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Rådgivende Ingeniører - Støj og vibrationer

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Offshore Wind Turbines - VVM

Underwater Noise Measurements, Analysis, and Predictions

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1 Introduction

On behalf of SEAS, Ødegaard & Danneskiold-Samsøe (ODS) has performed an investigation of the underwater noise emitted by existing offshore wind turbines. The purpose of the investigation was to estimate the expected underwater noise emitted from the planned offshore wind turbine parks consisting of 2 MW wind turbines.

The results of the investigation will be included as part of the background material of a VVM report (Environmental Impact Report) for proposed offshore wind turbine parks.

The investigation is based on measurements of underwater noise from offshore wind turbines with two types of foundation. The first type is a concrete foundation, which is placed on the seabed (Vindeby, Denmark). The second type is called a “monopile”- foundation. In this case, the foundation is a steel pipe that has been driven into the seabed (Gotland, Sweden). Because underwater noise from the wind turbine is emitted from the foundation to the water, two different types of offshore wind turbine foundations were measured to assess possible differences in noise emission.

The noise levels from the wind turbines was compared to the ambient noise (the background underwater noise) by performing noise measurements whilst the wind turbines were operating and whilst stopped. The frequency range used in the investigation has been selected to include the known frequencies that are audible for the appropriate sea animals.

The existing offshore wind turbines have the power of 500 kW. The proposed offshore wind turbines will have the power of 2 MW. To estimate the noise emitted from the future planned, more powerful offshore wind turbines, vibration measurements were performed at the foundations of the offshore wind turbine and compared to similar vibration measurements performed on a 2 MW wind turbine running on land.

The result of the investigation is an estimate of the underwater noise, which can be expected from the 2 MW offshore wind turbines. These results are subsequently going to form a base of the evaluation of the effect on the animal life.

Vindeby Windturbine

Concrete foundation (Vindeby)

Monopile-foundation (Gotland)

Figure 1
Pictures of offshore wind turbines off of Vindeby (Denmark) and off of Gotland (Sweden), where the measurements took place.

2 Method

The methodology chosen in the investigation was based on measurements of the underwater noise from existing offshore wind turbines. The results of the measurements is then used to estimate the expected noise contribution from more powerful offshore wind turbines, which will be used in future planned offshore wind turbine parks.

The noise from an offshore wind turbine is transmitted to the water in two ways. The noise is emitted both though the air, as airborne noise, entering the water and through the structure as structure-borne noise transmitted through the tower of the wind turbine to the foundation from where it is emitted to the water. The measurements of the underwater noise in this report are the total sum of the above-mentioned contributions. The measurements show, however, that the airborne noise has a negligible contribution to the underwater noise level. Therefore, it was concluded that the underwater noise from the wind turbines is transmitted primarily through the tower of the wind turbine and the foundation.

The measurements were performed with only one wind turbine operating in its park to eliminate possible noise contributions from other wind turbines. The ambient noise (background noise) was measured when the wind turbines were stopped. The noise from the wind turbine was determined from the difference in the noise level spectrum when the wind turbine was operating and stopped. The existing offshore wind turbines have the power of 500 kW and the proposed offshore wind turbines will have the power of 2 MW. To estimate the noise emitted from the future planned, more powerful offshore wind turbines, vibration measurements were performed at the foundation of the offshore wind turbine and were compared to similar vibration measurements performed on a 2 MW wind turbine running onshore.

Two places were chosen where offshore wind turbines are running: off of Vindeby (Denmark) and off of Gotland (Sweden). The offshore wind turbines off of Vindeby are mounted on concrete foundations placed on the seabed, while the offshore wind turbines off of Gotland are mounted on a steel pipe (monopile) foundation. The two types of foundations have been chosen, because similar foundation types are being considered for the future planned offshore wind turbines. Therefore an estimate of the noise level is presented for the two foundation types, the concrete foundation and the steel pipe (monopile) foundation.

Underwater noise from offshore wind turbines was measured 20 meters away from the turbines and vibration measurements were performed at the foundation of the wind turbines. With the 2 MW wind turbine on land, vibrations were measured at the foundation of the wind turbine.

The methodology can be summed up and presented in the following stages:

1. Measurements on existing offshore wind turbines:

- Measurement of underwater noise and measurement of vibrations on the tower of the tower of the wind turbines.

2. Measurement of a 2 MW wind turbine on land:
   - Measurement of vibration levels at the foundation of the 2 MW wind turbine
3. Comparison of the measured vibrations of the wind turbines to be able to estimate a scaling correction from 5 kW wind turbines to 2 MW wind turbines.
4. Estimation of the expected underwater noise from a 2 MW offshore wind turbine:
   - The estimate is based on noise measurement made on a 500 kW wind turbine and the scaling of the measured vibration levels on the two towers.

2.1 Selection of Frequency Range

The frequency range used in the investigation has been selected to include the known frequencies that are audible for the appropriate sea animals.

The porpoise and the seal can hear very high frequency sounds. Seals hearing has been measured to be between 100 Hz to 40 kHz. Porpoises can hear sounds with frequencies of 100 kHz and even higher. Fish hearing frequency range is below 20 kHz.

Taking into account the noise from the sea current moving across the hydrophones and other complications considering measurement of low frequency noise, the lowest frequency reported is 10 Hz. The evaluation covers the frequency area of 10 Hz to 100 kHz.

2.2 Evaluation of the structure-borne sound transmission at high frequencies

A theoretical estimation of the radiation of the vibrations in the tower and to the foundation and water with focus on the higher frequencies (above 10 kHz) has been performed. The purpose was to clarify if the sound transmission from the offshore wind turbines in the frequency area above 10 kHz could be considered negligible in this investigation.

The conclusion was that it cannot be excluded and that even very high frequencies can be transmitted down through the tower of the wind turbine and to the water. How much the wind turbine generates structure-borne noise at very high frequencies is questionable but could not be excluded. Therefore, documentation of the high frequency noise conditions was attempted by measuring in this frequency area.

A short presentation of the estimations that formed the conclusion is given in the following paragraphs.

