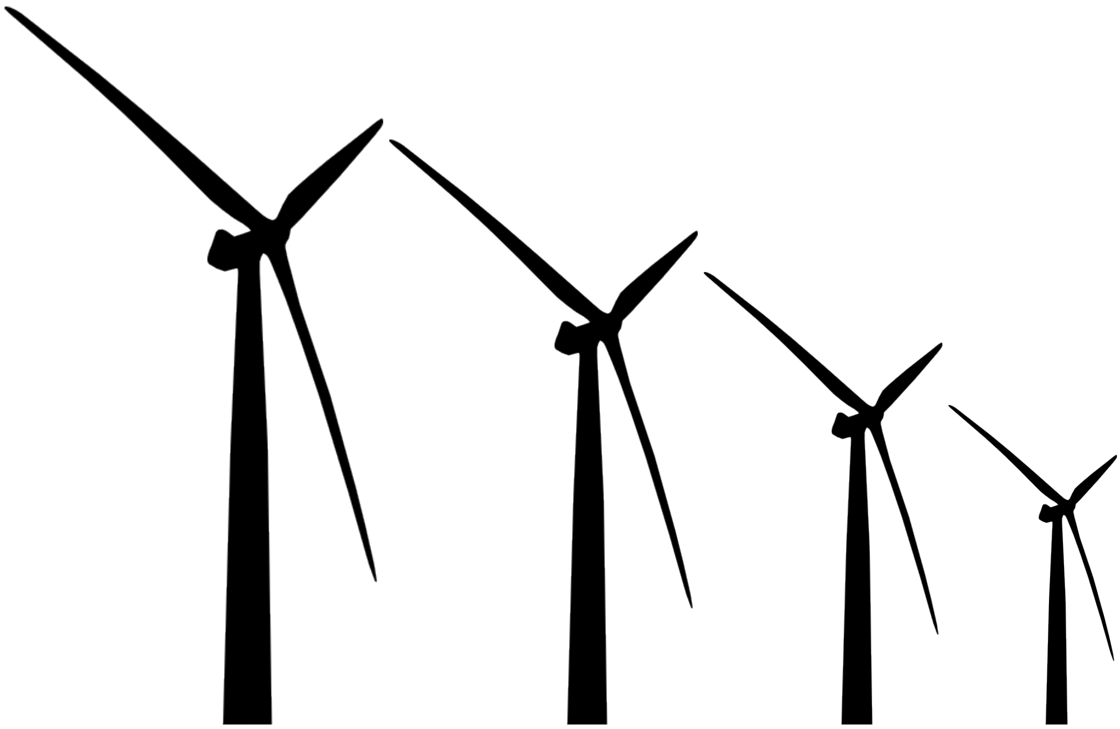

Noise Immission from Wind Farms

Master's Thesis in the Master's programme in Sound and Vibration

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Abstract

The noise from wind turbines at surrounding dwellings is not yet fully investigated with respect to noise level distribution, directivity or subjective experience. In the matter of noise, a single wind turbine is however relatively simple to describe in comparison to wind farms. In the literature it is possible to find examples of both a subjectively better situation with less amplitude modulation and a subjectively worse situation with higher noise levels. Thus there is a need to study how wind turbines standing close to each other radiate noise.

The work is based on measurements and recordings on a real wind farm with 5 large wind turbines. Additionally, the work includes development of methods to measure and evaluate immission levels from unattended measurements.

The research done in this report shows that prediction models of today may not be fully accurate when investigating wind farms. The farm investigated shows a completely different spectrum shape and higher sound pressure levels than calculated.

Contents

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1. Introduction

1.1. Thesis background

The Swedish advisory referendums on nuclear power on March 23, 1980, lead to the decision that nuclear power in Sweden should be phased out and no further nuclear power expansion was to take place. 'Linje 2' which got the most votes stated that 'Research and development of renewable energy sources shall be pursued under the leadership of the community'. This has lead to extensive research regarding renewable energy sources such as wind power.

As of today, a large wind farm near Piteå, Sweden, is in the planning stage. The farm would consist of 1101 turbines placed on an area of 15 square kilometres. However, this will only produce about the same effect as two of the ten nuclear reactors in commercial operation in Sweden today. If wind power should be a feasible alternative to nuclear power, there is a need for more wind farms.

Noise pollution from wind turbines is an important public health issue, and strict regulations regarding noise levels for nearby residents to a wind farm is a necessity. The fact that more turbines equals higher noise levels constitutes a problem, an expansion of turbines is needed but the nearby residents should not be affected. The Swedish environmental protection agency (SEPA) provides in the 'Swedish standard for wind turbine noise' regulations and prediction methods of noise from wind turbines; which estimates the noise immission levels from a wind turbine. Applying this method for a whole wind farm would give a summation of the noise immission levels for each turbine in a single immission point.

1.2. Thesis aim

The thesis aims to investigate and discuss two main points:

- How to identify wind turbine noise from unattended measurements, enabling to evaluate the immission levels
- By using the identified and measured wind turbine noise - is it possible to investigate if the prediction methods correlate with the measurements?

The work will be based on measurements and recordings on a real wind farm consisting of five turbines. The measured imission levels will be compared to the SEPA's prediction method.

1.3. Previous work

At the third international meeting of wind turbine noise in Denmark, June 2009, Bullmore et al. presented an article which stated that 'The large scale of modern wind farms means that seemingly small conservatism in the prediction of noise immission levels can translate to substantial lost development opportunities'. Bullmore further notes that a worst case assessment on a wind farm would mean that for instance all turbines experience the same wind conditions as the first upwind turbine, the ground is a hard reflecting surface and that all turbines emit higher sound power than test levels. In practice this is, according to Bullmore, an unlikely scenario.

Furthermore, Wagner (1996) shows in his book "Wind turbine noise" a dipole-like radiation pattern of a wind turbine, directly translated from the trailing edge noise of a helicopter rotor. The method of SEPA considers a pure spherical noise propagation approach of wind turbines.

In an article by Prospathopoulus (2007) the interaction between wind turbines in a farm is discussed. It is stated that depending on the wind direction and the carriage shadowing or non-shadowing of a nearby standing tower, the level of noise can increase or decrease substantially. This is due to the amount of atmospheric turbulence which the second tower is forced to operate in, a maximum shadowing between the wind turbines would increase the amplitude modulation and thereby create a higher quantity of disturbing noise.

2. Theory and background

When estimating the noise emission from a wind turbine and the corresponding sound pressure levels in nearby points, one must consider both the directivity of the sound emitting from the turbine as well as the external factors influencing the propagating sound wave. This chapter will present the main phenomena which affects the final sound pressure level in an arbitrary immission point, near the turbine.

2.1. Noise from the wind turbine

The sound power from a wind turbine emits from several different components of the structure. The table below lists the different parts and their noise characteristics to the total sound pressure level [Wag 96].

