VERIFICATION OF SOUND LEVELS FROM WIND FARMS USING IMMISSION MEASUREMENTS

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ABSTRACT

There are two main tactics for verifying sounds from wind farms; 1. Sound emission measurements combined with propagation calculation, and 2. Sound immission measurements. Both tactics have advantages and disadvantages, but neither method can be said to have such great methodological advantages that it removes the need for the other method. Verification should therefore continue to be allowed with both methods, and the choice should be made based on the conditions of the wind farm in question.

This paper presents the results from a Swedish research project on sound level validation of wind farms. One part of the project was to develop better sound immission measurement methods, and it is shown in this paper that by evaluating short time periods, typically 10 s, with regard to the wind turbines' production, wind direction and sound quality, it is possible to select periods that are relevant for sound immission level evaluation. With sufficient measurement periods, a distribution of sound levels can be compiled, and this distribution is shown in the report to be well suited for statistical evaluation. The proposed methodology does not include any measurement of the background noise level, nor any further compensation for it. The selection itself seems to be sufficient handling of background noise. Comparisons with controlled Nord2000 calculations are also shown in the paper. The tools presented in this paper are not in themselves a completely new method but can be implemented in existing methods and can thus be used to verify noise limits in existing environmental permits.

Keywords: *Wind turbine noise, Immission measurement, Verification*

1. INTRODUCTION

The sound from wind turbines is originally created from the air flow around the blades. A more detailed description of this can be found in, for example, the Environmental Protection Agency's guidance on noise from wind turbines [1] together with the references there and will not be described in more detail in this paper. The sound at the residence is a result of the sound that is created by the blades of the wind turbine and that is then changed by the impact of sound propagation over the topography in question. The vicinity of the dwelling also affects the sound pressure level through e.g., reflections in nearby buildings.

The Swedish Environmental Protection Agency specifies a guideline value that must normally be met at the residence, $L_{\mathrm{Aeq}} = 40$ dB. For each wind farm, consisting of one or more wind turbines, the licensing authorities then set a conditional value. The absolute most common conditional value in operating permits for wind farms corresponds to the recommended guideline value, i.e. it is stated that the sound from the wind farm must not exceed $L_{\mathrm{Aeq}} = 40$ dB in total for all nearby wind turbines.

This paper, which is a summary of the findings in a Energimyndigheten project [2], deals with how a wind farm's operating permit can be verified with regard to noise. A description is made of how sound immission measurements can be performed and evaluated in practice, using filtering of acoustic and other data.

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2. VERIFICATION OF INDUSTRY NOISE

Industries generally have an operating permit which, in the same way as for wind turbines, specifies conditional values for noise levels. There are two main principles for verifying noise levels from industries:

- Verification with sound emission measurements combined with sound immission calculations.
- Verification with direct sound immission measurements.

These two principles are described below, and the main advantages and disadvantages are described.

2.1 Verification with sound emission measurement and calculation

There are several internationally recognized standards that describe how the source power, i.e. the sound power level, should be measured. In Sweden, the measurement standard IEC 61400-11 is normally used. For calculating noise from wind turbines there are several calculation models that can be used. In Sweden, the Nord2000 calculation model has been used for many years and is also recommended in the Environmental Protection Agency's guidance. For wind turbines, Nord2000 has been verified [1, references therein].

The advantage of verification with calculation is that the noise level at all nearby residences can be verified. In this way, a complete assessment can be made as to whether the wind farm contains its conditions or not.

Furthermore, different operating conditions, varying numbers of sound sources and to some extent different meteorology can be studied and compared in calculations. In this way, any protective measures, such as noise limitation of the wind turbines, can also be tested. Measurement methods for determining sound power levels are also less sensitive to meteorological conditions and are therefore easier to implement. Verification with sound emission measurement and calculation is the most common control method for checking against a wind farm's operating permit.

The disadvantage of verification through sound emission measurement and calculation is that certain calculation conditions are assumed, and whether the calculated noise level is relevant for the actual noise level from the wind farm, is often debated.

