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The sound of high winds

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IX GENERAL CONCLUSIONS

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

IX.1 Effect of atmospheric stability on wind turbine sound

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

A stability dependent wind profile predicts the wind velocity at hub height more accurately. When a correct wind profile is used, calculated immission sound levels agree with measured night-time sound immission levels.

Sound immission measurements have been made at distances up to 2 km from the Rhede wind farm containing seventeen 98 m hub height, variable speed wind turbines, and at 280 m from a single 45 m hub height, two speed wind turbine at Boazum. Measured immission sound levels at 400 m west of the Rhede wind farm almost perfectly match (average difference: 0.1 dB) sound levels calculated from measured emission levels near the turbines. At distances up to 2 km the calculated level may underestimate

the measured level, but the discrepancy is small: 1.5 dB or less.¹ Thus, from the measurements both the emission and immission sound levels could be determined accurately. As both levels can be related through a propagation model, it may not be necessary to measure both: immission measurements can be used to assess immission as well as emission sound levels of an entire wind farm.

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

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

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

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

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

IX.2 Effect of atmospheric stability on ambient background sound

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

IX.3 Wind noise on a microphone

To avoid high wind induced pressure levels in windy conditions, outdoor measurements are best performed with a large diameter wind screen. The overall reduction from a bigger wind screen relative to a smaller one is

determined by the ratio of the screen diameters. A wind screen does not reduce noise from atmospheric turbulence at very low frequencies.¹

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

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

IX.4 Degree of atmospheric stability

Stability is a property of the atmosphere, in principle occurring all over the earth. It depends on surface properties and weather conditions which determine the magnitude and evolution over time of the heat balance in the atmospheric boundary layer. Most important are differences in heat transfer at the surface (water, soil) and in the atmosphere (atmospheric humidity and clouds, wind mixing). With current knowledge, the effects of stability on the wind profile over flat ground can be modelled satisfactorily. In mountainous 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.

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

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

IX.5 Measures to mitigate stability related effects

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

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

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

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

angle of attack to local conditions during rotation. This will probably also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the mechanical load ‘pulses’ on the blades accompanying the sound pulses.

Increased fluctuation due to the interaction of sound from different turbines can be eliminated by adding small random variations to the blade pitch or rotor load, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

IX.6 Recommendations

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

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

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

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

limits, but nighttime immission levels do not, a control system can be implemented to reduce the turbine speed when necessary.

In new turbine designs continuous blade pitch control could be applied to increase energy yield and reduce annoyance at the same time by eliminating the thumping character of the emitted sound.

