Wind turbine sound - metric and guidelines

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ABSTRACT

The meteorological conditions vary over the globe but also change over the day and the year and vary a lot depending on the terrain for a certain location. The meteorological parameters govern both the wind turbine emission sound levels and the sound propagation conditions and therefore gives rise to different sound immission levels. Long-time measurements of meteorological effects on sound propagation from wind turbines over forest areas have been performed at two sites in Sweden for more than two years. One site is located in the southern part with flat terrain and the other site is located in the northern part of Sweden with more hilly terrain. The aim of the project is to improve the knowledge of sound propagation from wind turbines and especially over varying terrain and weather conditions. Control measurements of wind turbine immission sound levels will be needed to see that they fulfill the noise regulations. It is therefore of most importance to be able to make representative measurements. Discussions about under what meteorological conditions the immission measurements have to be carried out, the sound metric and the impact of the guidelines are presented in this paper.

Keywords: Sound, Wind Turbine, Guidelines I-INCE Classification of Subjects Number(s): 24.6

1. INTRODUCTION

The large interest for renewable energy sources has increased the interest in wind energy. Wind Turbines, WTs, sometime raise concerns in the local environment. It has been found that the sound that the turbine produces is a source of disturbance (1, 2, 3). One of the issues today is therefore to derive accurate models to be able to predict the wind turbine sound level at a certain distance. These models must be validated and control measurements must be able to conduct. This is difficult because the sound propagation conditions change depending on the weather and the background sound level is sometimes close to the WT sound.

Wind turbines, WTs, have earlier been placed in open fields but localization in forest areas have increased especially in Sweden. Earlier studies have shown large effects of meteorological conditions on the sound propagation close to the ground. Differences in sound level of the order of 20 dB for a point source close to the ground has been found (4, 5). Even high elevated sources like WT is strongly dependent on the meteorological situation. For 12 wind turbines at 1 - 2 km a meteorological variation of 6 - 14 dBA were found for a period of two years depending on ground conditions and refraction (6) and will be presented in this paper.

Changes in wind and temperature with height forces the sound waves to bend either upwards from the ground or downwards toward the ground resulting in lower respectively higher sound level. Other effects are turbulent scattering and atmospheric absorption (7). Both the meteorological and the acoustic data presented in this paper have been collected during two years. One-year data for studying amplitude modulation of wind turbine sound has also been carried out at these sites (8).

MEASUREMENTS

1.1 The Dragaliden site

The site is located in northern Sweden (65.44°N, 20.52°E) with hills stretching around 400 – 500 m above sea level. The area is covered by forest and swamp. The little village Strömnäs with very

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few inhabitants is situated around 1 km north of the long-term measuring station and the ambient sound level is very low. Twelve Enercon-E82 (2.0 MW) wind turbines with hub height 108 and 138 m operate at the hill of Dragaliden. It is the first wind turbines in a large planned wind turbine park.

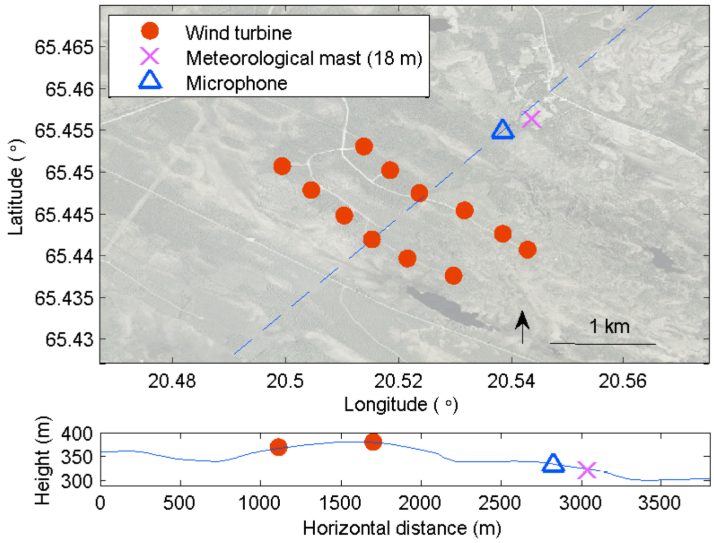

Figure 1 – Map of the Dragaliden site (courtesy to Google Earth). Sound speed gradients for this site are calculated along the dashed line. Positive direction is to the northeast. The height contour along the dashed line from southwest to northeast is shown in the bottom of the figure.