- Aerodynamic
  Noise associated with the interaction of turbulence with the blade surface. Mainly noise originated from the trailing edge of the blades
- Auxiliaries
  Noise from oil coolers and hydraulic power packs for blade pitch, air borne.
- Blade tips
  Noise radiating from the tip of the blades, connected to the tip turbulence. Noise emitted from the tip is in the region of 500-1000Hz.
- Gearbox (airborne)
  The air borne noise from the gearbox is not considered as influencing as its structure borne.
- Gearbox (structure borne)
  Mechanical noise, structure borne
- Generator
  Mechanical noise, including cooling fans etc.
- Hub
  Mechanical noise from the rotor part of the tower, the hub is located in the centre of the tower where the blades are fixed. Structure borne.

- Tower
  Structure borne sound from the tower.

As of today, according to SEPA [Nat 10], the sound emission of the blades and their aerodynamics together with the eventual mechanical noise of the gearbox; are the most contributing systems to the total sound emission level of the wind turbine.

2.1.1. Aerodynamic noise

Aerodynamic noise is the main cause of complaint regarding modern wind turbines. Its characteristics can be similar to the ones for regular wind noise and can therefore often be masked by heavy wind, but aerodynamic noise from a wind turbine can also take a "swoosh-swoosh" characteristic. This type of noise is a modulation of frequencies in the mid- and high frequency region, with its peak frequency in the region of 500-1500 Hz. This amplitude modulation increases the audibility of the noise and thus decreases the possibility of natural masking by the wind noise [Nat 10].

The modulation can be derived from the existence of turbulent flow near the blades. If turbulent eddies are apparent close to a sharp edge (e.g. a wind turbine blade) it increases the eddies efficiency as a sound source. This is referred to as turbulent boundary layer trailing edge interaction noise, or *Trailing Edge Noise* [Sal 01].

A turbulent environment, see figure 2.1, for the sound propagation can emerge in several different situations, atmospheric turbulence arises when there is a rapid fluctuation of the wind or temperature in the atmosphere. By placing the wind turbine blades on the downwind side of the tower, turbulent flows arise due to the tower shading of the wind - a rapid fluctuation of the wind speed directly behind the tower. This enables an unnecessary turbulent work environment for the wind turbine, which can result in a radiated sound with strong amplitude modulation and a large low frequency content. Most turbines of today places the blades on the upwind side of the tower to avoid this problem.

2.1.2. Mechanical noise

The characteristic of the mechanical noise, at the same noise level, from the wind turbine is often considered more disturbing than the aerodynamic noise. It mainly radiates in frequencies around 20-100 Hz. Mechanical noise from wind turbines is however rarely considered as a problem for modern wind turbines since it has been a well known problem for many years, and therefore a lot of development and research has been done on the subject [Nat 10].

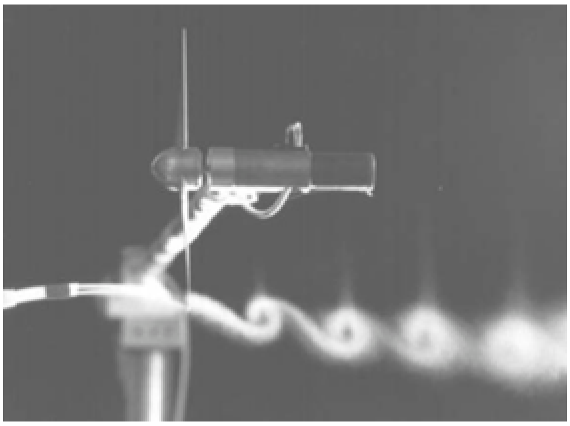

Figure 2.1.: The blades of a turbine naturally creates turbulence in the wake of the tower [Ver 03]

2.2. Outdoor Sound Propagation

Besides the natural decay with distance, there is a wide range of parameters influencing the final sound pressure level in an immission point. Highly influential factors for wind turbine noise propagation are presented below.

- Ground effect - Which is described by the reflection factor, given by the difference in ground and air impedance. The roughness of the ground is also influential on the sound propagation.
- Refraction - The refraction of the sound waves is created by the differences in wind direction and speed. In downwind conditions, the sound waves are refracted towards the ground in a more direct angle of attack which minimizes the ground effect on the sound propagation. For upwind conditions, the upward refraction causes the sound waves to approach the ground in a more gracing angle which increases the contribution from the ground effect.
- Temperature and humidity - The absorption coefficient is described by the air temperature and relative humidity, air absorption increases with frequency.
- Atmospheric turbulence - This causes variations in the phase and amplitude of the sound waves. For upward and downward refraction of the sound rays, the atmospheric turbulence causes scattering of the rays which affects the sound field. For a downward refracting turbulent atmosphere this effect reduces the interference between direct and reflected sound waves. This gives a considerable reduction in sound attenuation compared to a non turbulent atmosphere where the sound waves interfere [Sal 01].

3. Measurements and evaluation

In order to get as extensive data from the wind farm as possible, a number of measurements regarding both meteorological and acoustic conditions were carried out in the spring of 2011. The location for the measurements was in Källeberg, Falköping – Västra Götalands Län in Sweden. The nearby dirt roads have a sparse traffic situation.

3.1. Measurement site

The site consisted mainly of agricultural fields with few obstacles, the topography of the site was somewhat hilly and situated in a valley. The site consisted of five Vestas V90 2 MW turbines, 105 meters high and a rotor diameter of 90 meters, and one smaller ENERCON E-40 1MW, 65 meters high and a rotor diameter of 44 meters. The wind turbine itself is monitored by the manufacturer by the means of 10 minute averages of the produced power and wind gradient.

