Halmstad University

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Noise Spectra from Wind Turbines

L.B. Baath*

Halmstad University, PO Box 823, SE-301 18 Halmstad, Sweden

Abstract

This paper presents observations of audio noise in frequency range 20-20 000 Hz from wind turbines. The observations were performed around the theoretically calculated 40 dBA noise perimeter around the wind turbine farm at Oxhult, Sweden. This paper describes a newly designed and constructed a field qualified data acquisition system to measure spectra and total noise level of sound from wind turbines. The system has been calibrated at SP Borås. It is shown that it has a flat frequency response and is linear with amplitude and time.

The total noise level (as integrated 20-20 000 Hz) is shown to be below 35 dBA (below the reference background noise at 36 dBA) at a 10m altitude wind speed of 4-5 m/s. The measurements were made along the theoretical 40 dBA border at 8 m/s.

It is concluded that the theoretical 40 dBA border seems reasonable calculated if the manufacturer specifications are used to extrapolate the sound level to correspond to 8 m/s at 10m. Our data indicate that a simple sound propagation model is sufficient since the sound level is more affected by the nearby environment than the large scale forest structure. Also, the large scale forestry structure is bound to change with time and the error bars of measurements on total sound level are about 1 dBA, which is larger than any fine tuning with a more sophisticated model. More care should be taken to model the reflections from walls and other obstacles close to the microphones.

The distribution of the spectral noise level around the turbine farm suggests that the noise originates from individual wind turbines closest to the measurement location rather than from the wind turbine farm as a whole. The spectra show narrow band spectral line features which do not contribute significantly to the total noise at this level. The narrow band features are only detectable at very long integration time and at 1 Hz spectral resolution. The spectral features are typical to originate from mechanical noise.

The spectral acquisition method described in this paper can be used as a field qualified system for sound measurements in forest areas. The high spectral resolution is a viable remote diagnostic method for mechanical faults in the turbine machinery. Future work will concentrate on these two areas.

Keywords:

wind turbine, noise, spectrum

1. Introduction

Sound from wind turbines has been investigated for some years now. It is perceived as a problem mainly in Sweden and as yet less of a problem in the rest of Europe. Research on noise from wind turbine has extensively been presented. Good summaries can be found in two theses [1, 2]. These show clearly the state of the art knowledge about the perception and measurement of noise from wind turbines in rural landscape. Such measurements have not been done in forestry areas

though, and this paper present one of the first substantial investigation of sound from wind turbines in a dense forestry area. There the propagation of sound and the background noise is significantly different. The forest of Sweden is also substantially different from continental Europe. The Swedish forest is mainly planted for the wood industry. It consists dominantly of pines of the same age, and therefore of the same height. There is very little hardwood areas. We recommend reading Vindforsk report 6:08 [3] for further background.

The Swedish Environmental Protection Agency [4] has issued recommendations for the level of sound from wind turbines near inhabited areas. The limit is set to 40

*Corresponding author. Tel.: +4635167197

Email address: lars.baath@hh.se (L.B. Baath)

dBA sound intensity from the turbine at a dwelling measured at a wind speed of 8 m/s at 10 m height near the wind turbine, integrated over 20-20 000 Hz and measured over 4 hours. The limit is lowered to 35 dBA in specifically sensitive and dedicated areas such as natural parks. The limit is also lowered to 35 dBA if obvious tones are present in the spectrum. It is up to the owner of the turbine to show that this limit is not breached. The 40 dBA limit is for the wind turbine noise by itself, and therefore it is important to separate the wind turbine noise from other ambient noise, e.g. leaves, trees, birds and cars.

The standard accepted method to measure noise level in Sweden is with a sound level meter. The microphone is mounted on a solid plate placed on the ground for emission measurements or on the outside wall of a house for dwelling imission measurements. The sound level meter measures the level in dBA, dBC or dB linear integrated over a frequency range usually 63-8 000 Hz. The calibrated noise meters are expensive and the low cost versions are usually not very reliable. The meter should be tested and calibrated before use. Note that the mounting on a hard plate will add about 6 dB noise due to reflection on the plate. Usually the audio data are integrated directly in the meter. Time sampling of audio data can also be done [5]. The time sequenced data are then Fourier transformed to form a spectrum of the audio signal from the source.

