Department of Aeronautical
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MWL The Marcus Wallenberg Laboratory
for Sound and Vibration Research

Sound propagation around offshore wind turbines

”Ljudspridning kring havsbaserad vindkraft”

A summary of project results from
TRANS_G 1+2 and TRANS_K

By

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Sound Propagation around Offshore Wind Turbines. Measurement Techniques and Analysis

Background

Current knowledge[1] shows that there exists a risk for low frequency noise disturbances from sea based wind turbines. Some previous measurements[2] indicate that low frequency long range sound propagation over areas with small ground absorption (the sea, desserts), results in a sound level reduction with 3 dB per doubling of distance. This indicates cylindrical wave propagation rather than the spherical commonly assumed for sound outdoors. The difference is significant for large distances, since spherical propagation results in a 6 dB reduction per doubling of distance. A cylindrical model applied from a distance of 200 m is today the recommended procedure from “Naturvårdsverket” for calculation of noise from sea based wind turbines. The cylindrical propagation model implies in particular that low frequency noise from sea based wind farms could be heard at very long distances. With the planned expansion of sea based wind power in Sweden, it is essential to determine if and under what conditions the cylindrical propagation model is correct. The uncertainty around this model and the need for a validated model based on data obtained from the Baltic region, is the main motivation behind this project. In this report the results of the first and second phase of the project is summarized.

I. Project objectives

One objective of the project is to develop a measurement procedure for long-range (5-15 km) outdoor sound propagation. Such a procedure could be used to monitor and control the sound imisson from sea based wind farms, which is important but not the main project objective. The main objectives are instead: i) to use the measurement procedure to validate and improve an existing calculation model for sound propagation over the sea[3]; ii) to study in more detail the phenomenon called Low Level Jets and its link to cylindrical sound propagation. The results of the project will also be an input for revision of, if necessary, “Naturvårdsverkets” model for noise from sea based wind turbines. The work project has so far been conducted in two parts (TRANS_G 1 + 2) where the main work has been done by a doctoral student (M. Boué). The field measurements have also been supported by the industry (Airicole (E-on), ABB and Nordborg Acoustics) via a separate Vindforsk project (TRANS_K). This report summarizes the results from these parts. Presently a third and final part is conducted and the plan is that the work will be finished at the end of 2006.

II. Measurements

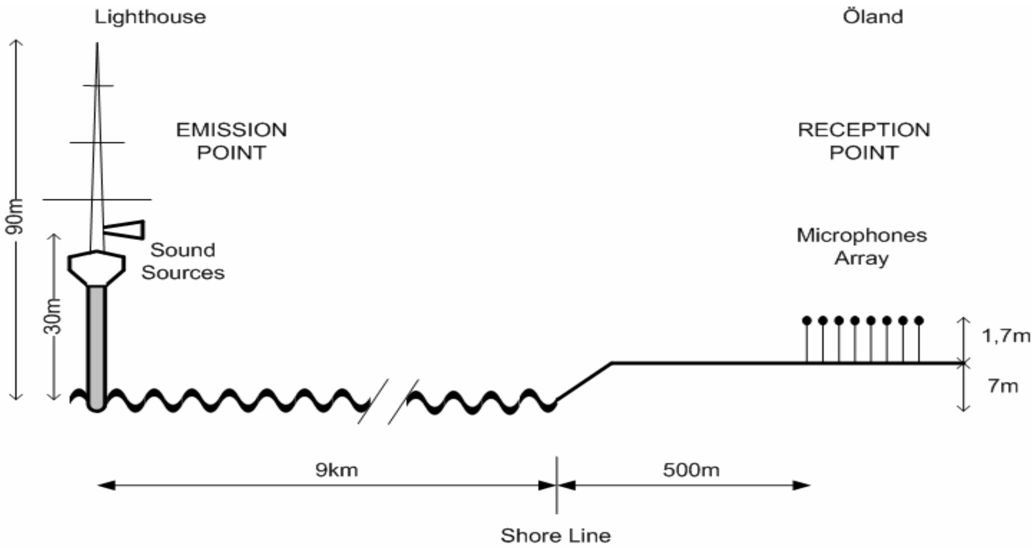

Figure 1 In situ setup

On the Utgrunden lighthouse (figures 1 and 2), now used as a scientific test station, situated 9 km from the coast line of Öland, a compressed-air-driven sound source (“Kockum Sonics Supertyfon”) was adapted with the support of ABB CRC to be used as a strong outdoor source. A microphone placed 1m in front of the siren was used to measure a 10-second source signal on each occasion. The source sound pressure level was 128 dB (at 1 m) and the sound consisted of a number of harmonics with a fundamental close to 200 Hz. In order to investigate the behavior of the sound propagation at other frequencies, a second source (figure 3), consisting of a loudspeaker and a 1.2m-long resonator tube was used. It could produce a single harmonic close to 80 Hz giving a sound pressure level of 105 dB (at 1 m).