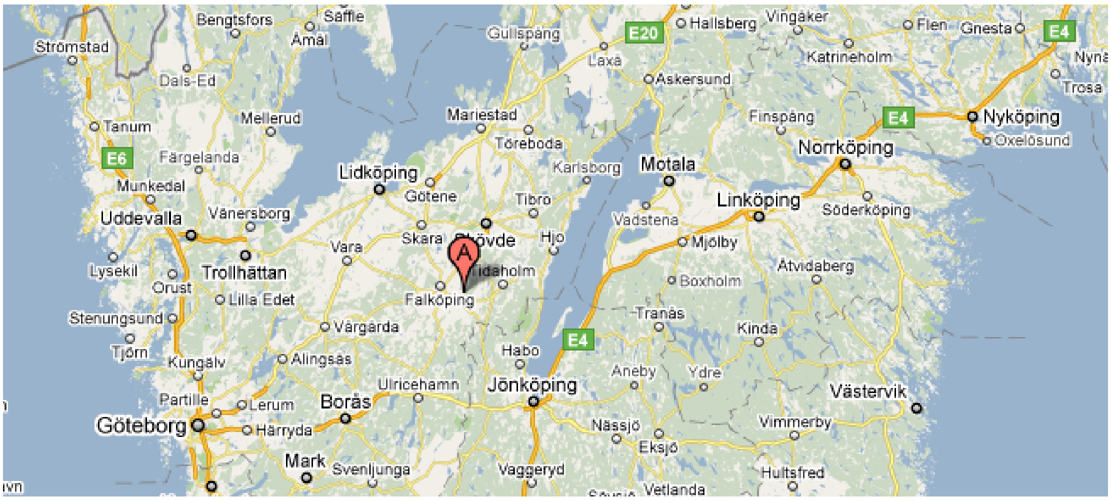

Figure 3.1.: Geographical location of wind farm

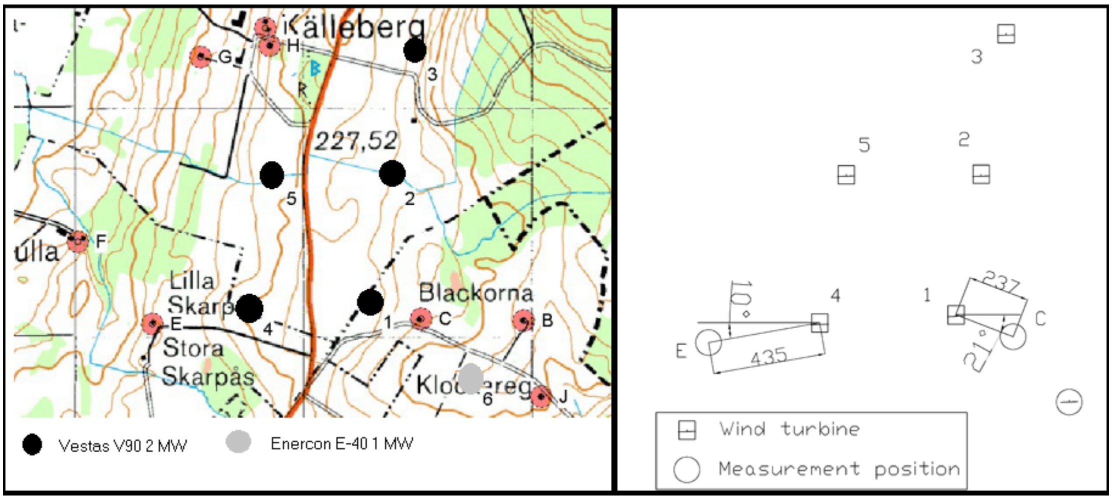

Figure 3.2.: Snapshot of wind farm

3.2. Long term immission measurements

The long term measurements was initiated on the 11th May 2011, a Norsonic Nor121 was set up at location E on the site map (figure 3.2). The equipment was triggered to record 30 seconds of the surrounding noise if the sound pressure level in the 250 Hz 1/3 octave band exceeded 42 dB for a longer period than 5 consecutive seconds, this in addition to the registering of 1/3 octave band level averages for each second.

The microphone was placed on a 2-glass window, on the upstairs floor of the dwelling. The normal of the measuring position pointed towards the nearest turbine minus approximately 10 degrees. The equipment used for this position is listed in table 3.1 below. After 12 days the hard drive of the analyser needed to be reset, consequently the outdoor microphone amplifier and capsule were switched. See table 3.2 below.

Table 3.1.: Equipment used during the in door measurements

Analyzer	Norsonic Nor121	SN: 31204
Microphone calibrator	Norsonic Nor1251	SN: 31964
Channel 1	*Outdoors*	-
Microphone amplifier	Norsonic Nor1201	SN: 26022
Microphone capsule	Norsonic Nor1230	SN: 24438
Channel 2	*Indoors*	-
Microphone amplifier	Norsonic Nor1201	SN: 30183
Microphone capsule	Norsonic Nor1230	SN: 24355

Table 3.2.: New equipment

Channel 1	*Outdoors*	-
Microphone amplifier	Norsonic Nor1201	SN: 23686
Microphone capsule	Norsonic Nor1230	SN: 48106

A Sigicom INFRA Master was set up at location C of the map (figure 3.2) – this is a simpler type of equipment which only registered the total sound pressure level at the measuring point. The microphone was placed on a 2-glass window, on the downstairs floor of the dwelling. The normal of the measuring position pointed towards the nearest turbine minus approximately 21 degrees.

Data regarding wind speed and direction for the time of the measurements was later gathered from the wind turbines and correlated with the acoustic data from the measuring equipment.

3.3. Measurement of noise emission levels

The following section is a brief summary on how to perform an emission measurement for a wind turbine according to standard IEC 61400-11. Consequently it consists of extracts from the standard IEC 61400-11, Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.

Equipment:
The measurement shall be performed using equipment in accordance to the standard.

Wind speed and direction measurements:
The wind speed and direction measurement device is mounted at 10 m height in the upwind direction of the wind turbine. The distance from the measured turbine shall be at a length between two and four rotor diameters. I.e. for a Vestas V90, which has a rotor diameter of 90 meters, the wind speed and direction measurement device shall be placed between 180 and 360 meters in front of the turbine.

Acoustic measurements:
Two different sound level measurements are performed in the same position, which is at a direct downwind distance equal to the total height - nacelle height plus rotor radius - of the tower. One measurement consists of the sound level with the turbine active and one measurement consists of the background noise, with the turbine deactivated. The measurements shall include the following information regarding the wind speed 6, 7, 8,

9 and 10 m/s at 10 m height and a roughness length of 0,05 m.

- The apparent A-weighted sound power level L_{WA}
- The one-third octave band sound power levels
- The tonality

During measurements of the background noise, efforts shall be made to ensure that the background noise measurements are representative of the background noise that occurred during the wind turbine noise emission measurements.

Evaluation:
The gathered data from the emission measurements is evaluated according to IEC 61400-11. By that, the following assumptions are made:

- The evaluation is made in 1 minute intervals
- All measurements are carried out in the same 1/3-octave band spectra interval
- The time resolution of both the sound and meteorological data is based upon the same and even 1 minute interval.

With permission, the evaluation files used are signed Pontus Thorsson, Akustikverkstan. Modification of the original time resolution in the file is made. This in order to alter the time resolution by command and compare data of both 1 and 10 minute averages, in this case.

The fileset lets the user evaluate eventual disturbances according to notes and spectras of the measurements, and eliminate those minutes that is considered to be not valid. By this, the only data evaluated in the operation is truly correct and valid data. This representing both the actual measurement as well as the background noise.

Meteorological data is also synchronized with the acoustic measurements, telling the user if the measured sound data corresponds to valid weather circumstances – regarding wind speed, temperature and air pressure.

By these means, evaluated and presented data by the fileset corresponds to the sound power level of the wind turbine considered at all wind speeds that have measurement data that is valid according to the standard.

3.3.1. Proceeding of measurements and sight descriptions

Equipment used for each measurement can be seen in table 3.3.

Table 3.3.: Equipment used during all five measurements

Analyzer	Norsonic Nor140	SN: 1403782
Microphone amplifier	Norsonic Nor1209	SN: 13098
Microphone capsule	Norsonic Nor1225	SN: 106957
Microphone calibrator	Norsonic Nor1251	SN: 32505
Weather station	Reinhardt MWS 5MV	SN: 1017775

The actual measurements inferred that the microphone was placed strictly downwind from the tower, on a hard board of 0.95x1.05 square meters and at a distance from the tower corresponding to the tower height plus the rotor radius. See figures in table 3.4. By the means of the standards described in the previous section, 6 dB was withdrawn from the measured immission levels. For each measurement all other wind turbines than the studied were switched off.