1.2 The Ryningsnäs site

The site is located in southern Sweden (57.28°N, 15.99°E) in a very quiet forest area. A road located 1.7 km south of the long-term measuring station carrying some traffic. Two Nordex 2500 LS (2.5 MW) WTs with the hub heights 80 and 100 m stand in the flat forest area.

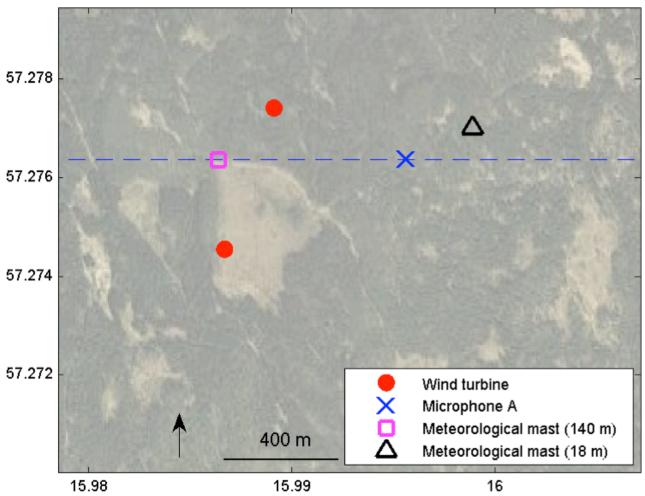

Figure 2 – Map of the Ryningsnäs site (courtesy to Google Earth). Sound speed gradients for this site are calculated along the dashed line. Positive direction is to the east.

1.3 Acoustic measurements

The sound measurements are carried out 1.5 m above ground inside the forest with a Norsonic Nor140 sound level meter. A Nor1214 outdoor ½" microphone with rain hood and dust mesh are used. It is a class I instrument and measures 1/3-octave bands between 6.3 Hz – 20 kHz. L_{Aeq} and the percentiles L_1, L_5, L_{10}, L_{50}, L_{90}, L_{95} for every 10-minute average were also sampled. Measurements with a 8 Hz sampling frequency were stored during one year for investigation of the amplitude modulation, AM, of WT sound. The data are downloaded with a modem. The stations are connected to main power by long cables. Calibrations are carried out when visiting the sites.

1.4 Meteorological measurements

Weather information is measured in a number of towers in the vicinities to the stations. All sites have similar meteorological measuring equipment. An 18 m short meteorological mast placed in the forest with WindSonic anemometers and ventilated temperature sensors at the height 0.5, 1.5, 5.0 and 18 m above ground. Wind speeds, wind directions and temperatures are measured at the same heights. The air pressure and the relative humidity are measured at 1.5 m height. Taller towers are also used at the sites.

At the Dragaliden site one 150 m high meteorological tower is located 10 km to the southeast and one 123 m high 7 km west of the measuring station. The tower southeast is located on a hill similar in shape and height as the Dragaliden and the meteorological conditions are expected to be the same. The tower west of the station is located on a 50 m higher hill and is only used in a period in the first summer when the southeast tower did not function after an attack from a bear.

At the Ryningsnäs site a 140 m meteorological tower, with sensors at 7 heights between 25-140 m is located close to the wind turbines.

The sound speed $c(z)$ in the source to receiver transect is calculated as the effective sound speed (9),

$$c(z) = c_0\sqrt{T(z)/T_0} + u(z)e_t, \qquad (1)$$

where c_0 = 331 m/s, T is the temperature (K), T_0 = 273 K, u is the wind speed (m/s), z is the height (m) and e_t is the horizontal unit vector pointing along the transect. The source to receiver transects for the two sites are assumed to go from a point in the middle of the WT parks to the receiver. The transects are indicated as a dashed lines in Figs. 1 and 2.