On the island Öland the receiver point was situated 500 m from the shore at 7 m above the sea level and 9500 m from the source. Here an acoustical antenna consisting of eight microphones (figure 4) was placed on a line parallel to the sound propagation to create an end-fire microphone array. All microphones had a receiver height of 1.7 m above the ground. The distance between the microphones was set to 40 cm in order to have the directivity pattern pointed towards the sound source at 200 Hz. The acoustic antenna as well as the software and hardware used for the data processing were developed in co-operation with Nordborg Acoustics.

Fig 2 and 3: Emission point
At Utgrunden, two sound sources were placed on the platform at 30 m above the sea level. *Collaboration with ABB CRC and Airicole* within TRANS_K.

Fig 4: Reception
At the reception point, an array of 8 microphones creates an acoustical antenna directed to the sound source. *Collaboration with Nordborg Acoustics* within TRANS_K.

The advantage of using a microphone array instead of a single microphone is that disturbances due to background noise can be canceled. For instance, influence of the noise coming from a small road situated 100 m inland from the measurement position can be avoided.

Moreover, to prevent the effect of the wind noise on the microphones, a special “rugby ball-shaped” windshield was developed. Tests in the laboratory showed that this wind protection was up to 5 dB more efficient at 200 Hz than the standard wind screens available. However, due to the very low levels from the sound sources at this long distance, the wind noise was sometimes disturbing and signal-processing techniques to increase the signal-to-noise ratio had to be used.

During one year, different measurements sessions from 3 days to 10 days have been performed. See Table 1 for the table summarizing the measurements. The measurements performed cover winter, summer and spring as well as a range of wind speeds and different directions.

For all the acoustics measurements wind, temperature and humidity were also measured at several heights on a meteorological mast at Utgrunden. Moreover, during the measurement campaign performed 15-21 June 2005, wind profiles were measured during the day using single theodolite tracking of free flying balloons (Collaboration with MIUU, Hans Bergström).

	"200 Hz"	"400 Hz"	"80 Hz"
	Number of measurements	Number of measurements	Number of measurements
OCT 2004	✗	✗	✗
FEV 2005	18	9	✗
AVRIL 2005	20	20	✗
MAI 2005	79	78	✗
JUIN 2005	174	173	177
TOTAL	**291**	**280**	**177**

Table 1: Summary of measurements.

III. Signal Processing

Three different signal-processing techniques were used in order to separate the signal from the noise. The first method developed to pick up the signal is based on the synchronized time averaging theory (TA). The time signal recorded is divided in different segments 1/f1 in size, where f1 is the frequency of the sound source. Then all the segments (say N) are added together and divided with the number of segments. The periodic source signal will not change during this operation while the noise (RMS) level will be suppressed with a factor 1/sqrt(N).