Källeberg 1313-38440 - 1:

Table 3.4.: Photos from measurements of Källeberg 1314, 2011-05-25

Wind turbine Källeberg 1313 was measured the 24th of May 2011. The microphone and analyser were placed 150 meters downwind of the wind turbine, the weather station 215 meters upwind. The weather was cloudy with decreasing air pressure - finally resulting in rain. The measurements of the wind turbine started at 09:10 and lasted for 70 minutes. Directly afterwards the background noise levels were measured for 80 minutes. During the measurements of the background noise the rain started about 20 minutes in and lasted for about 25 minutes.

The surroundings of the measurements can be described as flat fields with some growth. In the position of the microphone the grass were of about 30 cm of height - which gently was stomped flat to the ground, though still may causing some disturbances to the measurements. The wind direction altered some degrees during the proceedings, though still within range of standards. The roughness length was estimated to 0,05 meters.

Källeberg 1314-38441 - 2:
The wind turbine Källeberg 1314 was measured in the morning of 25th of May 2011. Microphone and analyser were placed 162 meters downwind, the weather station 220 meters upwind. Measurements of wind turbine started at 09:17 and lasted for 90 minutes. Disturbances during the measurement were caused by rain of 5 minutes and an owner of the wind turbines for about 10 minutes. A total of 15 minutes possible disturbance. The background noise measurement was undisturbed except for the strong wind and the fluctuations of it. Background noise measurement started 10:56 and lasted for 90 minutes.

Surroundings was open fields with minimal amount of growth, not causing any disturbance. Though, some trees in the area may influenced some deviations in the measurements because of the heavy wind at the day. The roughness length was estimated to 0,05 meters.

Källeberg 1315-38442 - 3:
Wind turbine Källeberg 1315 was measured the 30th of May 2011. The weather station was placed 220 meters upwind, microphone and analyser 140 meters downwind in a low gradient slope. Terrain could be considered as quite lively, with growth and trees in the surroundings. Following was twitter of birds and some disturbances of heavy trucks in the area.

The measurement of the wind turbine was started at 10:55 and lasted for 80 minutes. Subsequently the measurement of the background noise was started at 12:30 and lasted for 80 minutes. During this measurement both air traffic and heavy wheel traffic occurred and which may influenced the measurements. The roughness length was estimated to 0,05 meters.

Källeberg 1316-38443 - 4:
The emission levels of wind turbine Källeberg 1316 (wind turbine n:o 4 in figure 3.2) in Källeberg Vindpark was measured during the day of the 17th of May 2011. By the means of acceptable wind and weather, the circumstances were considered to be within a reasonable range of the standards. The weather station was placed 230 meters up-

wind, microphone and analyser 150 meters downwind. Measurement of the wind turbine started at 13:10 and lasted for 90 minutes. After about 60 minutes a tractor started ploughing the field - lasted for 15 minutes. Otherwise no particular disturbance. Subsequently the background noise measurement was started and lasted for 70 minutes. No particular disturbances except for a small amount of lightweight traffic in the area. The surroundings can be described as a homogeneous field without growth. Small gravel road about 100 meters away from the microphone with light traffic. The roughness length was estimated to 0,05 meters.

Subsequent to this an additional measurement was made by turning on wind turbine 1313 (1) in the same farm. Same positions and set-up as described above, though with two (1313 and 1316) wind turbines running. This by the means of interpret eventual influence of each turbine to the total radiated sound power. No disturbances except for the light traffic.

<u>Källeberg 1317-38444 - 5:</u>
Wind turbine Källeberg 1317 was measured the 25th of May 2011. The microphone and analyser were placed 150 meters downwind, the weather station 200 meters upwind. The measurement of the wind turbine was initiated at 14:10 and lasted for 100 minutes. The microphone position was fairly close to a small gravel road with some light traffic that caused unwanted noise. Further, next to the road a parkway of trees moved quite intensely because of the heavy wind of the day causing some disturbances as well. The background noise measurement was started 16:04 and lasted for 80 minutes. Again, some disturbances by traffic as well as some air traffic. The surroundings were otherwise mainly flat fields without growth. The roughness length was estimated to 0,05 meters.

4. Data processing - Spectral analysis

For the long term measurements, the recordings consisted of 1/3 octave band data for each second during a period of several weeks. In order to be able to identify wind turbine noise from these unattended measurements there was a need to sort out irrelevant noise.

The following method of identifying wind turbine noise from unattended measurements was developed by the authors, supervised by Pontus Thorsson, for this thesis. The method is divided into three main sections:

- Calculating the expected SPL at the immission point, based on the previously performed emission measurements.
- Comparing the calculated SPL at the immission point with the actual measurement – agreeing results indicating possible wind turbine noise.
- Evaluating the possible wind turbine noise

Thus answering the question – is it possible to identify wind turbine noise from unattended immission measurements?

4.1. Calculating the expected SPL at the immission point

A reference curve was calculated by estimating the sound pressure level in each 1/3 octave at the investigated immission point. This was done by using the measured sound power level for each turbine ($L_{WA,turbine}$), described in chapter 3, calculating what sound pressure level it would result in at the immission point (Equation 4.1), and finally adding the contribution for all turbines to a total SPL (Equation 4.1).

$$L_{p,turbine} = L_{WA,turbine} + 10 \cdot log_{10}(4 \cdot \pi \cdot r^2) - 0.005 \cdot r \quad (4.1)$$

$$L_{p,tot} = 10 \cdot log_{10} \sum 10^{L_{p,turbine}/10} \quad (4.2)$$

4.2. Comparing the calculated SPL at the immission point with the actual measurements

Preparatory work

In order to make a relevant comparison between the calculations and the measurements, irrelevant frequencies need to be excluded from the data before the actual comparison.

This is done by evaluating the emission measurements of the wind turbine and finding a reduced frequency spectrum which represents actual wind turbine noise. This by using the most contributing 1/3 octave band frequency as a starting point, then adding the levels from the immediately surrounding 1/3 octave band frequencies until a total sound power level within a range of 1 dB from the total sound power level of the turbine is achieved. This procedure is illustrated in figure 4.1. Since the shape of the spectrum is of interest, not the total SPL, all data was normalized to zero around the centre frequency.

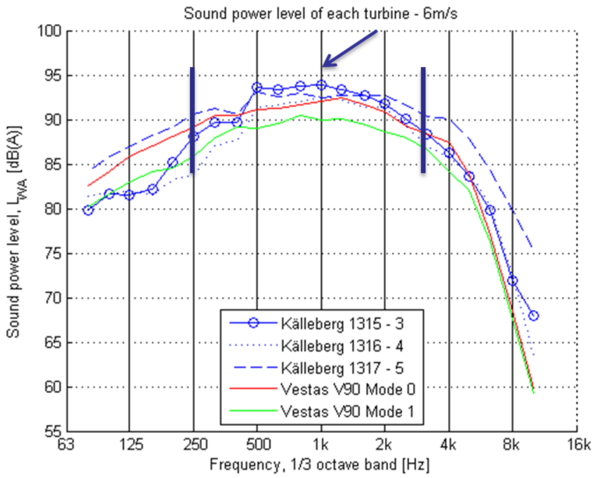

Figure 4.1.: Example of the discernment method for wind turbine noise

<u>Anemometer data</u>

To get information regarding the meteorological circumstances in the wind farm, reference data of the wind speed and direction as well as produced power for each turbine in the farm was provided by Vestas. The reference data available is presented as 10 minutes averages. Averaging of acquired one second data from the sound level measurements though, was made for 1 minute intervals. The one minute interval was chosen due to the assumption that the averaged weather conditions during one minute conforms to the averaged weather conditions during ten minutes.