Theoretical estimation of the radiation-ration at frequencies above 10 kHz

In the considerations below the wind turbine is split into 3 superior parts:

- Nacelle
- Wind turbine tower
- Foundation (Not ”monopile”- founded wind turbines)

As a starting point, it was assumed that the structure-borne noise originated from the nacelle. The nacelle transmits force and moment to the wind turbine tower. In the tower, the structure-borne noise is primarily radiated as longitudinal-, quasi-longitudinal and bending-waves. As far as the “monopile” is concerned, the waves will cause sound radiation underwater.

For a wind turbine configuration with a concrete foundation the structure-borne noise in the tower is transmitted to the concrete foundation, where the structure-borne noise will radiate even further. In the foundation the radiation will be very complex and many different mode shapes will occur.

However, it can be assumed that the sound radiation in the surrounding water mainly comes from surface waves in the foundation, as this type of waves radiates considerably more efficient than other mode shapes. The surface waves will presumably mainly be excited by the bending waves in the wind turbine tower. A first assumption would be that the high frequency structure borne noise was strongly damped during the radiation down through the tower of the wind turbine because of the considerable long length of the tower.

The propagation attenuation per length for the different propagation types is a function of the damping in the material and of the wavelength. For the given materials and dimensions the total propagation attenuation in the tower of the wind turbine is of the order of 1 dB for the relevant propagation types.

The structure-borne noise passes through different inhomogeneities radiating down through the tower will give further attenuation of the waves. The most important inhomogeneity is the joints between the tower elements. The attenuation of the joints will be dependent on the type of the joint (welded, coupling etc.). It is assumed that only one or two of joints will occur. One joint will most likely give an attenuation of at least 5 dB for the relevant propagation types.

As far as the “monopile” is concerned, the tower itself will radiate sound underwater. Therefore radiation index of the tower must be taken into account. The sound radiation from the tower will come from bending waves and as the propagation speed of these waves in the tower at high frequencies are much higher than the sound of speed underwater, the radiation index will be 1. The radiation ability in the high frequency range (above 10 kHz) of the tower is therefor efficient.

For the construction configuration of the concrete foundation, structure-borne noise will be transmitted from the tower to the foundation. As mentioned above, it is the surface waves that will radiate sound underwater. A certain loss must be assumed from the transmission of the different mode shapes in the tower to the surface waves in the foundation. The surface waves are however very complicated to describe analytically and therefore an estimation of the transmission loss has been neglected in this case. Also the estimation of the propagation attenuation of the surface waves in the foundation has been out of the scope of this study.

The radiation from the foundation is, amongst others, determined by the radiation-index of the foundation. It was found that for the concrete foundation, propagation speed of the surface waves are higher than the speed of sound underwater at high frequencies and that the radiation index therefor is 1. Thus, it can be concluded that the concrete foundation also has efficient radiation abilities in the high frequency range (above 10 kHz).

2.3 Measurement Arrangement

The measurements were performed with the use of accelerometers when measuring vibrations, hydrophones when measuring underwater noise and microphones when measuring noise above the water's surface. The signals were recorded on a DAT-tape recorder and on a data acquisition PCMCIA card on a laptop. Subsequently the analysis has been performed with a frequency analyser.

Below is a drawing of the field test set-up at the offshore wind turbines:

