in lift, decrease in induced drag and the turbulence along the blade surface decreases with this kind of blade with tubercles. WhalePower's wind turbines generate more power from a given wind speed than traditional turbines and they are quieter [15].

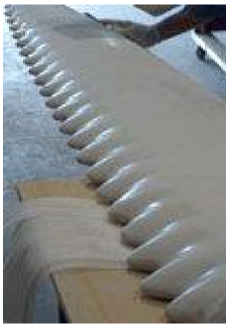

Figure 14. WhalePower Serrated Turbine Blades [31, 15].

An example of a new approach in designing turbines, based on principles from jet engines, is given in Figure 15 (prototype not yet produced at 2009). This kind of a construction, disrupting less air flows, would likely be quieter than traditional turbines [15].

Figure 15. FloDesign Turbine [15].

Vertical axis turbines look somewhat like corkscrews and they promise lower noise impacts. These designs are sized for home, office building or apartment building applications, they have not been scaled for use in wind farm settings [15].

The thumping type amplitude modulation can be minimized by keeping the angle of attack as constant as possible during the rotation of the blades. This can be realized, in principle, by cyclically varied blade pitch angle (individual pitch control). Such a continuous change in blade pitch is common in helicopter technology [7, 13]. This is advantage also 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 [7]. Because the swishing type amplitude modulation in the noise is only a function of the observer's position relative to a turbine, there is little that can be done to it [19].

The increase in sound level of several turbines due to constructive interference at night time can be eliminated by adding small variations to the blade pitch [7, 15], simulating the randomizing effect of scattering due to turbulence at day time.

5 Conclusions

The most remarkable noise source of wind power plants is their rotor blades that cause mainly aerodynamic noise. The broadband aerodynamic sound of rotor blades is composed of four major components caused by flow turbulence: the trailing edge sound (turbulent boundary layer – trailing edge interaction), blunt trailing edge sound, the tip vortex sound and the in-flow turbulent sound, the trailing edge sound being the most remarkable. The turbulence generates broadband aerodynamic noise in frequency range 60 – 4 000 Hz.

The angle of attack plays an important role in the action of a wind turbine and in broadband wind turbine noise generation. When the angle of attack increases from its optimal value, the turbulent boundary layer on the low pressure side of the blade grows in thickness, decreasing power performance and increasing sound level.

Atmospheric stability, occurring mainly at night time, leads to a situation where close to the ground the wind can be weak while higher up there is a strong wind. The strong wind shear causes that sound levels of wind turbines may be much higher at night time than expected, especially with modern, i.e., tall and variable speed, wind turbines. Discrepancies of even 15 dB have been observed at 400 m from a wind farm at quiet nights. Also the propagation attenuation is reduced in a stable atmosphere due to the lack of the scattering of sound from turbulences caused by rising warm, to the strong wind profile (downwind direction effect), and the temperature inversion in an extremely stable atmosphere. These aspects lead to an implication that noise measurements of wind power plants should also contain night time results representative for the worst case data.

In the noise caused by the rotor blades there exists an amplitude modulation of ± 2–3 dB typically at a modulation frequency of about 1 Hz (blade passing frequency). Trailing edge noise is the most likely source of the amplitude modulated sound. The process of the generation of the amplitude modulation has not been discovered quite unambiguously. According to the most obvious explanation, there affect two separate mechanisms in the generation of the amplitude modulation. One is swishing, which originates from the rotation of the strongly directive sound radiating blades. The other is thumping, which originates from the motion of the blades through unevenly distributed flows. The uneven flows are mainly due to wind shear being strong at night time in stable atmosphere. The angle of attack is changing all the time in this kind of situation, thus reinforcing the change in the amplitude of the sound. The amplitude modulation is one of the most important explanatory factors for the annoyance of the aerodynamic noise of wind power plants and the main reason of the extraordinary annoying properties of the noise.

Downwind machines produce low frequency sound (20 – 100 Hz) and infrasound. These sound components are produced, e.g., when the rotating rotor blade encounters localized deficiences of the air flow passing the tower. Infrasound may be generated also due to the periodically compressed air between the blade and the tower. Both of these phenomena cause periodic noise at the blade passing frequency and at its harmonics. Upwind machines do not produce as much low frequency sound and infrasound.