<u>Identifying possible wind turbine noise</u>

If the spectral data of the 1 minute intervals matches the reference curve described above within the total range of the investigated 1/3 octave band levels, +/-1 dB, we are considering the minute as possible wind turbine noise. The suspect times are then correlated with meteorological data from the wind turbines.

4.3. Evaluating the possible wind turbine noise

Parallel to the constant one second 1/3 octave band level registration of the noise at the site, sound recordings of possible wind turbine noise was performed by the same measurement device - as described in 3.2.

The actual sound recordings was processed to work as a "cheat-sheet" for the spectral analysis results. This was done by a manual evaluation of the 847 recordings, ranging in length from 10 seconds to 40 seconds. The evaluation consisted of listening to each recording and grading the amount of wind turbine noise present in each sound file – from 1 to 5.

1. No wind turbine noise, a lot of disturbance such as rain etc.
2. Maybe wind turbine noise, no amplitude modulation. Bad.
3. Small amplitude modulation. Reasonable/good recording with a lot of background noise.
4. Somewhat more clear amplitude modulation. Small background disturbances.
5. Very good recording! Distinct amplitude modulation with low impact of background noise.

Since it was recorded by the same measuring device, the graded sound recordings correlate to different spectral analysed minutes from the long term measurements, it is now possible to evaluate if the minutes that are identified as wind turbine noise by the spectral analysis also have a high grade – i.e. actually are wind turbine noise.

Evaluating the spectral analysis with sound recordings

In order to be able to evaluate how well the spectral analysis works, the irrelevant data - i.e. spectral "hits" which is not possible to listen to, due to the fact that the 42 dB trigger described in 3.2 was not activated - needs to be sorted out, this in order to only investigate those minutes that both are identified as wind turbine noise by the spectral analysis and that there is an actual recording of.

Each sound file was stored to the measuring devices' hard drive at a certain time, since no sound file has a longer duration than 40 seconds the recording either correlates to the same, the previous, or both minutes in the spectral analysis. Therefore, any minute in the spectral analysis which is not correlating to the same or previous minute as a sound recording was sorted out.

In the simplified example shown in table 4.1, the table shows that only minute 1,4,5,8 and 9 will be used when evaluating how well the spectral analysis works. This since these

Table 4.1.: Sorting of sound recordings

Minute	1	2	3	4	5	6	7	8	9	10
Sound recording	x	-	-	x	x	x	-	x	x	-
Spectral analysis	x	x	-	x	x	-	x	x	x	x
Analyzed?	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No

are the only minutes that are identified as wind turbine noise by the spectral analysis that there is an actual sound recording of. The comparison from table 4.1 was done for all 847 recordings and its correlating minutes and spectral analysis hits.

This method of evaluation has given detailed information regarding several different circumstances at the site during the long term measurement. It also sorts out anything that in spectral shape resembles what wind turbine noise at the immission point looks like according to SEPA, which now can be compared to the graded sound recordings. To summarize, this method gives:

- Which times are suspected wind turbine noise
- A sound recording of the suspected wind turbine noise
- Evaluation of the suspected wind turbine noise, based on a grade of the sound recording
- Meteorological data regarding wind direction for the suspect wind turbine noise
- The amount of electrical power produced by the wind turbine during the time of the suspect wind turbine noise - which can be translated to wind speed

5. Results

In this chapter the results from the evaluations and data processing are presented. The first section describes the results from the emission measurements of the wind turbines at Källeberg. The spectral analysis and gradings can be seen in the following chapter. Furthermore, long term measurement data and wind gradients are presented together with comments.

5.1. Emission measurements

The emission measurements according to IEC 61400-11 is presented below in table 5.1. Results commented with * relies upon two samples, according to the standard at least three samples is needed. A single dash means that no samples were collected for that particular wind speed.

Table 5.1.: Results of the emission measurements of the wind farm at Källeberg

Wind turbine	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	
Källeberg 1	-	102,9	103,0	102,9	103,0	dB(A)
Källeberg 2	101,5*	102,5	102,5	102,2	102,1	dB(A)
Källeberg 3	103,0	103,1	103,3	103,6	-	dB(A)
Källeberg 4	101,7	102,3	102,3	102,1	101,9*	dB(A)
Källeberg 5	104,5	105,2	104,8	105,4	105,0	dB(A)
Källeberg 4+1	-	103,5	103,5	103,4	103,2	dB(A)

Measurement "Källeberg 1+4" was performed as an emission measurement of turbine 4 with an additional turbine operating in the wakes of turbine 4 still active. This to investigate whether the influence of the wakes could increase the sound pressure level at the measurement point - compared to the calculations. The measured sound power level of the combined turbines is equivalent of a free-field value 47,5 dB(A) at the immisson point by SEPA's model. By adding the sound power levels of the emissions measurements of turbine 1 and 4, one should expect 47,0 dB(A) as the most.

5.2. Spectral analysis

The results of the gradings, evaluation of reference curves and correlation of wind data is presented in this section.

5.2.1. Reference curve of measurements

Figure 5.1 shows how well the spectral analysis works, the results are based on a reference curve calculated from the in situ emission measurements of the wind turbines, described in chapter 3. The sound identified as wind turbine noise is then correlated with its grading as described in chapter 4 and presented in the figure.

The sound recordings which are most frequently identified as wind turbine noise have been given the grade 2, this implies that spectral analysis using a calculated reference curve from SEPA:s prediction model mainly identifies noise where there is no amplitude modulation present.

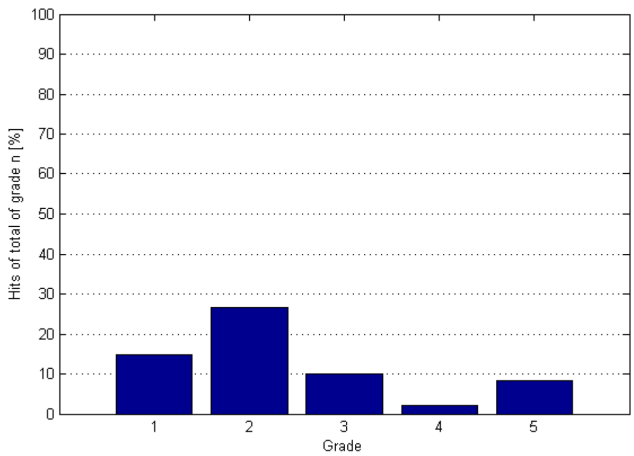

Figure 5.1.: Grades for the identified wind turbine noise

5.2.2. Reference curve of grading

Since the results from the spectral analysis were not satisfying, it was decided that a new reference curve was to be calculated. This time the sound recordings that was given the highest grade (i.e. clearly showing wind turbine noise) was to be used as a template for the new reference curve. This with the aim of investigating if the noise of the wind farm at the sight has a certain characteristic.