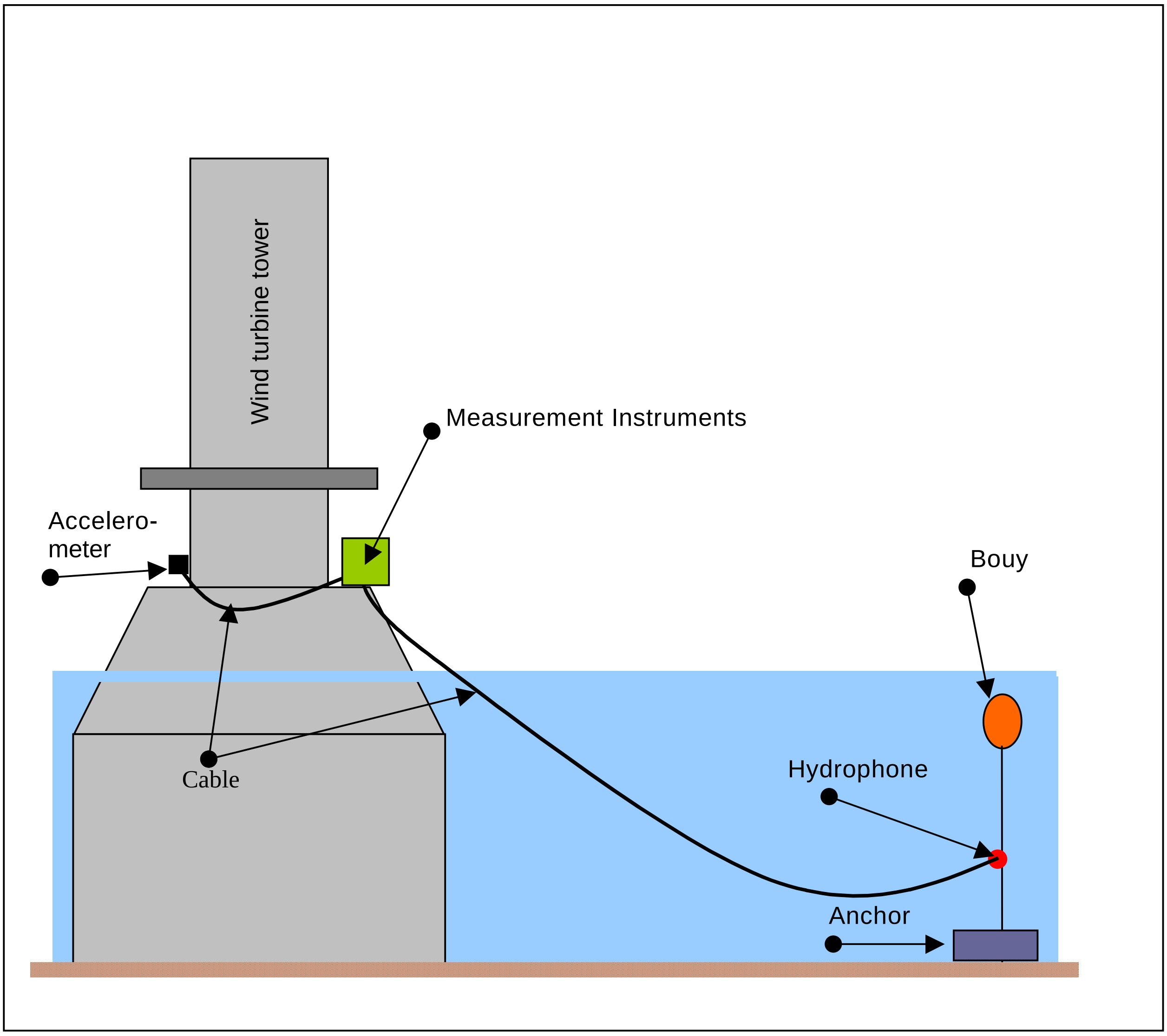

Figure 2

The field-test set-up at an offshore wind turbine.

The following measurement equipment has been used.

Measurement of Underwater Noise

- B&K 8101 hydrophone with preamplifier
- B&K 2804 power supply
- B&K 2693 Nexus DeltaTron amplifier
- Laptop with data acquisition PCMCIA card and data processing software
- Portadat PDR 1000 DAT-tape recorder
- B&K 4223 calibrator
- HP 35670A frequency analyser

Measurement of Noise above the surface

- B&K 2260 sound pressure level meter
- B&K 4231 calibrator

Vibration measurements

- B&K 4393 and 4384 accelerometers
- B&K 2692 Nexus charge amplifier
- Portadat PDR 1000 DAT-tape recorder
- B&K 4294 calibrator
- HP 35670A frequency analyser

2.4 Analysis of Measurement Data

The principles of the analysis of the different measurements are listed below:

Measurements of Underwater Noise

Two different analysis principles of the underwater noise measurements of underwater has been used:

- In the frequency range from 10 Hz to 20 kHz, the hydrophone signal is recorded on a DAT-tape recorder and later analysed on a Hewlett Packard frequency analyser.
- In the frequency range from 20 kHz to 100 kHz, the hydrophone signal was analysed directly on the laptop.

Analysis on the Hewlett-Packard (HP) Frequency Analyser

On the HP frequency analyser, analysis has been performed in 1/3-octave bands with linear averaging over 4-5 minutes. The spectres are shown as Power Spectral Density (PSD)-units on the y-axis to ease the comparison with the other relevant literature. The dB reference values is 1 μPa.

Analysis on Laptop

Analysis here has been carried out as Discrete Fourier Transform (DFT) with a maximum frequency of 100 kHz a resolution of 42 Hz. A number of spectres has been measured during a period of about 15-20 minutes each spectrum representing a “snap-shot” of the noise situation. After that 5 to 11 spectres were averaged linear to represent the whole measurement period. In order to ease the readability, the reported figures are slightly smoothed versions of the averaged spectres. As well, the figures are shown with Power Spectral Density (PSD)-units on the y-axis to ease the comparison with relevant literature. The dB reference values is 1 μPa.

Vibration Measurements

Firstly, the vibration measurements were recorded on a DAT-tape recorder and later analysed on a HP-frequency analyser. The analysis was performed in 1/3-octave bands and represent linear averaging over 3 minutes. The spectres are shown as velocity levels with a dB reference value of $1 \cdot 10^{-9}$ m/s.

3 Measurement Results

In this chapter the measured vibration and noise levels are shown.

3.1 Vindeby (Denmark) – Measurement of Underwater Noise

Vindeby measurements were made at a 450 kW Bonus wind turbine, which was mounted on a concrete foundation. This wind turbine has the name ”6E”. The measurements were carried out on February 11. 2000.

The underwater measurements were made in a distance of 14 meters from the wind turbine and in about 2.5 meter deep water. The hydrophone was placed 1.2 m under the surface. The measurement position was chosen in a direction so the wind was coming from the tower to the measurement position. The wind was coming from “Southwest”(SW) according to the Danish Meteorological Institute measuring station “Omø Fyr”.

In connection to the measurements, it must be mentioned that while the wind turbine was stopped a significant noise contribution came from a passing ship in a distance of about 7 km (within sight). The measurement of the background level in the frequency range up to 1000 Hz must be considered as much higher than if the ship had not been there.

The measured noise levels under water near the offshore wind turbine are shown in the two following figures.