2. METHOD AND RESULTS

2.1 Selection of Data

The measured sound levels from the WTs are very low compared to many other human made sound sources. It is necessary to have low background sound levels when measuring WT sound. Measurements of wind induced sound in vegetation, sound incidents from fly overs, human and animal activities (birds singing, spring time) must be rejected and only undisturbed measurements are chosen for the analysis. Careful documentation of the sound environment around the sites has been made and a number of measurement criteria (for the 10 minutes measurements) have been set to avoid disturbances of the WT sound measurements:

- $L_5 - L_{95} \leq 4$ dBA
- $L_1 - L_{95} \leq 15$ dBA
- The A-weighted 1/3 octave band sound from 800 Hz and above should not contribute to more than 1.5 dB to the total A-weighted sound level if the sound is above 23 dBA.
- The emitted sound power from the turbines should by calculation (free field propagation from a point source) contribute to at least 30 dBA at the immission point.

The first two criteria are based on the fact that a disturbing sound incident change the sounds level a lot during a short time, which the WTs would not do. The third criterion further insures that vegetation induced sound is not influencing the measurement. The WTs also needs to operate at a certain power and the lower the sound level the more sensitive to disturbances are also the measurements.

The selected measurements presented in this paper are taken from a period of two years (Dragaliden: December 2010 – December 2012, Ryningsnäs: August 2010 – June 2012) and represents 7 and 10 % of the total measurement time at Dragaliden and Ryningsnäs respectively.

2.2 Normalizing sound immission data

In this paper the deviation in the sound level from an expected value is presented during different weather situations. The expected value is calculated in the following way.

Emitted sound from the WTs was calculated using operational data and manufacturer´s specifications. Continuous functions of the electrical output and sound power spectra in 1/3 octave band from 50 Hz to 10 kHz were obtained by fitting second order polynomials between a number of discrete (electrical power - sound power spectrum) relations. Validation of the manufacturer´s specifications was not possible during this study. Some uncertainty in the sound power level could therefore be expected.

The relative sound pressure level (ΔL) was obtained by relating the measured sound pressure level to the calculated value:

$$\Delta L = L_{pA} - 10\log\sum_i 10^{(L_{WA_i} + D_{Ii} - 10\log(4\pi R_i^2) - \alpha R_i)/10} \quad (2)$$

where L_{pA} is the measured sound pressure level at the immission point, L_{WAi} is the calculated emitted sound power level from the i:th turbine, D_{Ii} is a directivity correction (10) depending on the angle between the i:th turbine rotor plane and the immission point, R_i is the distance in meters between the i:th source and the immission point and α is the atmospheric absorption coefficient per meter during the current weather (from our meteorological sensors).

2.3 Results

In Fig. 3 the relative sound pressure levels for different sound speed gradients are shown for the Dragaliden site. The propagation distances from different WTs are 1 - 2 km at this site. The median values for ΔL vary between -10 to +5 dBA depending on ground conditions and refraction. A large difference between snow and no snow conditions can be seen in Fig. 3. Ground attenuation seems to be more effective during strong negative sound speed gradient and snow on the ground. For moderate downward refraction the ground type is less important.

Figure 4 presents the results from Ryningsnäs. Even here we can observe that during moderate downward refraction is the ground type less important. The distances to the WTs are so close that no sound shadow can occur. We can get higher sound levels for both negative and positive sound speed gradients than for straight propagation.