The aerodynamic noise can be reduced by limiting the speed of the blade tip to a maximum value and by changing the blade angle in plants with blade angle control, to minimize the angle of attack.

The aerodynamic optimization of the blade reduces the aerodynamic noise. Especially, the modification of the blade trailing edge is important, using, e.g., sharp or serrated tailing edges. The tip vortex can be reduced by changing the tip geometry. It seems that totally new approaches, like serrated leading edge constructions, may be needed for efficient sound reduction furthermore.

The thumping type amplitude modulation can be minimized by keeping the angle of attack as constant as possible during the rotation of the blades, by cyclically varied blade pitch angle. This also optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.

6 Summary

The most remarkable noise source of wind power plants is their rotor blades that cause mainly broadband aerodynamic noise in frequency range 60 – 4 000 Hz. The angle of attack plays an important role in the action of a wind turbine and in broadband wind turbine noise generation. When the angle of attack increases from its optimal value, the power performance decreases and the sound level increases.

The strong wind shear in a stable atmosphere, occurring mainly at night time, causes that sound levels of wind turbines may be much higher than expected, especially with modern, i.e., tall and variable speed, wind turbines. Discrepancies of even 15 dB have been observed at 400 m from a wind farm at quiet nights. Also the propagation attenuation is reduced in a stable atmosphere due to the lack of the scattering of sound from turbulences, to the strong wind profile (downwind direction effect), and the temperature inversion in an extremely stable atmosphere. These aspects lead to an implication that noise measurements of wind power plants should also contain night time results representative for the worst case data.

In the noise caused by the rotor blades there exists an amplitude modulation of ± 2–3 dB typically at a modulation frequency of about 1 Hz. It seems that there affect two separate mechanisms in the generation of the amplitude modulation: swishing, which originates from the rotation of the strongly directive sound radiating blades, and thumping, which originates from the motion of the blades through unevenly distributed flows. The uneven flows are mainly due to wind shear in stable atmosphere. The amplitude modulation is one of the most important explanatory factors for the annoyance of the aerodynamic noise of wind power plants and the main reason of the extraordinary annoying properties of the noise.

The aerodynamic optimization of the blade reduces the aerodynamic noise. It seems that totally new approaches may be needed for efficient sound reduction furthermore. The thumping type amplitude modulation can be minimized by keeping the angle of attack as constant as possible during the rotation of the blades, by cyclically varied blade pitch angle (individual pitch control). This also optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.

References

1. Uosukainen, S., Generation, propagation and annoyance of the noise of wind power plants. Espoo: VTT, VTT Research Notes 2529, 2010. 35 p. (In Finnish)
2. Pedersen, E. & Waye, K. P., Perception and annoyance due to wind turbine noise – a dose-response relationship. J. Acoust. Soc. Am. 2004. Vol. 116, no. 6, pp. 3460–3470.
3. Pedersen, E., Noise Annoyance from Wind Turbines – a Review. Stockholm: Swedish Environmental Protection Agency, Report 5308, 2003. 25 p.
4. Di Napoli, C., Tuulivoimaloiden melun syntytavat ja leviäminen. Helsinki: Ympäristöministeriö. Suomen ympäristö 4, 2007. 31 p. (In Finnish)
5. Hubbard, H. H. & Shepherd, K. P., Aeroacoustics of large wind turbines. J. Acoust. Soc. Am. 1991. Vol. 89, no. 6, pp. 2495–2508.
6. Rogers, A. L., Manwell, J. F. & Wright, S., Wind turbine acoustic noise. Amherst, Massachusetts: University of Massachusetts, 2006. 26 p. Available at http://www.ceere.org/rerl/publications/whitepapers/Wind_Turbine_Acoustic_Noise_Rev2006.pdf
7. Van den Berg, G. P., The Sounds of High Winds, the Effect of Atmospheric Stability on Wind Turbine Sound and Microphone Noise. Groningen: University of Groningen, 2006. 179 p. + appendices. Available at http://dissertations.ub.rug.nl/faculties/science/2006/g.p.van.den.berg/ and http://tinyurl.com/78baby
8. Moorhouse, A., Hayes, M., von Hünerbein, S, Piper, B. & Adams, Mags, Research into Aerodynamic Molulation of Wind Turbine Noise: Final report. University of Salford, 2007. 57 p.
9. Schepers, J. G., Curvers, A., Oerlemans, S., Braun, K., Lutz, T., Herrig, A., Wuerz, W., Matesanz, A., Garcillán, L., Fisher, M., Koegler, K. & Maeder, T., SIROCCO: Silent rotors by acoustic optimization. Second International Meeting on Wind Turbine Noise, proceedings. Lyon, 2007.
10. Oerlemans, S. & López, B. M., Localisation and quantification of noise sources on a wind turbine. First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005.
11. Klug, H., A review of wind turbine noise. First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005.
12. Grosveld, W., Prediction of broadband noise from large horizontal axis wind turbines. AIAA J. Propul. Power 1985. Vol. 1, no. 4, pp. 292–299.
13. Palmer, W. K. G., A new explanation for wind turbine whoosh – wind shear. Third International Meeting on Wind Turbine Noise, proceedings. Aalborg, 2009.
14. Van den Berg, F., Wind profiles over complex terrain. Second International Meeting on Wind Turbine Noise, proceedings. Lyon, 2007.
15. Wind Energy Noise Impacts. Acoustic Ecology Institute Special Report 1/6/09. 30 p. Available at http://www.acousticecology.org/srwind.html.