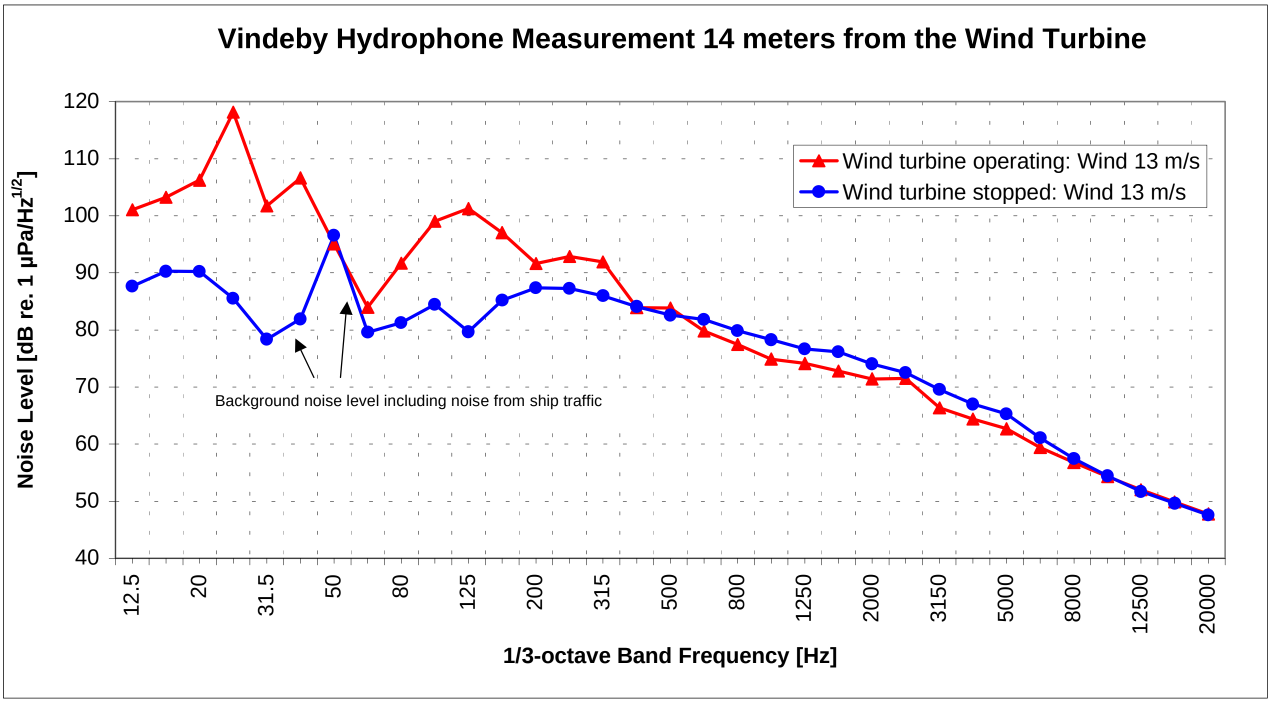

Figure 3

Underwater noise measured 14 meters from the wind turbine at a wind speed of 13 m/s. The frequency range from 10 Hz to 20 kHz are shown as sound pressures given in Power Spectral Density (PSD – units for the wind turbine running and stopped.

In Figure 3, the noise level shown is measured 14 meters from the wind turbine whilst the wind turbine is operating and whilst it is stopped. In both cases, the frequency range is from 10 Hz to 20 kHz and the wind speed was during the measurements 13 m/s.

From the figure, it can be seen that in the frequency range up to 400 Hz, the noise level is higher when the wind turbine is running. The difference is greatest at 20 Hz and is about 33 dB. In the frequency range above 400 Hz the difference between the two measurements are less than 3 dB, which is within the uncertainty of the measurements.

The difference between the measurement in the frequency range under 1 kHz is, as earlier mentioned, influenced by noise from the passing ship. The background noise level would probably have been significantly less, if the ship had not been there during the measurements. It is most likely the distant ship causing the high noise level in the 50 Hz band whilst the wind turbine is not stopped.

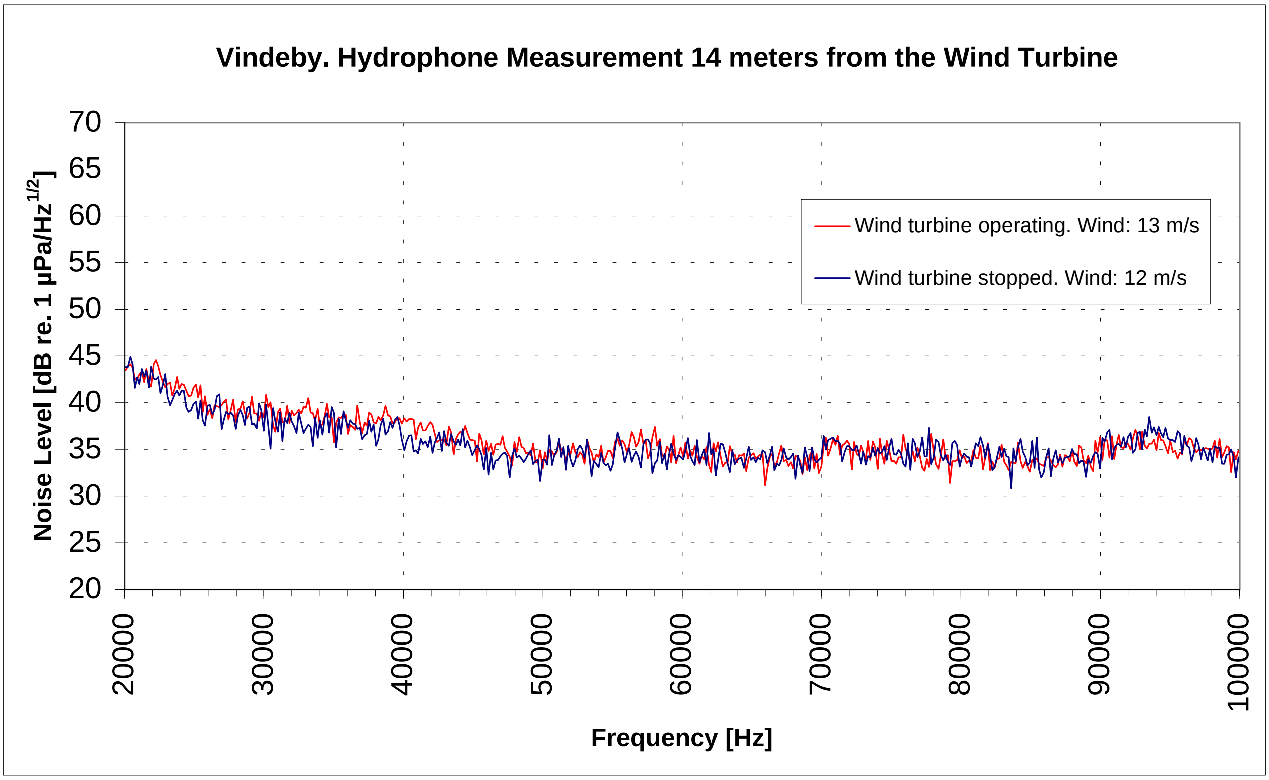

Figure 4

Underwater noise measured 14 meters from the wind turbine at a wind speed of 13 m/s and 12 m/s. The frequency range from 20 kHz to 100 kHz are shown as sound pressures given in Power Spectral Density (PSD) – units for the wind turbine operating and stopped.