2.2 Verification with sound immission measurement

Direct sound immission measurement has the advantage that it basically tests the condition value exactly where the control point is. There are several national guidelines and international standards that describe how such a sound immission measurement should be carried out for different types of activities. For wind turbines there is, for example, the so-called Elforsk method [3] which can be used for direct immission measurement of noise from wind turbines.

The advantage of verification through direct sound immission measurement is precisely that the condition value is checked on site, and then includes all effects regarding sound radiation, topography and meteorology.

During an immission measurement, only one point is however checked, and it cannot therefore be ruled out that there is more noise elsewhere.

A further disadvantage of direct immission measurement of sound from a wind farm is that the results are very dependent on all the individual conditions that prevailed during the measurement period. All in all, direct sound immission measurements are difficult to carry out, above all because the meteorological conditions cannot be influenced. This means that you are forced to wait for the "right" conditions, which can take a long time, sometimes several years. The results from direct sound immission measurements are also often questioned with objections as to whether the conditions that prevailed during the measurements are representative of the entire operation.

2.3 Analysis of the two principles for the case of noise from wind turbines

Noise from wind turbines should be handled in a way that is as equivalent as possible to other noise sources in society, i.e. the handling method should be as similar as possible relative to noise from road, rail and air traffic, from construction sites, from motorways and from industries. It is desirable that verification can be done using both principles outlined in the previous section.

During sound measurements, you can never turn off the background noise. All sound measurement methods, emission and immission, contain measures or prerequisites to ensure that measurement with the sound source itself running gives a sufficiently large difference compared to a measurement with only background. Common methods of doing this are to move the measurement position closer to the sound source or to lower the background level. Therefore, the measurement methods for immission from noise sources in society other than wind turbines, for example, contain a requirement that the measurements be carried out in light winds. Wind noise in vegetation and other objects near the measurement point is a common source of high background noise levels.

The general guideline value for noise from wind turbines, L_{Aeq} = 40 dB, is a low sound level compared to guideline values from e.g., roads and railways. The low sound pressure level to be verified means a requirement for very low background levels, which could be met only if measurements were made in light winds. However, one cannot set a methodological requirement that measurements must be carried out in weak winds, because the winds simultaneously affect the source strength of wind turbines. Weak winds would mean low noise levels from the wind farm.

As far as direct immission measurement of sound levels from wind farms is concerned, the management of background levels is therefore central. The noise from wind turbines near a residence can often be exceeded by wind noise, which poses challenges in determining the noise level from the wind farm alone. The background noise from wind noise often varies greatly, and large variations can occur even during the same minute. This means that wind power noise can be heavily masked in periods and more audible in other periods.

In the existing Elforsk method, background levels are managed traditionally, with a measurement series with the wind turbine in operation (sound from the wind turbine and background), and then a measurement series with the wind turbine switched off (only sound from the background). The traditional statistical method that the Elforsk method uses assumes that the measured wind speed at a height of 10 m at a point is directly determining the background level at the measurement point. Unfortunately, wind speed varies along all three dimensions (height, width and length), and also with time, in an apparent random manner. This means that the correlation between the measured background level at the measuring point and the measured wind speed is often poor. Statistically differentiating operation+background (total sound pressure level) and background alone (background level) is difficult in that situation. It is important to point out that the reason for this difficult situation is not created by poor performance by the measurement operator. It is created by an overly simplistic view of how to deal with background levels, in which case there is little difference to the overall noise level with the wind turbines in operation. The error is that one starts from the assumption that the measured wind speed uniquely determines the background level, often as mentioned the correlation is poor.

For direct sound immission measurement to be possible to use for the verification of wind farms, a more adapt method must be found to handle background levels. The measurement method should also function under as wide a range of conditions as possible so that it can be carried out without having to wait for exactly the right meteorology. The proposed Italian method described in [3] is an interesting alternative for immission measurements. In this method, sound and meteorological measurement data is combined with ISO 9613-2 calculations, and the energetic sum of the noise from the wind turbine and background noise are iteratively adapted to fit the measured sound levels. The adaptation is made using the equivalent mean rotation speed of the whole wind farm. The output of the method is both the operational and the background sound level, without the need for shutting down the wind farm. However, the method relies on 10-minute measurement intervals, a period length that has in our project been shown to be too long for assuming that meteorological factors to remain constant.

