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The sound of high winds

van den Berg, G.P.

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SUMMARY

Ch. I

This study was started after complaints of residents that the sound of a wind farm was louder and more annoying than predicted, especially when there was little wind in the evening or at night. The explanation appeared to be the occurrence of another wind profile than that used to predict the noise impact (the wind profile describes how the wind velocity increases with height). There are probably several reasons why this was not found earlier: 1) because wind turbines become taller, there is a growing discrepancy between prediction and practice; 2) measurements are usually done in daytime when the wind profile resembles more closely the commonly used standard profile; 3) based on the sound that occurs in daytime, it is hard to imagine the sound can be so different at night; 4) “there are always people complaining”, so complaints are not always a reason for a thorough investigation; 5) at least some wind energy proponents prefer to downplay the disadvantages rather than solve them.

Ch. II

According to Dutch legislation and international guidelines the sound production of a wind farm can only be checked by measurements when the wind farm operator cooperates. The consequence is an implicit partiality in favor of the operator detrimental to independent verification. Because of the level of detail of instructions measurements and assessments are hampered and there is no margin for the very expertise of an investigator. For a lay person understanding the jargon was already utterly impossible and he cannot but hire an expensive expert to argue his case.

From this study one can conclude that through the use of a restricted model of reality, *viz.* a forever neutral atmosphere, experts have lost sight (temporarily) of the true reality in which a neutral atmosphere is not very prevalent. It is precisely the occurrence of complaints that may indicate such errors.

Ch. III

The sound of modern wind turbines is generated mainly by the flow of the wind along the blades. In this process a turbulent boundary layer develops at the rear side of the blade where trailing edge sound of relatively high

frequencies originates and which is radiated into the environment. This turbulent boundary layer becomes thicker and produces more sound when the wind flows in at a greater angle.

The inflowing wind is turbulent itself. The blade cuts through these turbulent movements and as a result again sound is generated: in-flow turbulence sound. Here lower frequencies dominate. Finally a blade also radiates sound when the forces on the blade change because of a local variation in wind velocity. This happens every time the blade passes the tower because there the wind is slowed down by the tower. On the one hand this causes more trailing edge sound due to the change in inflow angle, on the other hand more infrasound is generated because of the sudden sideways movement at the rate of the blade passing frequency.

For all these sounds loudness increases when the speed increases. Because the tip has the highest speed the sound of a wind turbine mainly comes from the blade tips. Moreover, for human hearing the trailing edge sound is most important because it is in an area of frequencies that we can hear well.

It is often assumed that there is a fixed relation between the wind velocity at hub height and at a reference height of 10 meter. This is the relation valid in a neutral or 'standard' atmosphere. No other relations are given in legislation or international guidelines for wind turbine sound that are valid in other conditions of the atmosphere, *viz.* the stable and unstable conditions.

The atmosphere is *unstable* when in daytime the air near the ground is relatively warm from contact with the surface heated by solar insolation. In that case vertical air movements originate and the wind profile is not equal to the profile in a neutral atmosphere, though it does not differ strongly. A *stable* atmosphere however has a markedly different wind profile. The atmosphere is stable when the air close to the ground is relatively cold due to contact with the ground surface when this cools down at night by radiating heat. A stable atmosphere occurs especially in nights with a partial or no cloud cover and the wind is not too strong (close to the ground). In a stable atmosphere the turbulence has decreased substantially

and as a result layers of air are less strongly coupled. The lower layer of air is thus less taken along with the wind that at higher altitudes keeps on blowing, giving rise to greater differences between wind velocities at different heights.

Ch. IV

The present study was performed mainly near the Rhede wind farm close to the Dutch – German border. The farm consists of 17 1.8 MW turbines of 98 m hub height and three 35 m blades. The level of the incoming sound has been measured at a number of locations. The sound could be measured up to a distance of 2 km. It proved that, contrary to predictions, already at a weak wind (at 10 m height) the turbines could rotate at almost top speed and consequentially produce much sound.

It appeared that a wind profile proper to stable conditions could explain the measured sound levels excellently. At the same wind velocity at a reference height of 10 meter, wind turbines in a stable atmosphere generate more sound than in a neutral atmosphere, while at the same time the wind velocity near the ground is so low that the natural ambient sound due to rustling vegetation is weaker. As a result the contrast between wind turbine sound and natural ambient sound is more pronounced in stable conditions than it is in neutral conditions.

Ch. V

When the wind profile after sunset changes while the atmosphere becomes more stable, the difference in wind velocity over the rotor increases. This causes a change in the level of the trailing edge sound. At the low tip this is reinforced because the inflow angle already was less favourable due to the wind being slowed down by the presence of the mast. The differences in wind speed lead to variations in the sound radiated by the blade tips that reach their highest values when a tip passes the mast. For a modern, tall wind turbine the calculated variation is approximately 5 dB at night, whereas it is approximately 2 dB in daytime. This is perceived as a more pronounced fluctuation of the sound.

A more stable atmospheric boundary layer moreover implies that there is less atmospheric turbulence, so wind turbines in a farm will experience a more equal and constant wind. As a result, in a stable atmosphere wind turbines can, more than in daytime, run almost at the same speed and then

diverge again. With several turbines the fluctuations in sound can reinforce one another when they reach the ear of an observer simultaneously. With two turbines (at the same distance) this leads to an increase in level of 3 dB, with three turbines to an increase of 5 dB.

In measurements this reasoned upon effect indeed occurred. With a single 45 m high wind turbine at a distance of 280 m at night variations of 6 dB were found. Near the wind farm the variations were usually 5 dB, but they could rise to approximately 9 dB, as expected when the fluctuations of several turbines coincide.