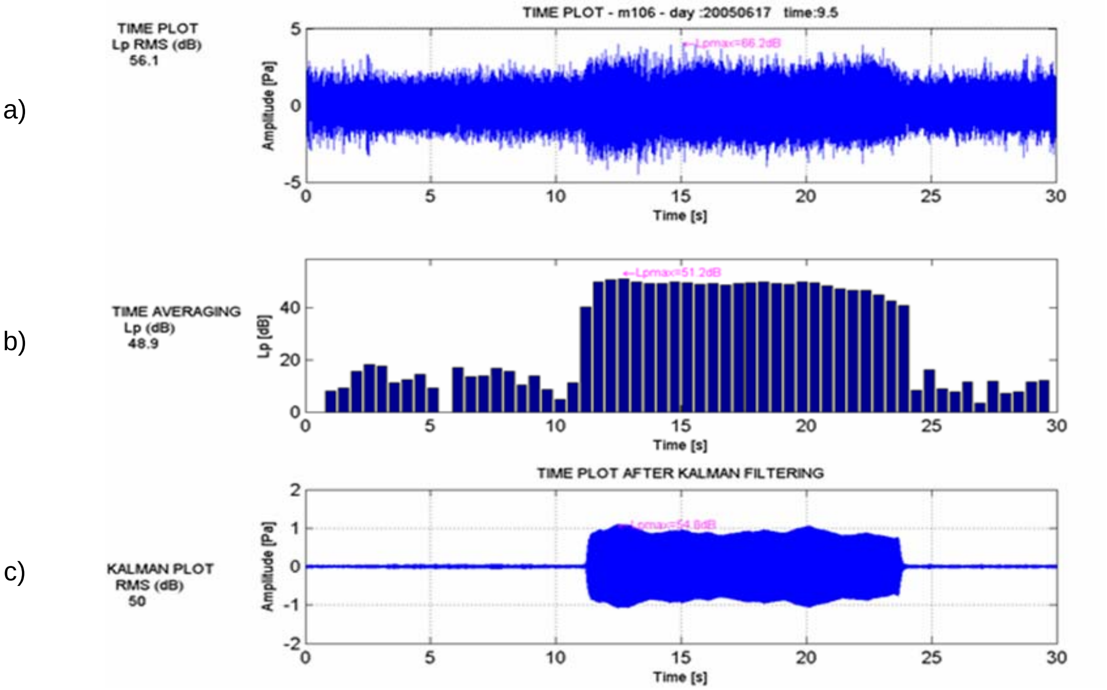

Figure 5 a) time signal, b) signal after Time Averaging, c) signal after Kalman filtering.

The method is simple and fast, giving valuable information about the sound pressure level of the signal. Moreover, small variations of the frequency do not change the result significantly. However, the time averaging method has some limitations. First, it takes into account all the harmonics of the studied frequency. Second, it introduces a 0.5 s error for determining the beginning and the end of the signal. A typical result from the time averaging method is depicted in Figure 5b.

Another approach to extract the signal is to use a Kalman filter (see figure 5 c). Our model is based on the method proposed by Zarchan and Musoff[4] and is based on detecting an harmonic signal with a known frequency buried in noise. The Kalman method is more accurate than the time averaging technique and the signal to noise ratio is larger than with the time averaging method. The main drawback is that the exact value of the frequency has to be known. A difference of 1 Hz can yield very different results. The Kalman method is also more time consuming to perform than the time averaging.

The last method used is a classic Fast Fourier Transform (FFT) over the part of the measurement containing the signal from the source. This method is the easiest but as the signal, even after the array processing, could be weak it was not possible to take the FFT only over the duration of the signal. So, a first analysis through the Kalman filter or the Time Averaging method was required before performing the FFT. On the other hand, by making a FFT just a few seconds before or after the signal start/stop we were able to determine the level of the background noise and compare it with the level of the signal. When the two levels present a difference of less than 10 dB, the measurement was dismissed.

As the three different methods give similar values for the sound level pressure, an arithmetic average is used in the analysis of the results presented below.

IV. Sound Transmission Data

The dependence of the sound propagation on different wind gradients was studied by performing 180 sound measurements at different times of the day between the 15th and 21st of June 2005. In this section, the statistical behavior of the sound propagation will be shown for the entire week. To simplify interpretation of the results, all values are corrected for the atmospheric absorption The temperature at the source is known from the meteorological measurement at the lighthouse.

In order to be able to use these results in different contexts we will refer all the data to the relative value of transmission loss (TL) defined by Attenbourough[5] as:

$$TL = -20\log\frac{acoustical\ pressure\ at\ the\ receivers}{acoustical\ \ pressure\ at\ 1\,m\ \ from\ the\ source}$$

Figure 6 shows the probability distribution (=percentage of occurrence) of a specific transmission loss value for 80 Hz and 200 Hz. Figure 7 shows the cumulative distribution for the same transmission loss i.e. in what percentage of the measurements the transmission losses are higher than a certain value. In both graphs, the bold line at 80 dB marks the theoretical transmission loss due to spherical spreading and 40 dB marks the case of cylindrical propagation from the source. The dashed line at 63 dB is based on “Naturvårdsverkets” model and assumes spherical propagation up to 200 m and then cylindrical.