3. VERIFICATION BY MEASUREMENT

Within the project, measurement data from 10 different wind farms have been used, with both measured emission and immission sound levels. The measurement data includes both sound level data with short time resolution, generally 1 s resolution, and sound recordings. In addition, there is production data from the parks as well as measured wind speeds with a 10 m wind mast. The project has chosen not to publish the names of the wind farms or any data that makes them identifiable.

3.1 Basic setup with 10 s periods

Noise from wind farms varies clearly over time, see Figure 1, and the variation in noise level comes both from variations in the wind farm's operation (influenced by the speed and direction of the wind) and variations in the background noise. The measured values in the figure are equivalent levels evaluated in 10 s periods.

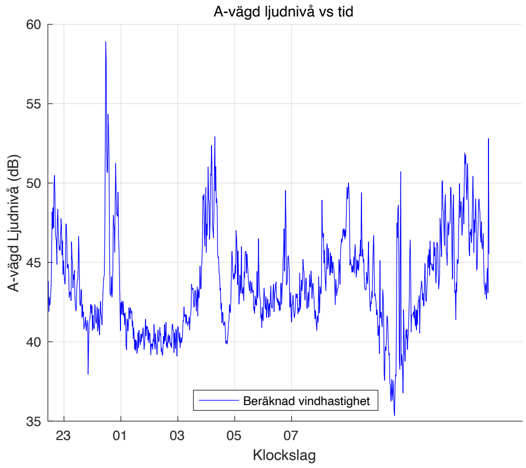

Figure 1. Measured A-weighted sound level in an immission point as raw data. The sound levels include both the wind farm in operation and background, evaluated as equivalent levels for 10 s.

Although the measured values are equivalent levels, the sound levels vary greatly between $L_{\mathrm{eq,10s}} = 35$ and 59 dB(A). A well-designed measurement method for direct sound immission measurement must determine a single number from this varying curve, a value that must be compared with the wind farm's conditional value, usually 40 dB(A), in a legally secure manner. That is the challenge of the presented project in a nutshell.

The guideline value for noise from wind turbines is formulated as an equivalent level. However, it is not clear during which time the equivalent level should be evaluated. The Environmental Protection Agency's guidance states that the sound must be evaluated for a total of at least 30 minutes, but that it does not have to be a continuous measurement period. The same time period of 30 minutes is also stated in Elforsk report 98:24 [4].

The project's working hypothesis was that evaluation of sound data during short time periods can be used to determine whether the sound during that particular time period is dominated by wind turbines or background noise. Each time period must be determined as either a "wind power period" or a "background period", although there are certainly some periods that have an equal contribution from both types. The advantage of the division is that you can then make evaluations only on the wind power periods or the background periods. All periods must also be the same length to give the same weight in a later statistical analysis. The desirable situation is illustrated in Figure 2.

The length of each time period must be chosen with care. As stated previously, the conditions vary rapidly, which suggests that the length should be short. It must also be remembered that at the basis of all evaluation methods using equivalent levels, is the assumption that all conditions can be considered constant over the time period. This also indicates that the length of time must be short for the method to be relevant. A time period of 10 minutes, which has been used previously in investigations [5], is far too long for the assumption of constant conditions to be considered valid.

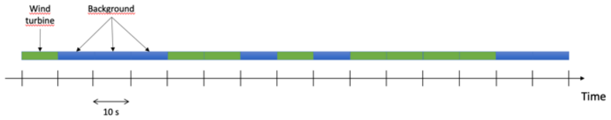

Figure 2. Illustration of the timeline of the acoustic data, where some time periods are dominated by wind power noise (green periods) and some periods are dominated by background noise (blue periods).