16. Van den Berg, G. P., Wind gradient statistics up to 200 m altitude over flat ground. First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005.
17. Van den Berg, G. P., Effects of the wind profile at night on wind turbine sound. J. Sound Vib. 2004. Vol. 277, pp. 955–970.
18. Dunbabin, P., An investigation of blade swish from wind turbines. Internoise 96, proceedings. Liverpool 1996.
19. Bowdler, D., Amplitude modulation of wind turbine noise. A review of the evidence. Institute of Acoustic Bulletin. Vol. 33, no. 4. Available at http://www.wind-watch.org/documents/wp-content/uploads/bowdler-amofwindturbines.pdf.
20. Oerlemans, S. & Schepers, G., Prediction of wind turbine noise and comparison to experiment. Second International Meeting on Wind Turbine Noise, proceedings. Lyon, 2007.
21. Richarz, W. & Richarz, H., Wind turbine noise diagnostics. Third International Meeting on Wind Turbine Noise, proceedings. Aalborg, 2009.
22. Van den Berg, G. P., Do wind turbines produce significant low frequency sound levels? 11th International Meeting on Low Frequency Noise and Vibration. 2004.
23. Kelley, N. D., McKenna, H. E., Hemphill, R. R., Etter, C. L., Garrelts, R. L. & Linn, N. C., Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact, and Control. Golden, Colorado: Solar Energy Research Institute 1985, SERI/TR–635–1166. 262 p.
24. Facts about Wind Energy and Noise. American Wind Energy Association. Available at http://www.docstoc.com/docs/2282669/FACTS-ABOUT-WIND-ENERGY-AND-NOISE.
25. Wind Turbine Measurements for Noise Source Identification. ETSU W/13/00391/REP. Flow Solutions Ltd, Hoare Lea & Partners Acoustics, Renewable Energy Systems Ltd. 1999.
26. Wind Power in the UK. Sustainable Development Commission, 2005. 166 p. Available at http://www.sd-commission.org.uk/publications/downloads/Wind_Energy-NovRev2005.pdf.
27. Lutz, Th., Herrig, A., Würz, W., Braun, K. & Krämer, E., Constrained aerodynamic & aeroacoustic design of wind-rotor airfoils. First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005.
28. Schepers, J. G., Curvers, A. P. W. M., Oerlemans, S., Braun, K., Lutz, T., Herrig, A., Wuerz, W. & López, B. M., SIROCCO: Silent rotors by acoustic optimalisation. First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005.
29. http://www.gmf.fcm.ca/files/Program_Docs/2005_German_Mission/Enercon_wind_turbines.pdf
30. Fish, F. E. & Lauder, G. V., Passive and active flow control by swimming fishes and mammals. Annu. Rev. Fluid. Mech. 2006.38:193–224.
31. http://www.whalepower.com/drupal/