In Figure 4, the noise level shown is measured 14 meters from the wind turbine whilst the wind turbine is operating and whilst stopped. In both cases the frequency range is from 20 kHz to 100 kHz. During measurements whilst the wind turbine was operating, the wind speed was about 13 m/s and about 12 m/s during measurements when the wind turbine was stopped.

From Figure 4, significant difference cannot be seen in the noise levels when the wind turbine is operating and stopped. In certain frequency ranges, a difference of 1-2 dB can be seen, but a difference of this size is within the measurement uncertainty. It can be concluded that the wind turbine does not produce noise higher than the background noise level under water in the frequency range from 20 kHz to 100 kHz.

It can also be seen in Figure 4 that the levels decrease from the lower frequencies to until around 45 kHz. From 45 kHz and up the level is almost constant. The reason for the constant level is that the lowest levels that can be measured with the set-up used is about 35 dB. In the frequency range from 45 kHz to 100 kHz the measured values is comparable with the set-ups lower limits or less than the set-ups lower limit.

When comparing Figure 3 and 4, a level difference of about 4-5 dB is seen at 20 kHz. The reason for this difference is to be found in the time differences between those analyses, which are forming the base of the figures. Figure 3 is based on linear averaging over 5 minutes, where as Figure 4 is based on an average of 10 spectres taken from a time period of 20 minutes. Firstly, the last mentioned figure represents "snapshots" of a strongly variant media, secondly, the wind speed has probably varied during the 20 minutes. The visible difference between the two figures is therefor within the expected variation range caused by the above mentioned differences in the time of analysis.

3.2 Gotland (Sweden) – Measurement of Underwater Noise

Gotland measurements were made on a 550 kW Windworld wind turbine, situated on a steel pipe "monopile" foundation. This wind turbine has the name "No. 4". The measurements were carried out January 26. 2000.

The measurements have been performed about 20 meters distance from the wind turbine in 4-meter deep water. The hydrophone was placed about 2 meters under the surface. The measurement position was chosen in a direction so the wind was coming from the tower to the measurement position. The wind was coming from "West"(W) according to the Swedish Meteorological Institute measuring station in Visby, Gotland.

In connection to the measurements, it must be mentioned that while the wind turbine was stopped the measurement was influenced by noise coming from a passing ship in a far away distance. The ship was audible but not visible. The measurement of the background level in the frequency range up to 1000 Hz must be considered as a little higher than normal because of the ship.

The measured underwater noise levels near the offshore wind turbine are shown in the two following figures.

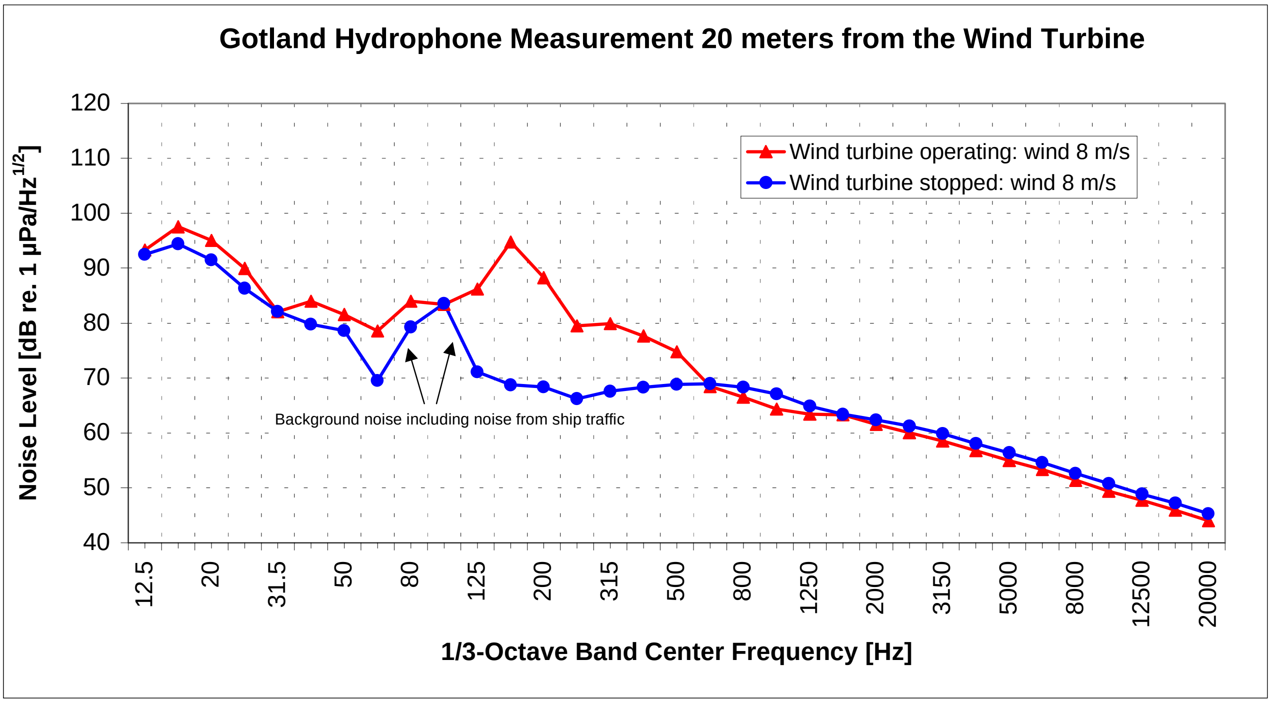

Figure 5

Underwater noise measured 20 meters from the wind turbine at a wind speed of 8 m/s. The frequency range from 10 Hz to 20 kHz are shown as sound pressures given in Power Spectral Density (PSD) – units for the wind turbine operating and stopped.