The time period must also not be too short, as there must be enough data during the period for the measured values to be evaluated. In the context of wind power, one wants to be able to evaluate amplitude modulation, and it typically occurs at frequencies between 0.5 – 1 Hz. The time periods must therefore be significantly longer than 2 s.

In the project we concluded that a time period length of 10 s is a well-functioning compromise. The measurement method for sound emission from wind power, IEC 61400-11, also uses 10 s time periods. This means that it is practically possible to obtain production data from the wind turbines that are synchronized with the sound data.

3.2 Different data that can be used for selecting periods

The measurement method should not set any limit on how high or low the sound levels can be, since that would mean an indirect limit on the measurement result. The measures used in the determination should instead be focused on the sound character. Here, the project has taken inspiration from studies of subjective experience and/or disturbance of sound from wind power and from other sound sources [6,7]. A brief summary of the conclusions of such studies:

- Higher sound level gives a stronger experience and thus increases the disturbance.
- The frequency spectrum of the sound affects how strong the sound is perceived.
- Clear impulse sounds, regular or irregular, are easy to distinguish and strongly affect the perception and disturbance.
- Clear tones in the sound increase the disturbance.

Although tonalities are sometimes present in wind power sounds, it is not so common that it can be used for selection.

In connection with the permit application for all wind farms, a calculation of noise levels at nearby residences is made. The shape of the frequency spectrum at the measurement point is thus possible to use for distinguishing time periods that are dominated by noise from wind turbines. This method has been used before [8,9]. The spectrum similarity method is described in section 3.3.

Amplitude modulation is a sound characteristic that is clearly associated with sounds from wind turbines [1,7]. A method to evaluate the amplitude modulation in an audio signal is presented in section 3.4.

A non-acoustic measurement value that is natural to use in the selection of wind power periods is the produced electrical power. It is stated in [1] that sound calculations shall be made for the highest sound power level of the wind turbine regardless of wind speed. A reasonable trigger would be to find the lowest electricity production where the A-weighted sound power level has dropped by 1 dB from the highest value. In a wind farm, the electricity production in the wind turbine closest to the measuring point should be used for the selection with regard to production.

As previously described in this paper, meteorological data varies greatly with both location and time. This makes it difficult to use such data for the selection of suitable time periods. The combined experience of disturbances from wind turbines [1,7] is, however, that downwind from the turbine is perceived by local residents as the most disturbing. Therefore, it is reasonable that selection can be made based on wind direction. In [4] it is stated that tailwind within +- 45 degrees from the nearest wind turbine, or group of wind turbines, must prevail during sound immission measurement.

3.3 Use of spectrum similarity

The method assumes that you have access to a reference spectrum at the immission point. The reference spectrum can come from a calculation or from a preliminary evaluation of selected measurement periods. Conclusions from previous use of this method are that the shape of the reference spectrum is very important to give reliable results [8,9].

Limiting the frequency range in which the similarity is tested provides better signal to noise conditions. A simple way to determine this is as follows:

- Obtain the L_W spectrum of the nearest wind turbine, between 25 Hz and 10 kHz.
- Calculate the air damping for all frequency bands using a standard meteorology e.g., 101.3 kPa, 15 °C and 70% relative humidity.
- Calculate the A-weighted sound pressure level at the immission point for each of the third bands.
- Normalize the all sound pressure levels to the highest one-third octave band value.
- The most important frequency range is the third band which has values higher than -10 dB.

The lowest one-third octave band should not be chosen higher than 50 Hz. The highest one-third octave band depends on the L_W spectrum and distance. Common values can be 2 kHz at short distances (up to about 500 m) and 1.25 kHz at longer distances (about 2 km).

The steps performed to determine spectrum similarity are:

- Evaluate the normalized sound pressure spectrum as described above. This gives a test spectrum.
- Take the absolute value of the differences between the test spectrum and the reference spectrum.
- The spectrum similarity for the current time period is the arithmetic mean of the differences across the bands.