The human perception of sound differs between individuals [6]. It is probable that some, up to 15% of humans may perceive noise from wind turbines at levels much lower than 40 dBA. However, it is standard to set the limit at the level where 10-15% of humans may perceive a disturbance. The human mind is extremely good at detection patterns, so also in sound. The swishing noise from wind turbines originates mainly from the downcoming tip of the wings [7] and can be detected at levels 10 dB below (or 10% below) the ambient noise [8]. It is however judged that the 40 dBA immission level is just and will remain the agreed noise limit near habitats.

This study was initiated to develop an objective method to measure sound levels in forest. This paper presents results and techniques from measurements of spectra and broadband noise in the audible range around a wind turbine farm in the south of Sweden.

The wind farm studied here is at Oxhult, Laholm, Sweden. It consists twelve Vesta V90 turbines with 45 m wings. The hubs are at 105 m above ground. The farm is placed in an industrial pine forest at geodetic coordinates 56°26'54"N 13°16'06"E.

. The pines are of the same age and all about 20m

in height. We also measured the undisturbed sound at a similar area without wind turbines. This area was at Stjärnarp, Halmstad, Sweden.

2. Noise sources

Sound is a pressure wave with a rms pressure of P . The equivalent sound level is proportional to the square of the pressure, usually described as referenced to a reference level P_{ref} of 20 μPa . The equivalent sound level is then given as amplification in decibel (dB) as:

$$L_P = 10 \cdot \log_{10} \left(\frac{P^2}{P_{ref}^2} \right) \quad (1)$$

The sound recorded is a time-dependent voltage $V(t)$, which is proportional to the sound pressure P as:

$$V(t) = P(t) \cdot g \quad (2)$$

where g is a gain factor for the instrument. The gain factor is usually frequency dependent $g(f)$.

The sound recorded has multiple origins which we, for a forest with a wind turbine, at time t and position r attributes to the sum of the direct noise from the wind turbine (V_t), an indirect reflected signal from the turbine (V_{tr}), the scattered noise from the wind turbine (V_{ts}), the diffuse background noise (V_{dbg}), noise from local sound sources (V_{loc}), and flow induced noise on the microphone (V_{airfl}) and noise generated from the turbulence in the atmosphere (V_{airt}). The total time dependent recorded voltage can therefore be written as:

$$V_{tot}(t) = V_t(t) + V_{tr}(t) + V_{ts}(t) + V_{dbg}(t) + V_{loc}(t) + V_{airt}(t) + V_{airfl}(t) \quad (3)$$

This can be Fourier transformed to frequency space as a complex voltage:

$$V_{tot}(f) = V_t(f) + V_{tr}(f) + V_{ts}(f) + V_{dbg}(f) + V_{loc}(f) + V_{airt}(f) + V_{airfl}(f) \quad (4)$$

The intensity spectrum of the sound can be calculated as

$$S_{tot}(f) = V_{tot}(f) \cdot V_{tot}^*(f) \quad (5)$$

or,

$$S_{tot}(f) = S_t(f) + S_{tr}(f) + S_{ts}(f) + S_{dbg}(f) + S_{loc}(f) + S_{airt}(f) + S_{airfl}(f) + noise \quad (6)$$

Noise includes the cross-correlation terms.

The equivalent sound level from the wind turbine is the sum of all parts as:

$$S_t(f) = S_{tm}(f) + S_{tw}(f) + S_{tr}(f) \quad (7)$$

S_{tm} represents the noise from the turbine machinery, e.g. tones from fans or gear box. S_{tw} represents the noise from the wings, usually heard as a swooshing sound, and S_{tr} represents other undefined noise from the turbine. Reflections of the turbine (and other external noise) from nearby walls are as standard assumed to be half of the noise level, or an assumed noise level increase of 3 dB.

3. Observations

3.1. Data acquisition system

The audio data are recorded as digitized time sequence. Two channels are recorded, one with a microphone with a wind protection muff, the other without wind protection. The microphones were mounted at the same 2 m level at 60 cm from each other.