In Figure 5, the shown noise level was measured 20 meters from the wind turbine whilst the wind turbine is operating and whilst stopped. In both cases, the frequency range is from 10 Hz to 20 kHz. In both operation conditions, the wind speed was about 8 m/s. In the frequency range of 63 Hz to 630 Hz, it appears that the noise levels are highest when the wind turbine operates. The difference in the noise level at the two operation conditions is greatest at 160 Hz and makes a total of about 25 dB. In the rest of the frequency ranges, the difference between the measurements are less than 3 dB, which is within the measurement uncertainty. It can be seen that in the range from 2500 Hz to 20 kHz, the difference is constantly around 1 dB. This constant difference can be explained by a slightly higher wind speed during measurements when the wind turbine was stopped than when the wind turbine was operating.

Likewise, it can be observed that, as previously mentioned, the difference between the measurements in the frequency range below 1 kHz is influenced by a passing ship. The background noise level would probably have been lower, than if the ship had not been there during the measurements.

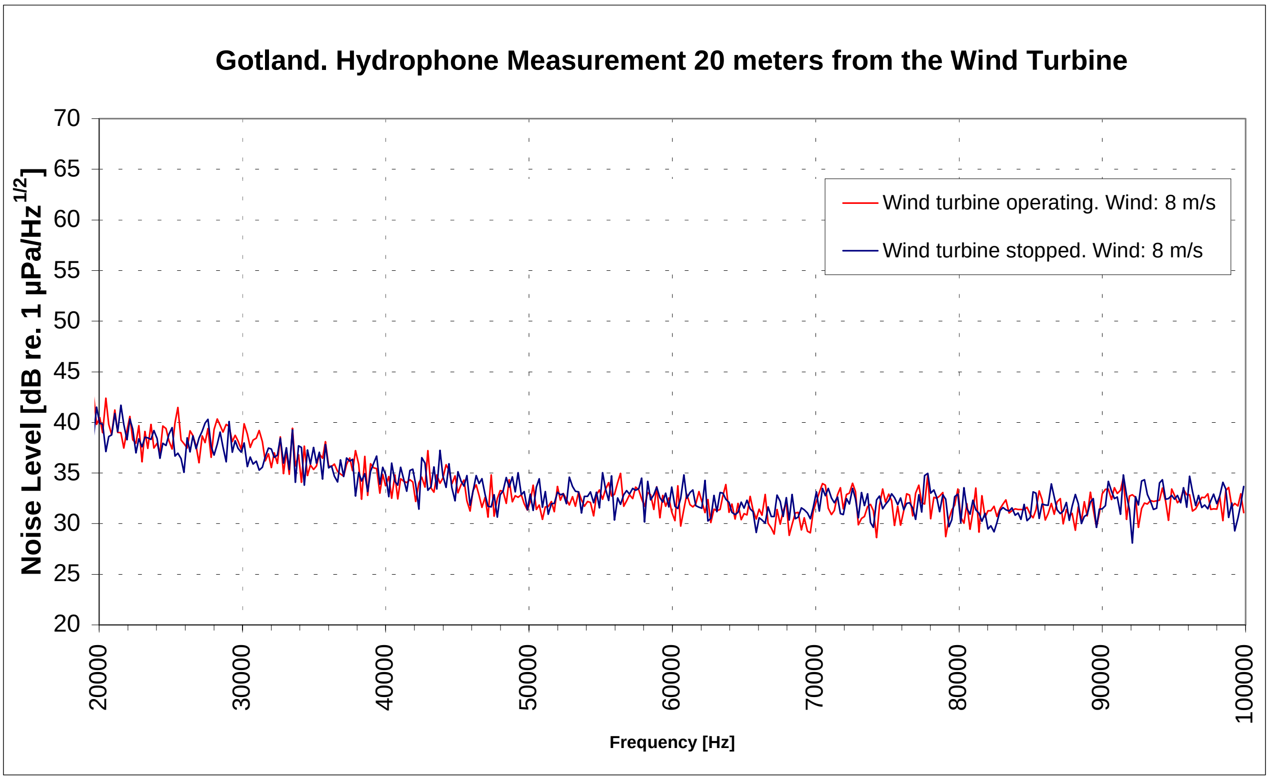

Figure 6

Underwater noise measured 20 meters from the wind turbine (Gotland) at a wind speed of 8 m/s. The frequency range from 20 kHz to 100 kHz are shown as sound pressures given in Power Spectral Density (PSD – units for the wind turbine running and stopped.

Figure 6 shows the measured noise level 20 meters from the wind turbine whilst the wind turbine operates and whilst it is stopped. In both cases the frequency range is from 10 Hz to 20 kHz. In both operation conditions the wind speed was about 8 m/s. From the figure it can be concluded that the difference in the noise level when the wind turbine operates and when the wind turbine is stopped are a few dB, which is within the measurement uncertainty. Thereby it can be concluded that there are no significant differences in the noise level from 20 kHz to 100 kHz when the wind turbine is operating and when it is not.

It can also be seen from Figure 6 that the levels decrease from low to higher frequencies until around 45 kHz. From 45 kHz and up the levels are almost constant. The reason for the constant level is that the lowest levels that can be measured with the set-up used is about 35 dB. In the frequency range from 45 kHz to 100 kHz the measured values is comparable with the set-ups lower limits or less than the set-ups lower limit.

When comparing Figure 5 and 6 level difference of about 4-5 dB is seen at 20 kHz. The reason for this difference is the same as explained in the comments about the Vindeby measurements in chapter 3.1

3.3 Measurement of Vibrations

At Hagesholm (Denmark) a 2 MW NegMicon wind turbine has been measured. The wind turbine represents the type of wind turbine, which will be put up in the sea wind turbine parks. The measurement was done January 6. 2000. The wind was coming from "South – Southwest" (SSW) according to the Danish Meteorological Institute measurement station in Holbæk.

The vibration levels measured on the foundation of the wind turbine are shown in the following figure.