After evaluations for 8 wind farms, it seemed that 2-3 dB can be a suitable value of the spectrum similarity to determine whether the sound during the test period is dominated by wind power or not. A smaller value gives stricter selection but can also mean that time periods with a slightly deviant spectrum are not detected as wind power. A higher value does not provide as good removal of background levels.

3.4 Using Amplitude Modulation – RPM Matching

The amplitude modulation has a frequency that corresponds to the number of blades that pass a reference line, e.g., the tower, during 1 second. For wind turbines with three blades and a rotation frequency between 10 and 15 rpm, the amplitude modulation frequency is between 0.5 and 0.75 Hz. To match with production data the rotation frequency needs to be determined with an accuracy of 1 rpm. This corresponds to a frequency resolution for the amplitude modulation of 0.05 Hz. A FFT of a 10 s long signal gives a frequency resolution of 0.1 Hz regardless of sampling frequency, which is thus not sufficient. Zoom-FFT can be used to evaluate the RPM.

The first step is to evaluate whether amplitude modulation appears to be present in the signal within a frequency range relevant to the rotation frequency. This is done by first calculating an FFT of the amplitude of the A-weighted audio signal, including an upwards limitation in frequencies as in section 3.3. The existence of amplitude modulation is identified by finding a peak in the modulation spectrum within the frequency range 0.4 – 1.0 Hz. A peak means that amplitude modulation is detected.

Step 2 is then to do a simple Zoom-FFT within the frequency range $\pm\Delta f$ from the frequency of the peak (Δf is the frequency resolution in the FFT). The simple Zoom-FFT consists of evaluating the Fourier integral for the amplitude modulation frequencies you are interested in, e.g., with the step 0.05 Hz or finer. The amplitude modulation frequency is evaluated as the frequency where the absolute value of the Fourier integral has its highest value.

The wind turbine's rotation speed can be calculated and matched to the production data. Time periods where the rotation speed is within ± 2 rpm can be considered as wind turbine dominated time periods. In the same way as for the spectral similarity, a tighter limit can be used, but at the expense of the number of measurement periods that pass the filter.

3.5 Aggregate evaluation of measurement data

The list below indicates the main features of how all measurement data combined into a final measurement result:

- Synchronize audio data with production data so that the produced power and rotational speed of the nearest

- wind turbine can be matched to equivalent levels and amplitude modulation for the same 10 s periods.
- Compile which periods simultaneously fulfill the condition for produced electrical power and wind direction.
- For the selected periods, further analysis can be carried out for spectrum similarity or amplitude modulation.

When all these steps have been completed, the number of time periods has been clearly reduced. How many remain depends entirely on the current situation, including how high the background level has been during the measurement period. According to the Environmental Protection Agency's guidance, noise from wind turbines should be evaluated for a total of at least 30 minutes, which means that you should have at least 180 periods of 10 s left.

Note that the above compilation does not include any background measurement or background compensation. The evaluation process as described above selects time periods during which the wind turbine is likely to be the dominant noise source. It basically means an assumption that during the selected time periods the noise level from the wind farm is sufficiently higher than the noise level from the background so that no additional background correction is needed. Not compensating for the background level can result in slightly higher noise levels than the sound from the wind farm alone.

The A-weighted equivalent level ($L_{\mathrm{Aeq,10s}}$) for all individual time periods is compiled in a histogram to study the distribution. The histogram can be evaluated using standard statistical methods; equivalent value, median value, standard deviation and quantile levels.

There have been concerns that a selection process as described above would favor time periods with relatively high noise levels from the wind turbines, and thus present a value which is higher than the “true” value. However, the example evaluations carried out within the project show that this does not seem to be the case.

The proposed evaluation method is not limited to A-weighted total levels; it can also be used to evaluate levels in selected frequency bands.

4. EXAMPLE EVALUATION OF A WIND FARM

The evaluation methodology has been tested on measurement data from 8 different wind farms. For the example wind farm, 80% of maximum power corresponds to a wind speed of 10 m/s. The Elforsk method gave a measurement result of 41.8 – 42.5 dB(A). A Nord2000 calculation to the immission point gave the immission noise level as 43.3 dB(A).