In order to get a new reference curve based on the recordings with the highest grade, a FFT was made on the parts of the sound files which were manually identified as the most audible wind turbine noise. The result from this are presented as the thin lines in figures 5.2 and 5.3.

As can be clearly seen in figure 5.2 and 5.3, the reference curve calculated from the measurements does not at all resemble the thin lines which represent the most audible wind turbine noise. By creating a new reference curve based on the gradings it is possible to see if spectral analysis works using a “correct” spectrum. Worth to notice is that the low frequency region of the immission measurements shows a clear resemblance over a majority of the samples. In the upper high frequency region the deviation between the samples increases.

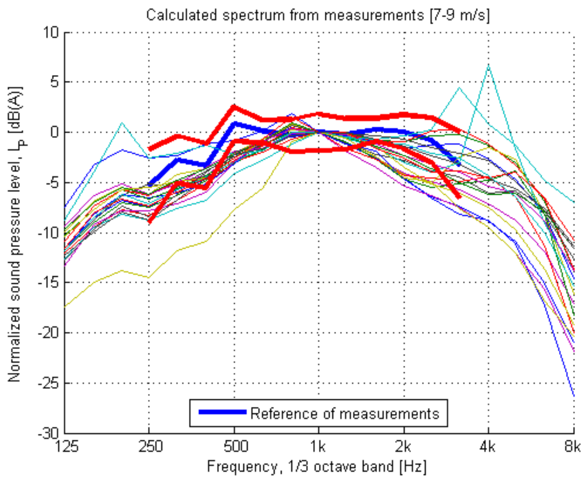

Figure 5.2.: Reference curve based on calculations compared to recordings with grade 5

Figure 5.4 shows that when using a reference curve based on the most audible amplitude modulated wind turbine noise, it identifies the sound recordings given the grade 4 and 5 as most likely to be wind turbine noise. In other words, there is a characteristic of the noise from the wind farm at this sight which can be identified.

5.2.3. How much of the total amount of noise is wind turbine noise?

With the reference spectrum calculated using the grades, it is now possible to evaluate how much of the total recordings that the spectrum analysis identifies as wind turbine noise:

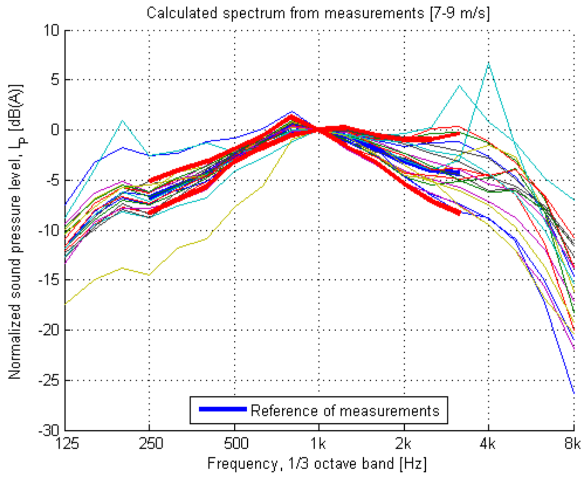

Figure 5.3.: Reference curve based on recordings with grade 5

The histogram in figure 5.5 shows that the maximum allowed level from wind turbines, 40 dB(A), is exceeded nearly 6% of the total time (4 hours in total during the week) – this only considering the noise that is identified as wind turbine noise.

The equivalent level for the identified noise is 40.5 dB(A).

5.2.4. Wind data

The polar diagrams in this section shows the meteorological conditions for the wind turbine noise, when the sound pressure level exceeds 40 dB(A). Figure 5.6 shows the produced power for the nearest standing wind turbine and figure 5.7 shows the total sound pressure level at the immission point. Due to availability from the wind turbine manufacturer, all plots are based on 10 minute intervals. Note that figure 5.7 indicates sound pressure levels up to 60 dB(A) from the wind turbines at the immission point, though we will emphasize that this is mainly caused by the background noise. The spectral analysis find resemblance with the wind turbine noise and indicates that the turbines is in fact audible even if they do not contribute to the total sound pressure level.

The figure 5.8 shows the total distribution of the wind direction during the whole period. The angle for each mark represents the wind direction - the measuring position is located at 260 degrees.

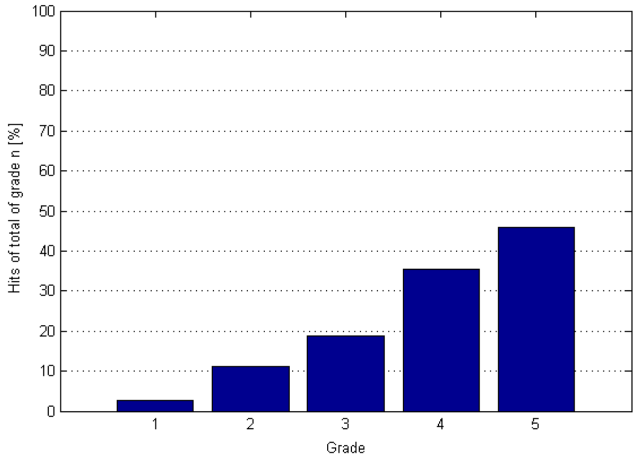

Figure 5.4.: Grades for the identified wind turbine noise, new reference curve

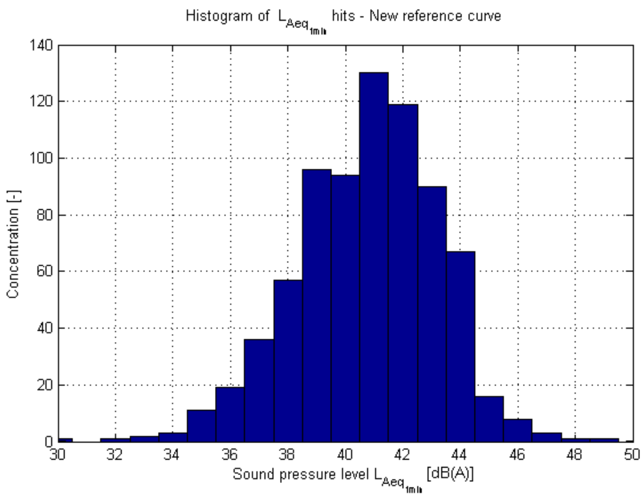

Figure 5.5.: Histogram for the investigated period, using the new reference curve