From other research and from descriptions of residents one can establish that the sound of a wind turbine or wind farm becomes more annoying because of ‘swishing’, ‘sloshing’, ‘clapping’, ‘beating’ or ‘thumping’. All descriptions mention a periodic variation on top of a constant noisy sound. This corresponds to the calculated and measured modulation of trailing edge sound. From psycho-acoustic research it has been shown earlier that human sensitivity to sound fluctuations is high at frequencies that occur in the night time sound of modern wind turbines. If this fluctuating sound is sufficiently loud in a bedroom it can cause sleep disturbance.

In the temperate climate zone a stable atmosphere is to be expected between sunset and sunrise over land if there is a -partly- clear sky (because clouds hinder the radiation of heat) and the wind is not too strong (because a strong wind promotes vertical heat exchange). From an analysis of measurements of the KNMI at Cabauw, in the central part of the Netherlands, up to an altitude of 200 m, it appears that there is a diurnal and seasonal pattern in the wind profile that correlates with the diurnal and seasonal variation in the heat exchange between the earth’s surface and the atmosphere. The fact that at sunset the wind often lies down is a consequence of the increasing atmospheric stability, and this decrease in wind velocity close to the ground is accompanied by an increase at higher altitudes. This has significant consequences for the energy production of a wind turbines, where the rotor height plays an important part. If one starts from the measured wind velocities at Cabauw at 10 m height and a forever neutral atmosphere, the annually averaged electrical power generated by a 80 m high, 2 MW (reference) wind turbine would amount to almost

500 kW. However, based on the real, measured wind speed at 80 m height the annual power in reality amounts to 600 kW. So, because of atmospheric stability there is, relative to a neutral atmosphere, a significantly higher yield at night time hours, that even amply compensates for the lower yield in daytime hours.

The higher wind velocity at night on the rotor also causes a higher level of generated sound. If again one starts from the measured wind velocities at Cabauw at 10 m height and an atmosphere assumed to be neutral, the average sound power level generated by the reference wind turbine is 102 dB(A). In reality, however, it is 2 dB higher. This is also an average over an entire year; in separate nights the difference can be substantially higher, *e.g.* when a turbine rotates at (almost) top speed at a time it was expected to not produce at all because of the low 10 m wind velocity.

The degree of atmospheric stability at Cabauw is hardly different from what was observed at the Rhede wind farm. At other locations in countries in the temperate zone stability occurs to a similar extent. The consequences of atmospheric stability as described here, will thus occur at many wind farms that exist or are to be built in the temperate zone. However, above large bodies of water stability is rather a seasonal than a diurnal phenomenon, en in mountainous terrain the consequences of stability on the wind profile can be strengthened as well as weakened due to changes induced by height variations in the area.

The sound of a wind turbine or wind farm can thus become more annoying after sunset for two reasons: it becomes louder and the sound exhibits stronger fluctuations. At a given rotor diameter a blade can only be made less noisy with a different design or by slowing down the speed. A decrease in speed however reduces the generated electrical power and must therefore be applied only when necessary. To achieve this a control can be applied that lowers the speed when a noise limit is exceeded, increasing the speed again when the limit allows. This control could work on the generator and/or the pitch angle of the blades.

By changing the pitch angle while the blades rotate, the wind can flow in at an optimal angle at any position on the rotor, by which the energetic efficiency will increase on the one hand and the fluctuation strength of the sound will decrease on the other hand, even rendering the fluctuations inaudible. The total sound power will then decrease even relative to a neutral atmosphere, because the in-flow turbulence sound level will be lower due to the relative absence of atmospheric turbulence. Tilting the rotor to change the pitch angle during rotation does not appear to be a fruitful strategy: the tilt must be so great that the disadvantages will dominate.

The fluctuations near a wind farm can be stronger due to interference from the fluctuations of several turbines. This can be prevented by desynchronizing the turbines, as it happens in daytime by large scale atmospheric turbulence, by adding small and uncorrelated variations in the load of the rotors or the pitch angle of the blades of the individual turbines.

Controlling the sound production thus requires a new strategy for managing wind turbines: in daytime there is often more margin available for sound production than at night and this margin can be used in daytime in exchange for more restrictions at night.

Finally another, very different problem was addressed: the influence of wind on a microphone in or without a wind screen. When there is sufficient wind the microphone signal contains a low frequency, rumbling sound disturbing the measurement of ambient sound. This rumble is not sound from the environment, but is generated by pressure fluctuations caused by turbulent wind velocity variations. With a pressure sensitive microphone these pressure variations are not distinguishable from acoustical pressure variations. It appears that a wind screen is effective only by damping contributions of small turbulent eddies. A wind screen has no effect when eddies are bigger than the wind screen.

The strength of atmospheric turbulence does not only depend on the (average) wind velocity, but also on the local roughness of the earth surface and the stability of the atmosphere. These last two factors cause friction and thermal turbulence, respectively. The turbulence strength is

well known for an unobstructed wind flow over flat land. Turbulence is weaker in a stable and stronger in an unstable atmosphere.

The 'sound' pressure level based on atmospheric turbulence appears to agree well with measured and published levels of wind induced pressure levels. Thus the influence of wind on a sound measurement in wind can be calculated. In reverse this calculation model yields a new method to measure the strength of atmospheric turbulence.

To conclude, it can be stated that with respect to wind turbine sound an important phenomenon has been overlooked: the change in wind after sunset. This phenomenon will be more important for modern, tall wind turbines and in view of the many wind farms that are planned. If this problem is not recognized and solved it will hamper the expansion of wind energy.