In the evaluations, the power limit has been set at 80% of maximum power, the spectral similarity limit at 2 dB, and the RPM matching limit at 2 rpm.

The performance of the evaluation method is evaluated both by comparison of the evaluated A-weighted sound level at the measurement point by other methods, and by the standard deviation of the resulting distribution of sound levels. A low standard deviation for the distribution indicates a measurement result with little variation, i.e., a measurement result with low measurement uncertainty.

Figure 3 shows measured sound levels with and without truncation of which one-third octave bands are included in the A-weighted total value, as described in section 3.3.

Figure 4 shows histograms for the measured sound levels for all measurement periods, and for the periods that had a electrical power production of at least 80 %. In the figure, the distribution with high power has clearly higher noise levels. The distribution of the periods with high power still has the form of a normal distribution.

Figure 5 shows distributions for spectrally similar periods with measurement periods only with high power. In the evaluation for the wind farm, a reference spectrum was used that was evaluated from the immission measurement itself, here by using the RPM matching filter.

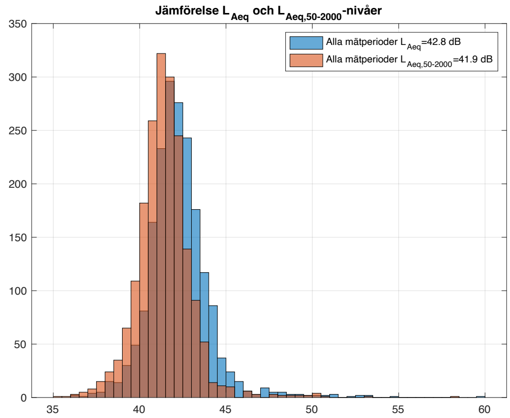

Figure 3. Histogram of A-weighted sound level for all measurement periods for the wind farm, with and without limitation of frequency bands included in the A-weighted total value.

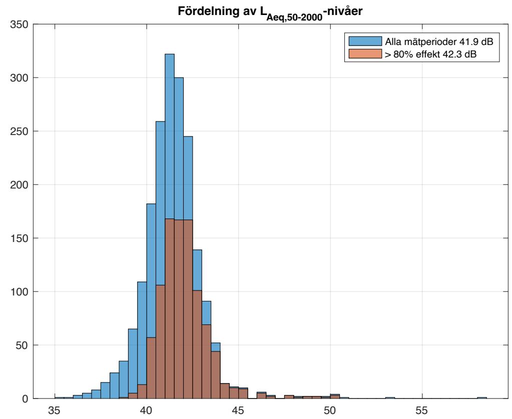

Figure 4. Histogram of A-weighted sound level for all measurement periods for the HB wind farm, and the periods where produced power was at least 80% of maximum power.

The evaluation efficiency of the RPM matching filter is shown in Figure 6. It is clear from the figure that the distribution after the RPM matching filter has the same distribution shape as the power filter alone. The results in figures 5 and 6 show that possible fears that the sound quality filters would sort out measurement periods with a preferably high sound level are not justified. For this example, wind farm, the distributions have the same shape before and after the sound quality filters. A summary of the evaluations for the wind farm is shown in Table 7.

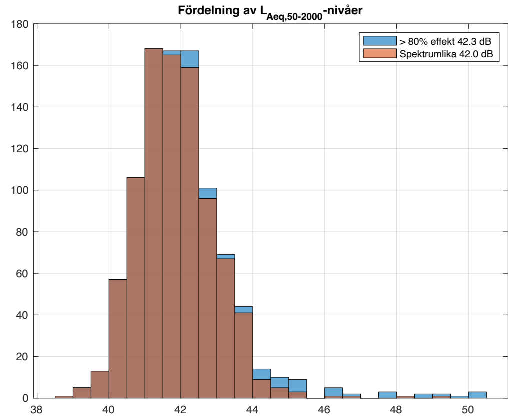

Figure 5. Histogram of A-weighted sound level for measurement periods where produced power was at least 80% of maximum power, and measurement periods that passed the spectral similarity filter.