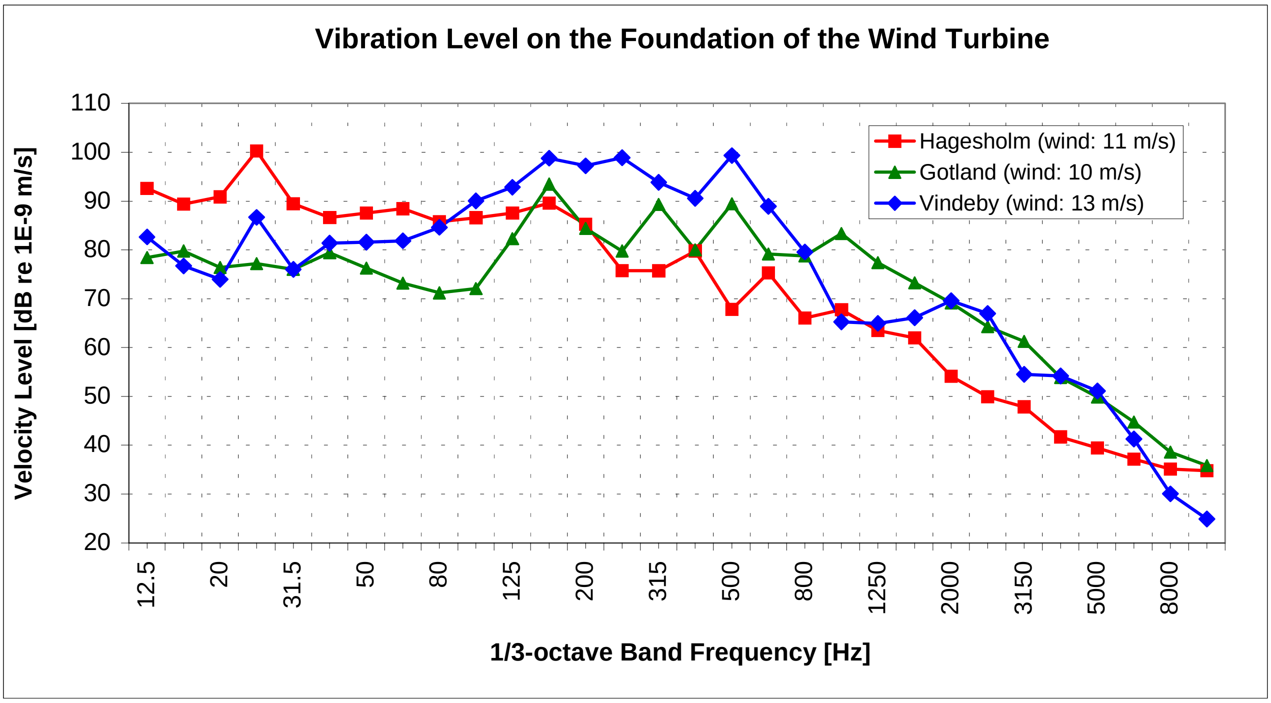

Figure 7

Vibration levels measured on the foundation of a Wind turbine. The shown measurement results are from 3 different wind turbines: Hagesholm (NegMicon 2MW), Gotland (Windworld 550 kW) and Vindeby (Bonus 450 kW). The frequency range 10Hz – 10 kHz are shown as velocity levels in 1/3-octave bands for the wind turbine running and stopped.

It can be seen that the vibration level measured on the 2MW wind turbine is more powerful in the frequency range below 100 Hz and a little less at higher frequencies.

4 Estimated Underwater Noise from Offshore Wind Turbines

The Underwater noise from the offshore wind turbines is given in a distance of about 20 meters from the wind turbine. The noise from the wind turbine will decrease with the increasing distance. A rough estimate of the reduction of the noise level as a function of the increasing distance is that 3 dB is subtracted for every doubling of the distance. That means, that in a distance of 40 meters the noise level will be 3 dB less than the noise levels measured in 20 meters distance. In a distance of 80 meters, the noise level will be 6 dB less than the measured values.

A rough calculation of the noise level in other distances from the wind turbine can be found by using the following equation.

$$L_{p2} - L_{p1} = 10 \cdot \log \frac{r_2}{r_1}$$

Where L_{px} is the noise level in position x

r_x is the distance from the wind turbine to position x

As it appears from the noise measurements, the noise from the wind turbines are masked by the ambient noise when the frequencies approaches 1000 Hz. Therefor scaling is only used at those frequencies where the noise from the wind turbine are higher than the ambient noise.

By using the equation above, it is also possible to calculate the noise level in 1-meter distance, as an indication of the source strength. 13.0 dB is to be added to the noise levels measured in 20 meters distance to get the noise level in 1 meters distance. 11.5 dB is to added to the values in the figure to get the values in 1 meters distance.

Underwater Noise from a Offshore Wind Turbine with Concrete Foundation

The expected underwater noise level in a distance of 14 meters from the wind turbine is presented below.