Two DBX-RTA-M measuring microphones have been used, one for each channel. These microphones has a very straight spectral response between 20 20 000 Hz. The reception is nearly omnidirectional. It is normally used for reference measurements of wide bandwidth noise.

The digital recorder use is the field recorder FOSTEX-2LE. It has two channels each with a connector for a 48 V microphone. The data are stored in wav format on a high capacity exchangeable Compact Flash card. The recording was started with a digital clock. The instruments were powered individually by 12 V batteries.

The audio signal from both channels are digitized and recorded simultaneously at a data speed of 44 100 samples per second and with 24 bits sampling depth. The high data rate is required to detect signals out to 22 050 Hz. The 24 bits sampling is required to achieve a high dynamic range so as to detect a low signal next to a high signal.

3.2. Data reduction

Data for each recording instrument were read in wav format into Matlab. The data streams for the two channels were then separately divided into 1 second sections. Each such section was Fourier transformed and the intensity was saved in 20 000 frequency channels at 1 Hz resolution ranging from 1 Hz to 20 kHz. The intensity was converted into dB scale and scaled to dBA. The

frequency channels were then calibrated separately for each recording channel:

$$S_{spectra}(t, f) = 10 \cdot \log_{10}(S_t(t, f)) + dBA(f) - G_{dB}(f) \quad (8)$$

where $G_{dB}(f)$ is the gain $g(f)$ in dB.

The broadband noise was determined by adding up the calibrated linearized intensity channels from 20 Hz to 20 kHz as:

$$S_{broadband}(t) = 10 \cdot \log_{10} \left(\sum_{f=20}^{20000} e^{S_{spectra}(t, f)/10} \right) \quad (9)$$

The spectra over time were averaged over a longer time period of 4 hours as:

$$S_{broadband}(t) = 10 \cdot \log_{10} \frac{\left(\sum_{n=1}^T F(t) \cdot e^{S_{spectra}(t, f)/10} \right)}{\sum_{n=1}^T F(t)} \quad (10)$$

where $F(t)$ is the filter function 0 or 1 at time t as discussed below.

3.3. Calibration

The specifications of the manufacturers of the microphones and the recorder showed that the spectral response of the system should be exceptionally flat. One of our instruments, HH001, was designated to be our reference standard. This instrument was taken to the Swedish National test laboratory SP in Borås Sweden.

The other 32 receiver systems were then similarly calibrated at our lab against our designated and calibrated standard instrument. A table of calibration gain values was made for each instrument and for each receiver with its individually designated microphone. The gain knobs were all glued to fixed positions.

3.3.1. Spectrum and total gain

A tone of known frequency was emitted into a shielded drum where the microphone under test was mounted together with a well calibrated tester. The signal intensity was set to 60 dB for each frequency in a series of frequency tests from 50 Hz to 10 kHz and for each of the two channels separately. The receiver system was shown to be as specified with a rms variation of 0.1 dB over the entire band. The gain knob was glued in place for both receiver channels and the gain was determined to be independent of frequency so $G_{dB}(f) = G_{dB}$ = 13.3 dB for channel 1 and 17.5 dB for channel 2.

Figure 1: Map showing the observational area around Oxhult. Blue dots refer to wind turbines, red dots are measurement positions. Wind direction and measurements are shown in the figure and discussed below.

3.3.2. Subsystems test

The microphones were calibrated against each other by recording data with mic1 into receiver 1 and receiver 2 and with mic 2 into receiver 1 and receiver 2. The combinations showed that the gain of the microphones differed from each other as did the gain for the two receiver channels.

The conclusion is that the microphone and receiver must be calibrated together as a single unit.

3.3.3. Sensitivity

The sensitivity of the system was tested in the following way. A signal at a specific frequency was transmitted and received and recorded. The signal amplitude was varied 50, 100, 200, 500 and 1 000 mV for each of the frequencies 100, 200, 500, 1 000, and 2 000 Hz. We conclude from this test that the receiving system has a linear response to change in input intensity.