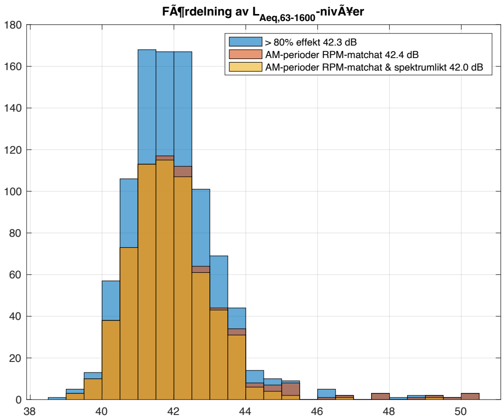

Figure 6. Histogram of A-weighted sound level for measurement periods where produced power was at least 80% of maximum power, and measurement periods that passed the RPM filter. A combination with the spectral similarity filter is also shown.

Table 7. Summarized evaluation results for the wind farm. P: Produced power at least 80% of maximum power, SL: spectrum similarity, RPM: RPM matching.

Filter	N (-)	N (%)	L_{Aeq} (dB)	L_{Amedian} (dB)	Std (dB)
None	1918	100	-	-	-
P	950	50	42,3	41,9	1,4
P+SL	899	47	42,0	41,8	1,1
P+RPM	644	34	42,4	41,9	1,4
P+SL+RPM	608	32	42,0	41,8	1,1

For this wind farm, a large percentage of the measurement periods passed the filters, leaving a distribution of sound levels with low standard deviations, 1.1 to 1.4 dB(A). These numbers are comparable with the measurement uncertainty you usually get in sound emission measurements.
Furthermore, evaluated equivalent levels and median levels agree with results from the Elforsk method, well within 1 dB. When compared to the Nord2000 calculation, the measured levels are slightly below the calculated result of 43.3 dB(A). Evaluated as a percentile, the calculated value corresponds to the 75% percentile of the measured sound levels. It is not strange that the calculation is a little higher, since the

calculation assumes downwind from all wind turbines at the same time, and that the calculation does not take into account the directivity of wind turbines.

5. CONCLUSIONS

A conclusion that can be directly drawn from the example presented above, and from other measurements using the same method, is that the method of dividing the measurement data into short periods, here 10 s, provides good opportunities to filter out favorable periods. The resulting distribution of sound levels is apparently normally distributed, at least if you do not select too hard.

The filtering of the data should be in the following order:

1. Filter on produced electrical power
2. Filter by wind direction
3. Filter by sound quality

There is no relevance whatsoever in determining whether a measurement period has the correct frequency spectrum or whether amplitude modulation is present if you do not first show that the wind turbine is in operation.

In the presented example, the wind direction has not varied so much that the measurement point has fallen outside +-45°, so it can neither demonstrate nor reject any effectiveness in that filter.

The spectrum similarity filter and the RPM matching filter both seem to work well, provided that the input measurement data itself is of good quality.

The spectrum similarity generally seems to give a smaller standard deviation than the RPM matching, and it is not understood why this occurs. More work is needed in the development of a complete measurement method. The evaluated standard deviations must still be stated as relatively small. It must also be pointed out that the spectrum similarity filter is very sensitive to using a correct reference spectrum. In the examples studied so far, a measured spectrum at the immission point has given the best selection of measurement periods. A calculated spectrum from Nord2000 has not worked as well. This is supported by the study in [9] which reached the same conclusion.

In conclusion, it must be pointed out that none of the filters limit the sound level either up or down in sound level; all filters are based on a quality. No further processing of the data, such as manual clipping of data, has been carried out. Only the filters have selected the measurement data.

A distribution that contains at least 180 selected periods meets, in any case according to the project's opinion, the requirements for measurement according to the guidance of the Swedish Environmental Protection Agency [1].

6. ACKNOWLEDGMENTS

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