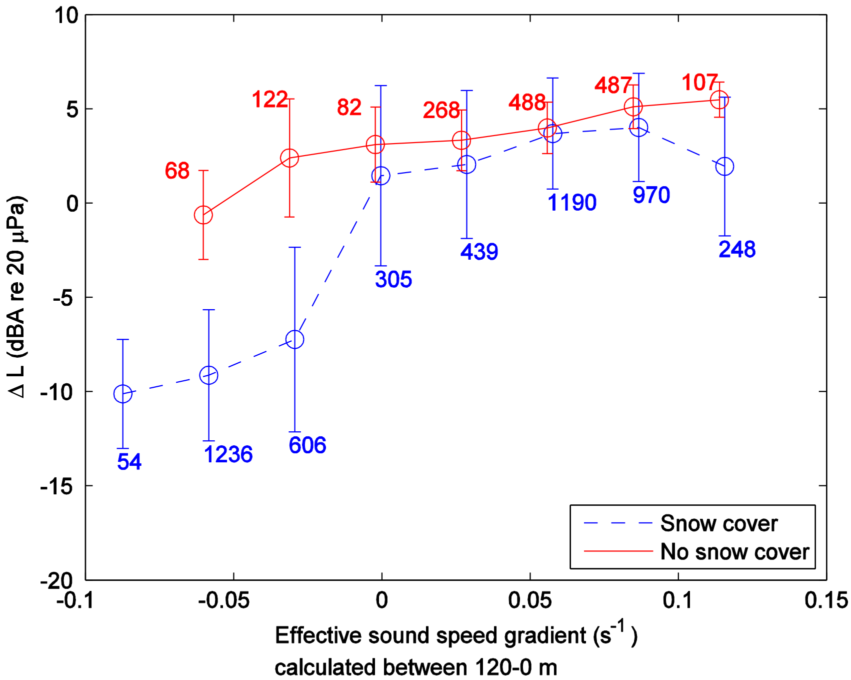

Figure 3 - Relative SPL (ΔL) (calculated with eq. 2) versus sound speed gradient during different ground conditions for the Dragaliden site. The sound speed gradient is calculated from 120 m height to the ground. The numbers indicate the total number of selected measurements within each bin and the circles (o) gives the median in each bin. The bars indicate one standard deviation of the data.

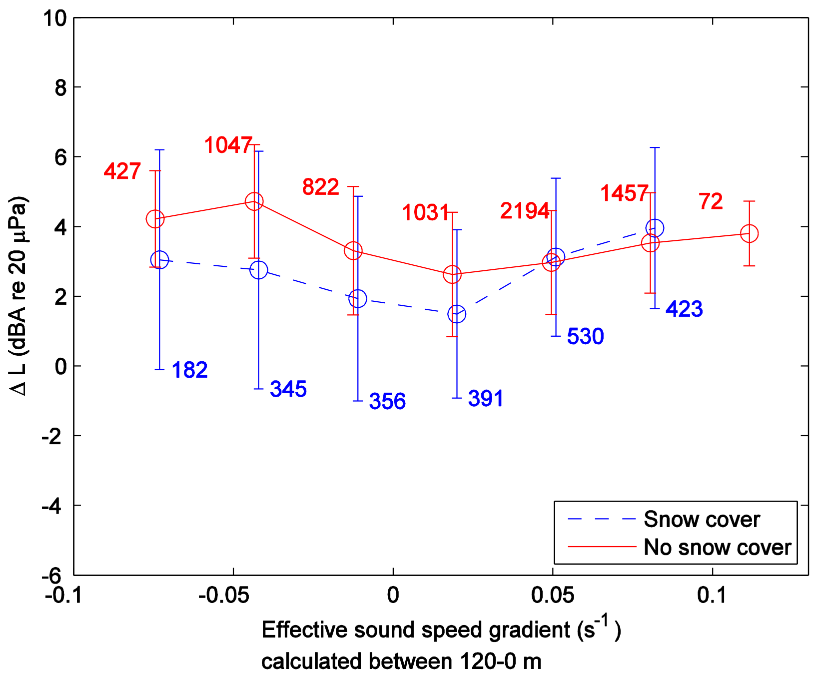

Figure 4 - Relative SPL (ΔL) (calculated with eq. 2) versus sound speed gradient during different ground conditions for the Ryningsnäs site. The sound speed gradient is calculated between 120 m height and the ground. The numbers indicate the total number of selected measurements within each bin and the circles (o) gives the median in each bin. The bars indicate one standard deviation of the data.

We conclude therefore that meteorological effects on wind turbine sound increase with distance and start to be important at distances somewhere between 400 and 1000 m from turbines.

The condition of Atmospheric Boundary Layer, ABL, is very important for the propagation of sound from WTs. We can clearly see how the sound speed gradients affect the sound level in Fig. 3 above. The radiation balance at the ground drives the ABL and normally during daytime we get more gusty winds due to more turbulence and therefore also more wind-induced vegetation sound. One to two hours before sunset the unstable daytime ABL will break down and a stable nighttime ABL will be built up from the ground with lower wind speed close to the ground with less vegetation-induced sound.