3.3.4. Stability

The longtime stability of the system was tested by transmitting a known signal at a known frequency for 30 seconds of time. The data were received and recorded. The variability over time was about 0.3 dB (formal standard error) for each channel. The difference of the channels has a standard deviation of about 0.2 dB. We suggest that most of the long time instability is external to the receiving system. Some of the instability for the individual channels may be individual non-coherent noise. The majority of the noise is from external sources since it is coherent in both channels. This suggests that this noise originates mostly from the transmitting system. The individual channel noise is therefore in the order of 0.1-0.2 dB, consistent with the errors determined in the test at SP. The conclusion is therefore that the receiving system also is independent of time.

3.4. Data filtering

The data were filtered for local wind puffs directly into the microphones. The two channels were recorded as one with a microphone with a wind protection muff, the other without wind protection. The noise level from the two microphones were compared for each 1 second time segment and the noise level from the wind protected microphones is recorded only for the times when the two noise levels agree within 3 dB. This showed to be an efficient way to filter out data which are dominated by sudden wind bursts which induces flow gradient pressure directly onto the microphone membrane.

3.5. Observations

Instruments were installed at fourteen locations (Figure 1) in the wind direction from the wind turbine farm at Oxhult, outside the city of Laholm, Sweden, and one location up-wind used as a reference. The locations were on the theoretically estimated 40 dBA perimeter around the area, separated by 300 m from North by East to South. The perimeter is about 10 km in length. Wind direction was from the south-west at around 210° with wind speed 6 m/s at hub level 105m and 4 m/s at 10 m. Two additional locations downwind and upwind were used as references.

Data were simultaneously recorded for four hours at the sixteen positions.

4. Results

4.1. Spectra

4.1.1. Ambient spectra

Wind turbine manufacturers give model values for the sound emission from their turbines. Figure 2 shows a synthetic spectrum from a VESTA V90 turbine at a distance which represents a broadband noise level of 40 dBA superimposed (blue line) on the background spectrum (red line) observed at a quiet, but windy, forest location Stjärnarp close to Halmstad, Sweden. Note that the wind turbine signal would be detectable by our instrument against the background noise even though its broadband level is 40 dBA as compared to background of 48 dBA.

Figure 2: Synthetic model spectrum from wind turbine

Figure 3 shows noise level spectra over 20-20 000 Hz observed near measurement point 6. Each spectrum is 1 second and the observing time is 100 seconds. X-axis is the frequency 0-20 000 Hz, Y-axis is the time in seconds since the beginning of the data recording, and Z-axis is the noise intensity in dBA. The increased noise levels at some times have all been traced back to cars passing on the road. These cars can be followed between measurement points. Cars on the road may therefore also contribute substantially to the background noise level within and outside the turbine area.

Figure 3: Spectrawith noise from local traffic

Figure 4 shows noise level spectra over 20-20 000 Hz observed on 2009-06-10 near the measuring point 13 at Linghult. Each spectrum is 1 second and the observing time is 100 seconds. X-axis is the frequency 0-20 000 Hz, Y-axis is the time in seconds since the beginning of the data recording, and Z-axis is the noise intensity in dBA. This is a three dimensional figure showing sound intensity in dBA as peaks and color (red is most intense, blue is less).

The large bumps around 2000-3000 Hz varies with time in a way which is NOT correlated with wing motions. This particular noise originates from birds which seem to sing at regular intervals. The bird song clearly outperforms the sound from the wing turbines, even though the observations were made downstream from the turbines. Birds therefore may substantially contribute to the background noise.

During one of our background observations we noted a local audio source in the form of barking dogs. The barks can be seen in the overall time-averaged spectrum (top) at around 500 Hz. Figure 5 shows all of the 1 second spectra. The barks from the dogs are seen in the

Figure 4: Spectra with typical bird song

beginning of the time series. The conclusion from this exercise is that the system is fully capable of detecting and determining local and other audio sources from the broad band background signal.

Figure 5: Spectra with barking dogs

Other external audio signal we have seen includes sound from passing airplanes. This is seen in the spectrum as a fairly wide spectral feature which is shifting in frequency with time. The frequency shift is caused by the Doppler effect when the airplane is moving across the observing area.