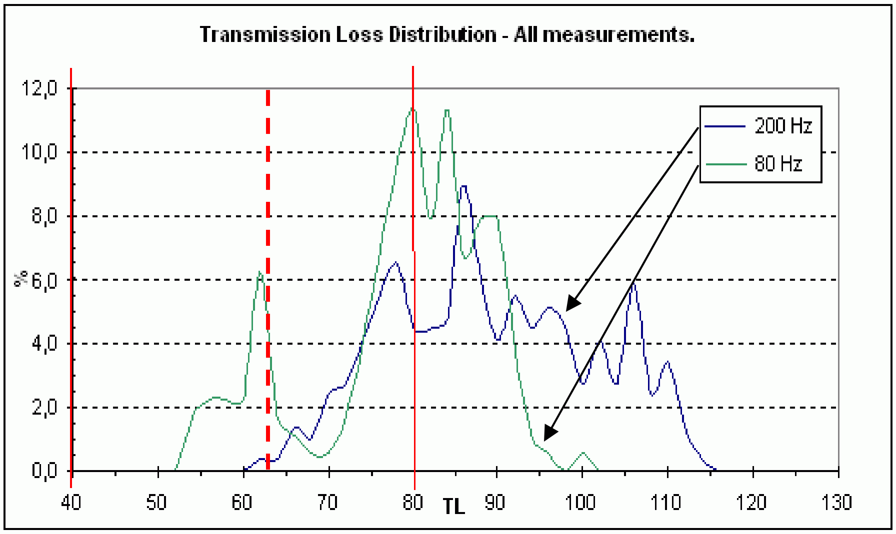

Figure 6: Transmission Loss probability distribution for 200 Hz and 80 Hz tones.

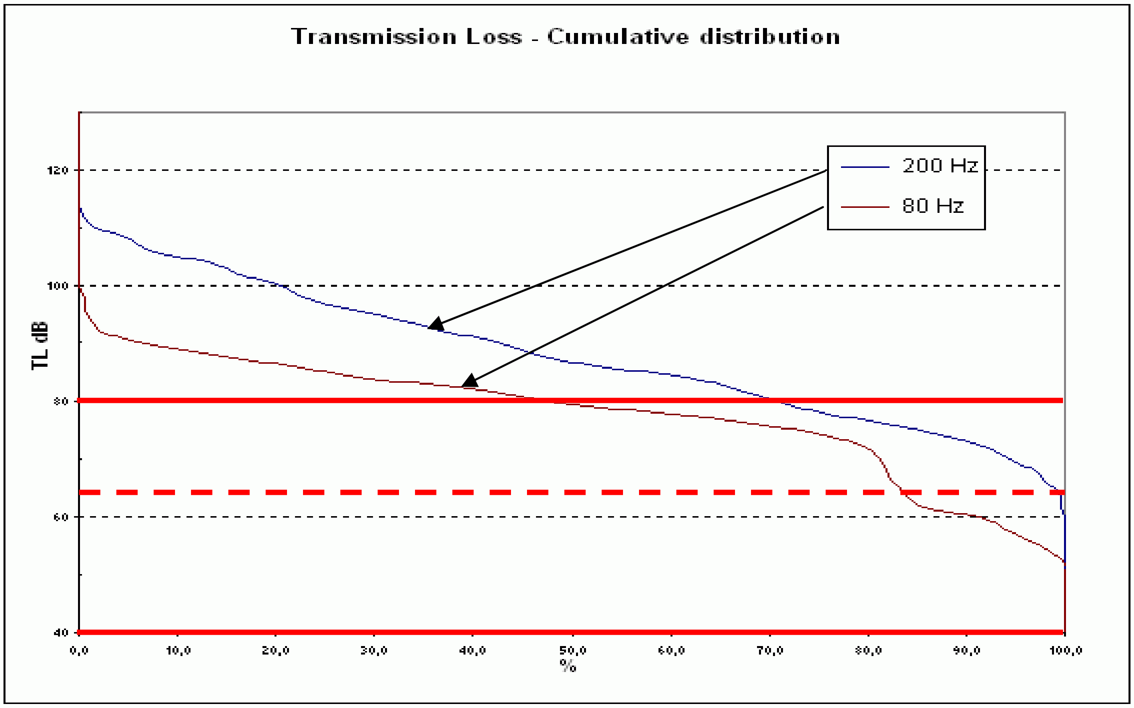

Figure 7: Cumulative Distribution of the Transmission Loss for 200 Hz and 80 Hz.

The fact that the transmission loss sometimes is larger than for spherical propagation can be explained by factors such as; scattering at the shore line, scattering by waves on the sea and temperature and wind gradients not taken into account in the calculations.