For the sites Ryningsnäs and Dragaliden the occurrence of AM sound increases during evening, night and morning and then decreases during the day (7). This pattern follows perfectly how the temperature inversion is built up during the evening and nights and breaks up from ground when the rising sun heats the ground. For a specific wind direction we can get AM sound between 30 - 40 % of the time. The total fraction of time for AM sound for the Ryningsnäs and Dragaliden site is 33 and 19 % respectively.

By and large we can conclude that both the WTs sound level and the amount of AM will often increase during the evening, night and morning and that must be included in environmental studies for WT sites.

2.4 Control measurements

Control measurements of WT immission sound levels will be needed to see that they fulfill the noise regulations. Depending on the site the quality of a control measurement varies largely. If the background level (sound from other sources than the WT) is high or in the same level as the WT sound the accuracy of such a control measurement is very low and can only be used as an indication of the WT sound level. An improvement of the accuracy could be to investigate if the background level has any time dependence. Usually there are variations in the background level during the day or the year. Normally background levels are lower during nighttime and the sound propagation conditions are more favorable during evening, night and morning, se above. Control measurements are therefore much easier to perform if they are carried during evening, night and mornings than during daytime. A control measurement including a stop of the WTs is valuable and recommended if it is possible.

Fig. 3 show median ΔL-values down to -10 dBA for upbending conditions. Although our site at Dragaliden is a quite one we could get lower ΔL-values if we measure at an even more silent site. Numerical calculated sound speed levels show therefore lower sound levels in upbending than our measurements (11).

Looking at the results from our long time measurement we have to avoid measuring in upbending conditions if we want to capture the representative high WT sound levels. Looking at the results from Fig. 3 we can se that allowing only downbending sound propagation conditions give median values from +1 to +5 dBA. Single measurements could of course deviate more, which is indicated by the standard deviations in the Figs 3 and 4. Large WTs have normally so high hub heights that strong downwind could ensure downward bending of the sound waves for the whole area between hub height and ground even during the most negative temperature gradient in daytime. That give us the opportunity to put up the demand on the meteorology parameters to measure in downwind condition and allowing ±45° from the center of the WT park to the receiver could be a good choice.

If we want a more strict definition we have to use a meteorological window, i.e. $0.05 \leq$ Effective sound speed gradient ≤ 0.1. Our results from the long time measurements give median values from +4 to +5 dBA for those conditions. But we have to consider that we still have the same magnitude of the standard deviation as the wider definition allowing all downward conditions.

Another interesting finding for areas with snow is that the results for different ground conditions (snow or bare ground) do not deviate much for downbending sound propagation conditions. For downbending sound propagation conditions measurements can be performed even during snow conditions if we exclude situations when we have lot of snow on the trees, which damp the sound effectively.

2.5 Guidelines and sound metric

Many countries around the world use equivalent sound level as the noise criteria for WTs. Acoustical measurements should use the same averaging time as meteorological standard measurements in order to get accurate measurements for the actual time.

The predicted or measured equivalent noise level should not exceed 35 – 40 dBA during 10 minutes is a rather common formulation. Normally you do not calculate or monitor the sound level during a so long time so you get all possible sound propagation conditions (weather conditions) for the site. You just do a limited number of measurements or you calculate for a certain sound propagation condition, which may or may not be typical for the site. Even if it is common condition it does not have to be a sound level that is one of the highest sound level for the actual location.

On the other hand a person living at a certain point hear and observe the variation of the WT sound level during the day and the year. Sometimes the WT cannot be heard at all and sometimes it could be heard very well. The equivalent value is not necessary a good descriptor for the sound climate over a long time at every locations and certainly not for a person that fell disturbed. The sound climate is dependent on the whole sound level distribution. Calculating with models including the differing sound propagation conditions such as weather, ground conditions or monitoring sound level over a longer period can give the sound level distribution for a certain location.

The formulation above that a sound level should not exceed has to be considered. Sound propagation conditions are depending on the weather conditions such as wind- and temperature profiles and the atmospheric absorption varies a lot due to temperature, relative humidity and air pressure. These changes in the environment are coupled to the time of the day and the year and vary at different locations around the world.