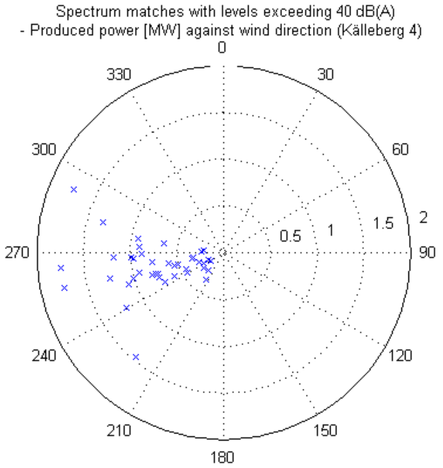

Figure 5.6.: Polar diagram of the produced power for wind turbine 4, and corresponding wind direction - Identified wind turbine noise for the period 2011.05.11-2011.05.17

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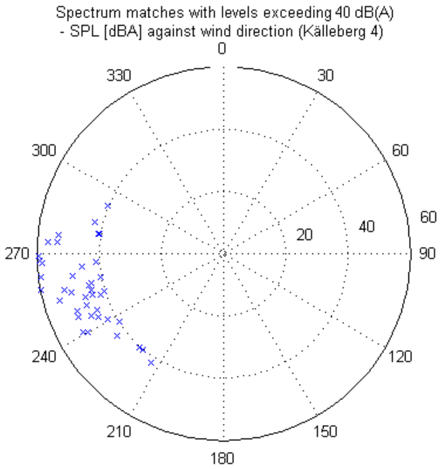

Figure 5.7.: Polar diagram of the SPL at the immission point, and corresponding wind direction - Identified wind turbine noise for the period 2011.05.11-2011.05.17

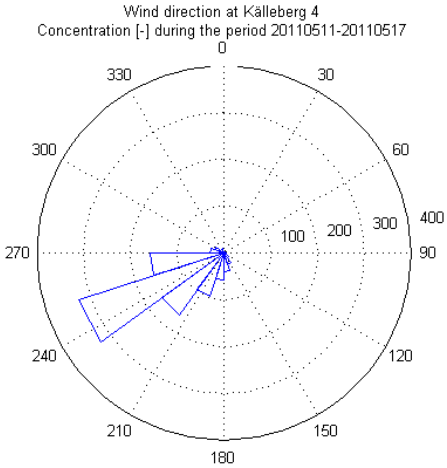

Figure 5.8.: Polar diagram of the wind direction for the period 2011.05.11-2011.05.17

6. Discussion

In this report we have developed a method to identify wind turbine noise from unattended immission measurements. This has been done both based upon calculations but also using frequency analysis of actual sound recordings. We will in this chapter discuss and summarize the results in this report.

6.1. Why does the calculated and measured values not correlate at the immission point?

It is clear that the spectrum at the immission point is not what could be expected when considering the measured emission values from the turbines. That there is wind turbine noise present is proved by the sound recordings. However, at this site, the frequency spectrum shape substantially changes on a distance of 435 meters from the nearest turbine - which can be compared to the 150 meters on which the emission levels was measured. The predicted maximum sound pressure level from wind turbines - 40 dBA - is also exceeded at such a great number of times, for recordings with clearly audible wind turbine noise, that it can not be disregarded as just high influence of background noise.

The fact that the long term measurement from May of 2011, see chapter 5, shows a lot of "hits" during a relatively short period of time, and that the long term measurement from January of 2011, presented in Appendix A, shows quite few "hits" during a longer period of time implies that the meteorological conditions and propagation effects such as ground impedance (snow cover) has a clear impact on the spectrum shape of the wind turbine noise. As can be seen in section 5.2.4, both long term measurement were performed during quite strong wind at roughly the same wind direction, residents nearby have noted that wind turbine noise was present during both measurement, the only known difference is the climate.

In this thesis emission measurements were conducted for each turbine in the wind farm. In addition to this, the emission from turbine 4 was measured with turbine 1 active; i.e two turbines measured as one (as can be seen in table 5.1).The combined measurement shows a slightly higher sound power level from turbine 4 than what could be calculated using SEPA:s model, with the contribution from turbine 1 set aside. The measurement shows 0,5 dB higher values than calculated, which is in the margin of error. However, the calculation implies downwind conditions from both turbines, which is false.

This situation can, according to [Pro 05], cause a significant increase in sound emitted from the turbines, compared to if they would be active in a more laminar environment.

The aspect of differences in air impedance and its impact on sound propagation of wind turbine noise is not investigated in this thesis. It cannot be ruled out that this may influence the sound propagation in this specific area. The investigated site do have favourable conditions for large fluctuations in the air layers, with densely placed turbines and hilly surroundings.

6.2. Is it reliable to measure the emission levels according to standard and use them in a prediction method such as SEPA:s?

By using actual emission measurement data for each turbine and incorporate it in a calculation model as SEPA's or Nord2000, one will be able to calculate a more reality adapted situation for the nearby dwellings. Even though this procedure has its deficiencies, it is the authors opinion that this is more applicable in real life situations than the often contaminated immission measurements at an investigated dwelling.

The uncertainty of a calculation model has to be taken into account for every calculation, but by using real evaluated emission data of the turbines some of these uncertainties will be eliminated.

The emission measurements performed during this thesis shows that even if the wind turbines at the site have the same technical specifications, they differ in resulting sound power levels and frequency spectrum. This depends upon both the evaluation of the emission measurements but also the individual components of the turbines.

However, there is also a possibility that wind turbines cannot be modelled as omnidirectional point sources. A more complicated source model which can describe both temporal, i.e. amplitude modulation, and directional effects of wind turbines in a more realistic way, should also give more realistic results.

7. Conclusions

In this report we have developed a method to identify wind turbine noise from unattended immission measurements. This has been done both based upon calculations but also using frequency analysis of actual sound recordings, which have been subjectively evaluated.

When planning and constructing wind farms, one should not completely rely upon the model of SEPA - which models the turbines as omnidirectional point sources, unaffected by i.e. atmospheric turbulence - and interpret the method as sound levels that would result from an actual immission measurement.

This thesis concludes that the turbines have a different frequency spectrum at a near-field (emission) point than at a far-field (immission) point. The reason for this is probably a combination of the change in angle, distance and environment between source and receiver in near and far points. SEPA's model for describing noise of wind farms is in those terms not fully accurate. In sensitive areas where one could predict that the model itself may be too kind in its predictions, such as over sea and wind sheltered areas - perhaps the solution would be to be aware of the problem and strive to avoid it.

As of today, complaints regarding excessive noise from wind farms can be read about in the newspapers. It is not always a problem, but it occurs from time to time, sometimes somewhat unexplained. Due to this, together with the research in this report, one may want to further investigate the area of prediction of wind farm noise.

Based on this report and research it is the authors opinion that the wind turbines in the investigated farm are likely to be more affected by its surroundings than predicted in the calculation models of today. This report is just a brief view and research of the area and we encourage further research and development on the topic.

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A. Appendix

Long term measurements were also executed for a period of three weeks during January 2011. Since measurements on wind turbines are not considered valid when there is snow present on the ground, the data gathered from this was mainly aimed to be used as aid in building the prediction models.

The figures A.1, A.2, A.3 and A.4 each represent the same plots as described in section 5.2.4 but for the period of 2011.01.09 - 2011.01.17.