As can be seen the transmission loss data seems to tend more towards cylindrical for the 80 Hz case. For the 200 Hz case the damping almost never will reach the level predicted by “Naturvårdsverkets” model. But for the 80 Hz case the damping value will be less than the value from this model 15 % of the time. The trend that the cylindrical effects become more predominant the lower the frequency seems clear and is supported by some older data obtained at very low (< 20 Hz) frequencies[6].

One reason that the cylindrical wave spreading is less apparent at 200 Hz could be that the scattering from sea waves plays a larger role at that frequency. A more detailed understanding of the effects of this as well as the meteorological conditions can hopefully be gained from the work on the simulation model. Here the detailed meteorological data obtained with the help of MIUU during the June 2005 campaign will play an important role. A first effort to compare acoustic and wind profile data in order to correlate the transmission to so called low level jets has been done, see Figure 8. The colors in the plot show the wind speed, while the arrows give the direction of the wind, where a downward pointing arrow indicates northerly winds, while an arrow pointing left indicates easterly winds etc. As seen from the figure there is a low level jet (layer with higher wind speed) starting at a few hundred meters and extending up to 1000-1500 meters.

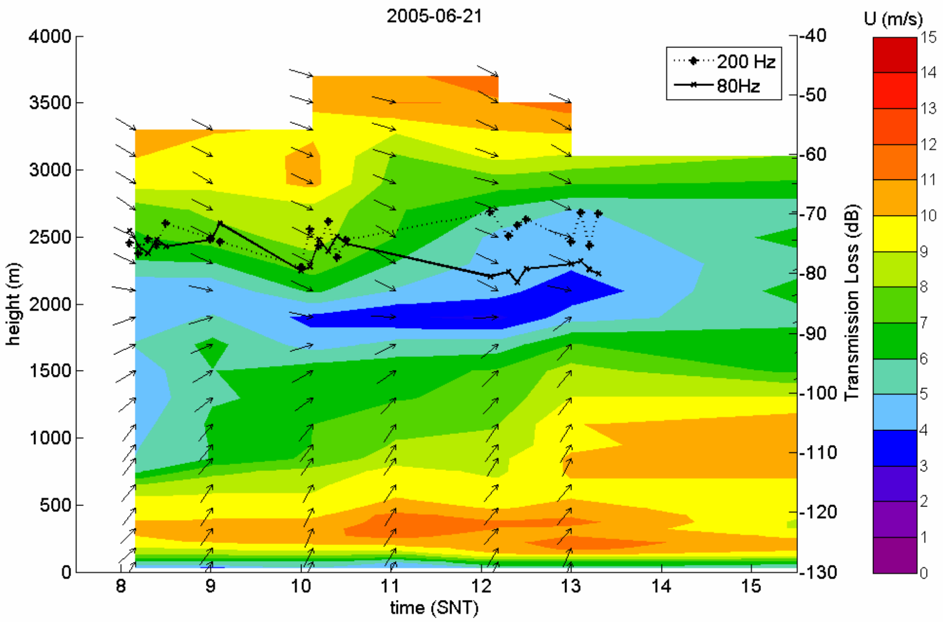

Figure 8 Variation of transmission loss and the speed and direction of the wind, at Hammarby the 21st of June, 2005.

V. The Simulation Code

Work on the code developed in an earlier VindForsk project[3] has continued and it has been found that the standard version of the parabolic equation used in the code suffers from some limitations. The main problem being the convergence for large distances. Therefore, a modified so called Greens function based solution of the parabolic equation, believed to perform better in particular for large distances, is being tested and will be used in phase 3 of this project. Furthermore, it is planned that a comparison with ray-tracing codes will be done by co-operation with MIUU (Conny Larsson) and FOI (Alex Cederholm).

VI. Summary and Conclusions

Long-term measurements of sound transmission over the sea have been performed during more than one year in Kalmarsund. A new measurement procedure for long-range (5-15 km) outdoor sound propagation has been created: at the reception point, an array of 8 microphones creates an acoustical antenna directed towards the sound source and different numerical models have been developed in order to increase the signal to noise ratio.

The measurements show an increased risk for cylindrical sound propagation at low frequencies, see Figures 6&7. In order to get sufficient data to finally determine the importance of cylindrical propagation some additional measurements at low frequencies (< 80 Hz) and different distances are needed. This is planned for phase 3 of this project. In phase 3 work on the parabolic equation code will also be finalized and the code validated against the data collected during the project.

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