Let us look at the measurements from Dragaliden given in Figure 3. The results are from sound measurements during 10 minutes when we are convinced that all other sound than from the WT not effect the measurements. The measurements are considered to be of good quality and measure the WT sound for the actual sound propagation condition. We compare all theses good quality measurements of L_{Aeq} and find that the variations are quite large between the highest and lowest 10-minute period. If we now do not want the sound level to exceed a certain limit than we have to measure the sound during all possible sound propagation conditions that can occur at the site. Holding in our mind that some of these conditions are very rare and may be occur once a year, once a thirty-year or even once a hundred year or so. Even a very sophisticated sound propagation model cannot take all such situations into consideration. It is therefore necessary to accept that such rare conditions are not to be considered.

A formulation that *the predicted or measured equivalent noise level ($L_{Aeq,10}$) should not exceed 35 dBA – 40 dBA more than x % of the time* is a much better formulation. The choice of the x % has to be investigated for different parts of the world. A suggestion for using 5 or 10 % seems to be consistent with WT locations that are operating today.

We must remember that it is not the mean or median value that can disturb people but it is the so-called highest levels. The highest levels can hardly be calculated or measured so we have to formulate our guidelines to something that can be measured or calculated and also hold strict in a courtroom.

The findings that we have AM sound during many evening-night-mornings has in the future to be included in the guidelines.

3. CONCLUSIONS

Sound from wind turbines is strongly dependent on the meteorological situation. The meteorological variability, due to refraction and ground, increases with distance. For 12 wind turbines at 1 - 2 km, in a heterogeneous terrain with forest, we have found a variability of 6 – 14 dBA in the propagation.

The lowest sound levels for distances around 1 km are found for negative sound speed gradients (upward bending sound waves) when large ground attenuation occurs. It shows the strong coupling between refraction and ground attenuation. The ground attenuation and refraction are closely linked and could hardly be separated.

Amplitude modulated sound from wind turbines is an effect of both meteorology and acoustics and are observed during 30 % of the time at 400 m from 2 WTs and 19 % of the time around 1 km from 12 WTs. AM sound is influenced by conditions in the propagation path. It is most common in the evening, night and morning, associated with positive temperature gradients, when the turbulence intensity is low and the sound waves is not so much disturbed as in the day.

Control measurements have to be carried out in downwind conditions ± 45° from the center of the WT park to avoid the upbending conditions. Downwind measurements could also be carried out during snow-covered ground if situations with lot of snow on the trees are avoided.

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REFERENCES

1. Pedersen, E., Waye, K.P. Perception and annoyance due to wind turbine noise – a dose- response relationship, *J. Acoust. Soc. Am*. 116(6), 2004, 3460-3470.
2. Pedersen, E., Waye, K.P. Wind turbine noise, annoyance and self-reported health and well being in different living environments, *Occup. Environ. Med.*, 64(7), 2007, 480-486.
3. Pedersen, E., v d Berg, F., Bakker, R., Bouma J. Response to noise from modern wind farms in The Netherlands, *J. Acoust. Soc. Am.* 126(2), 2009, 634-643.
4. Larsson, C. Effects of meteorological parameters on sound propagation, *Abstracts of Uppsala Dissertations from the Faculty of Science*, 714, 1984.
5. Larsson, C., Israelsson S. Effects of meteorological conditions and source height on sound propagation near the ground, *Appl. Acoust*. 33, 1991, 109-121.
6. Öhlund, O. Wind Turbine Sound Propagation in the Atmospheric Boundary Layer. (Licentiate Thesis). Uppsala University 2014.
7. ISO 9613-1 Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere, International Standards Organization for Sound and Vibration Research, 1996.
8. Larsson, C, Öhlund, O. Amplitude modulation of sound from wind turbines under various meteorological conditions, *J. Acoust. Soc. Am*. 135(1), 2014, 67-73.
9. E. M. Salomons, Computational atmospheric acoustics, *Kluwer Academic Publishers*, 2001
10. Friman, M. Directivity of sound from wind turbines, Thesis for the degree of Master of Science, The Marcus Wallenberg Laboratory, 2011.
11. Bolin K., Almgren. M., Ohlsson E, Karasalo I. Long term estimations of low frequency noise levels over water from an off-shore wind farm *J. Acoust. Soc. Am*. 135(3), 2014, 1106-14.