4.1.2. Wide band turbine spectra

The sound from the turbines is expected to be dominated by the sound of the wings moving through the air. This sound has been described as swooshing or changing in amplitude with time, correlated with the motion of the wings. Figure 6 below shows 1 minute of spectrum at 1 second resolution in time and 1 Hz resolution in frequency. The swooshing can clearly be seen as the corrugated feature. Most of this noise is broad band and changes over the whole spectrum up to about 10 000 Hz.

Figure 6: Spectra of turbine wings

The wide band spectrum 20-5000 Hz is shown in figure 7. This was measured with the turbine turned off and on. The turbine spectrum was then determined by taking the difference in channel noise for each frequency channel. The spectrum was measured at position A05, downwind from the wind turbines at that day.

Figure 7: Spectrum with turbine turned off (blue) and on (red)

4.2. High resolution narrow band turbine spectra

The turbine spectra were then measured at positions around the 40 dBA perimeter. The noise level in each narrow band frequency lines is very high with conventional short integration times of minutes, and we therefore time averaged our spectra for the full 4 hours of observing time. The narrow band spectrum in our reference position up wind A08 is shown in figure 8.

Figure 8: Spectrum observed at our reference position up wind from the turbines

Figures 9, 10 and 11 show spectra observed at positions A24, A25 and A26 directly downwind from the turbines. Note that there are narrow band features in the spectrum, especially at 100, 200, 370 and 500 Hz. These are very narrow, therefore contain very little power, and will not show in spectrum with short averaging time or wider channels. Note also that the spectral features are dependent on position. This is even more pronounced in spectra observed at positions away from the direct downwind as shown in figures 12 and 13.

Figure 9: Spectrum observed at position A24 downwind from the turbines

Figure 10: Spectrum observed at position A25 downwind from the turbines

Figure 12: Spectrum observed at position A19 at northern end of the area

Figure 11: Spectrum observed at position A26 downwind from the turbines

Figure 13: Spectrum observed at position A30 at southern end of the area

4.3. Broadband noise levels

The instantaneous equivalent sound level measurement, taken at 1 second integration time at position A24, is shown in figure 14. These data are unfiltered and the variation in equivalent sound level with time is typical for what we measured around the perimeter. We then calculated an averaged number for the equivalent sound level over the observing time of 4 hours. This averaging was filtered as shown in equation 10.

Figure 1 shows the measured equivalent sound levels on the map with the wind direction. We note that the maximum equivalent sound level is not in downwind direction, but slightly off. However, the maximum levels are measured where individual wind turbines are closest, suggesting that the major contribution are from individual turbines rather than from the superimposition of all. The total equivalent sound level as measured at each location is shown in figure 15. The mean level downstream is 36 ± 1 dBA for locations A18-A30. This is at the same level as measured at the reference location, A08. We therefore conclude that the total noise level from the wind turbines is less than 35 dBA at the 40 dBA border at this wind speed.

Figure 14: equivalent sound level in dBA measured at position A24

Figure 15: equivalent sound levels measured at Oxhult 3 November 2011

5. Discussion

The Swedish standard for noise measurements requires that the measurements are taken at wind speed of 8 m/s at 10 m above ground. The data were observed at the lower wind speed of 4 m/s at 10 m above ground. The wind speed at hub level of 105 m was 6 m/s, and the wings were moving at full speed. The lower wind speed was chosen so that the noise from vegetation and atmospheric turbulence would be less and therefore the noise from the turbines would be easily separated from the ambient noise.

The data reduction requires heavy filtering to avoid influence of direct wind pressure into the microphone as well as external noise sources such as traffic, air planes and birds. The total noise level to measure is so low that even a single bird may sing sufficiently loud to corrupt

the measurement.