Another measurement was also performed during the late of May 2011, these mea-

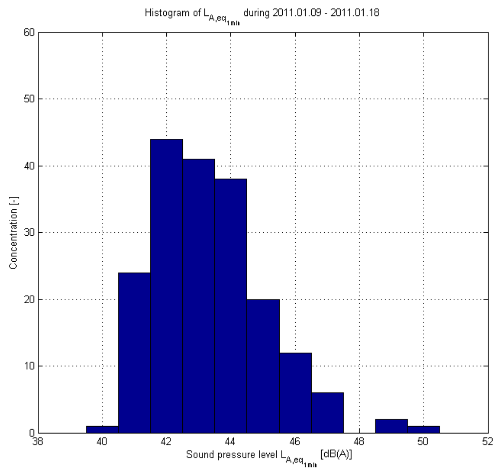

Figure A.1.: Histogram for the period of 2011.01.09 - 2011.01.17, using the new reference curve

surements were supposed to be registered by a sound recorder as described in chapter 3, but due to excessive sound levels and "cutting" in the recordings, they were considered impossible to grade.

The figures A.1, A.2, A.3 and A.4 each represent the same plots as described in 5.2.4 but for the period of 2011.05.23 - 2011.05.25.

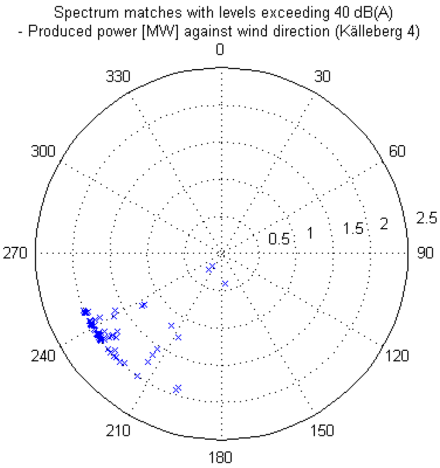

Figure A.2.: Polar diagram of the produced power for wind turbine 4, and corresponding wind direction - Identified wind turbine noise for the period 2011.01.09-2011.01.17

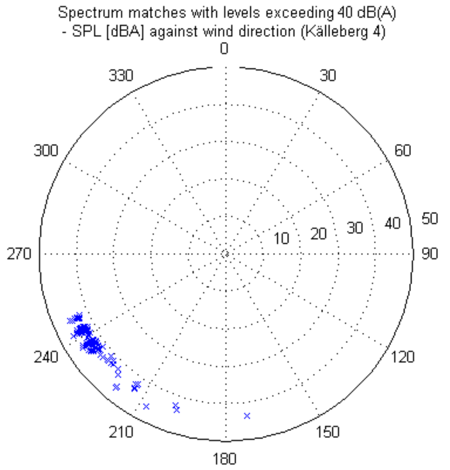

Figure A.3.: Polar diagram of the SPL at the immission point, and corresponding wind direction - Identified wind turbine noise for the period 2011.05.11-2011.05.17

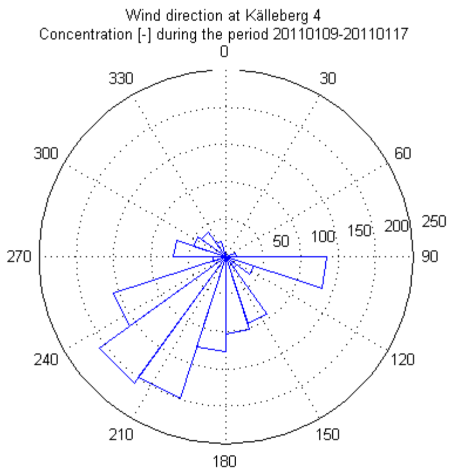

Figure A.4.: Polar diagram of the wind direction for the period 2011.01.09-2011.01.17

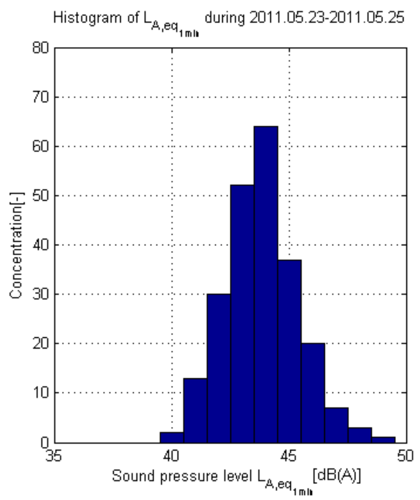

Figure A.5.: Histogram for the period of 2011.05.23 - 2011.05.25, using the new reference curve

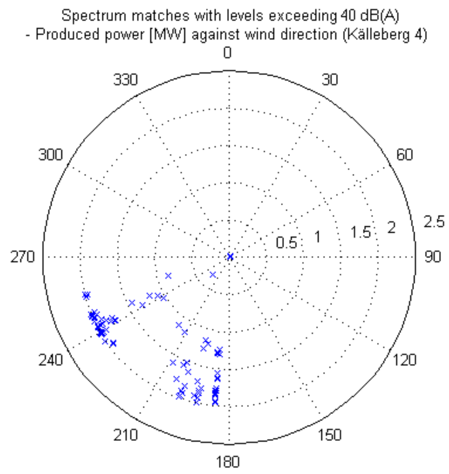

Figure A.6.: Polar diagram of the produced power for wind turbine 4, and corresponding wind direction - Identified wind turbine noise for the period 2011.05.23 - 2011.05.25

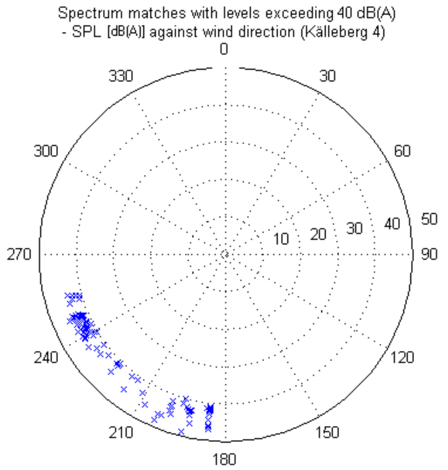

Figure A.7.: Polar diagram of the SPL at the immission point, and corresponding wind direction - Identified wind turbine noise for the period 2011.05.23 - 2011.05.25

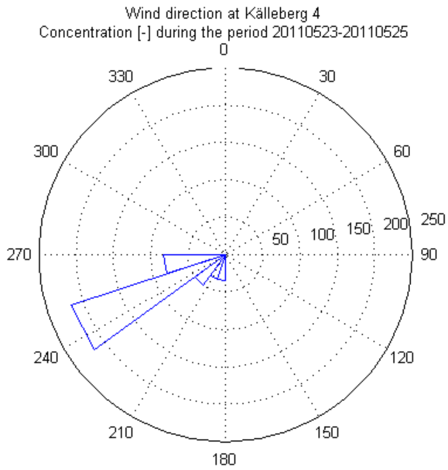

Figure A.8.: Polar diagram of the wind direction for the period 2011.05.23 - 2011.05.25