The noise from the turbine contributes mainly between 500 and 2000 Hz (figure 7), as expected from the theoretical noise figure discussed above (see figure 2). The increasing noise below 1000 Hz in the ambient spectrum, where the turbine is turned off, is probably mainly due to vegetation noise, leaves, branches etc., and turbulence in the air flow. This is more pronounced in the wide band spectrum from Oxhult (figure 7) than from Stjärnarp 8 (figure 2). This is expected since the Oxhult area has more forest and thus more noise from vegetation. It is also expected to have more turbulence above the tree tops at Oxhult than at the flatter landscape of Stjärnarp.

The narrow band spectra at 1 Hz resolution were averaged over 4 hours to show spectral features above the high individual channel noise. There are very narrow band spectral features present in each of the spectra we have observed around the 40 dBA perimeter. These features are dependent on individual positions around the farm, clearly indicating that they are individual to each turbine. However, these features are only a few channels wide and would not be observed in a conventional octal band spectrum. Each spectral line feature contains very little power and does not contribute anything significant to the overall integrated noise level. We suggest that the features are mechanical, probably from cooling fans, bearings, and gear boxes. Note that there are also spectral features shown in the spectrum observed at the reference position up wind from the wind turbine area. This indicates that there is indeed also ambient narrow band noise, probably from the farming equipment.

The integrated broad band noise level measured by us is 36 ± 1 dBA at all points downstream of the turbine farm. Most of this is what would be expected from ambient noise at the wind speed. The contribution from the wind turbines is therefore estimated to be less than 35 dBA at each measurement point, given that the reference noise level is 33 dBA as measured down wind.

The variation in equivalent sound level with time is very high at any specific site, up to 10 dB at some times. The variation is position dependent. This was traced to be local to the position, mostly from direct wind pressure directly into the microphones, but also from local traffic which can be traced between observing points. Our procedure to use two microphones seems to be quite useful to filter these data out. The large peaks in equivalent sound level are very short in time, suggesting that none of them originates from the large wind turbines.

The error budget in measurement of total equivalent sound level is:

- 0.1 dB from calibration of reference system;
- 0.1 dB from calibration of systems relative reference system;
- 0.5 dB from filtering errors;
- 0.5 dB from reflection of sound.

The error budget is further complicated by that some of the errors are true gain errors, e.g. calibration errors, while others are additive noise, e.g. filtering and reflection. However, we will for the purpose of calculation estimate a total error on measurements of ± 0.7 dBA. In addition there will be a ± 0.7 dBA error in the estimate of the background noise, resulting in an error of ± 1 dBA in any estimate of the noise from the turbines.

Differences in total equivalent sound level are also observed between nearby sites. The difference can clearly be attributed to the positioning of the microphones, where they at one site are on a small hill, while on another site they are in a sound shadow in a small valley. Such differences in position cannot be avoided in a forest, and has to be added as an additional source of measurement error.

The data indicate that a simple sound propagation model is sufficient since the equivalent sound level is more affected by the nearby environment than the large scale forest structure. Also, the large scale forestry structure is bound to change with time and the error bars of measurements on total equivalent sound level are about ± 1 dBA, which is larger than any fine tuning with a more sophisticated model. More care should be taken to model the reflections from walls and other obstacles close to the microphones

6. Conclusions

The measurements around the 40 dBA perimeter around the Oxhult wind turbine farm indicate that:

- The data acquisition and reduction system was proven to work well in the forest environment.
- The integrated noise level from the turbines is at or below the expected theoretical level at all places downwind from the turbines.
- The broad band spectra show that the contribution from the wind turbines is very close to the noise data from the manufacturer.
- There are narrow band spectral features.

– These originates from individual turbines, are very narrow band and therefore contains very small amount of power.

– The narrow band features do not contribute any significant part to the total power spectrum of the area.

– The narrow band features are probably originating from mechanical sources.

The conclusion is that the theoretical 40 dBA border seems reasonably calculated with a simple model if the manufacturer specifications are used to extrapolate the equivalent sound level to correspond to 8 m/s at 10m.

7. Future

Future projects in this area will aim at developing the field qualified recording system which can be set by unqualified personnel to record data in forest areas. The data will then be processed off-line.

The high resolution field data acquisition system is therefore shown to be useful as a remote diagnostic tool for turbine machinery. Further investigations include Further investigations include to track down each spectral line feature to specific mechanical parts.

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