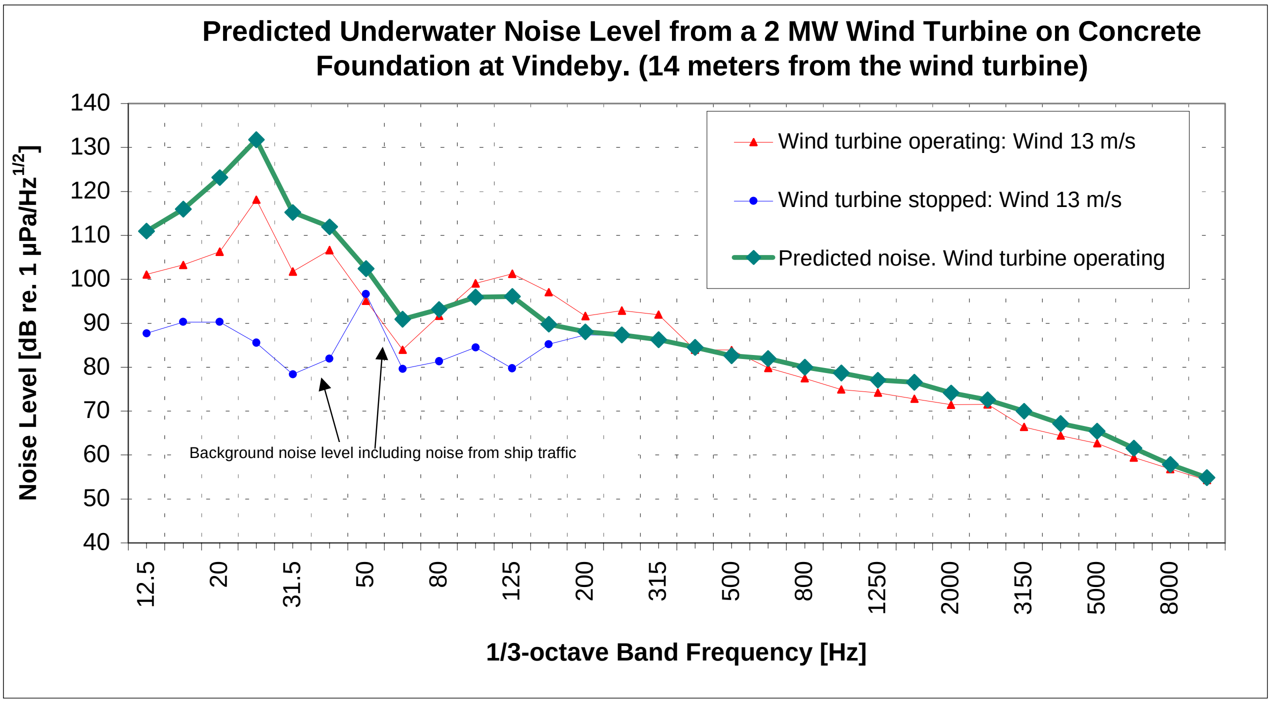

Figure 8

Estimated underwater noise level in a distance of 14 meters from the wind turbine at a wind speed of 13 m/s. The frequency range from 10 Hz to 10 kHz are shown as sound pressures given in Power Spectral Density (PSD) – units for the wind turbine running and stopped. The thin curves are the measured noise levels and the thick green curve is the predicted noise from a 2 MW offshore wind turbine.

Underwater Noise from a Offshore Wind Turbine with a“Monopile” Foundation

The expected underwater noise level in a distance of 20 meters from the wind turbine is presented below.

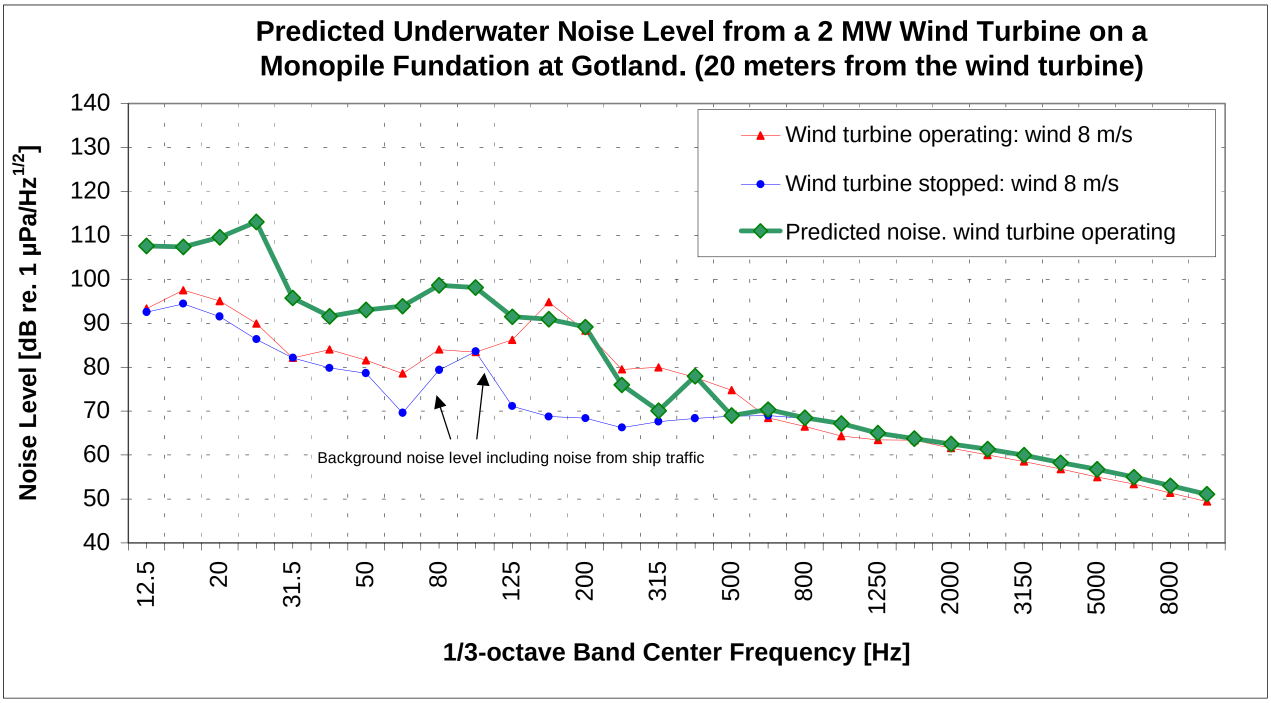

Figure 9

Estimated underwater noise levels at a distance of 20 meters from the wind turbine with a wind speed of 8 m/s. The frequency range from 10 Hz to 10 kHz is shown as sound pressures given in Power Spectral Density (PSD) – units for the wind turbine running and stopped. The thin curves are the measured noise levels and the thick green curve is the predicted noise from a 2MW offshore wind turbine.

5 Noise from a 2MW Offshore Wind Turbine at 8 m/s - Normalisation

In order to compare the measurement results from the two different foundation types, the estimated noise levels were “normalised” to the same wind speed and ambient noise. This "normalisation was performed by scaling the measurements as described below.

The scaling has been done to a reference situation with a wind a speed of 8 m/s and a vibration level corresponding to a 2MW wind turbine and in a distance of 20 meters from the wind turbine.

The vibration level in the tower of the wind turbine and with that the noise from the wind turbine under water follows as a first approximation the expression below:

$$L_{p2} - L_{p1} = 10 \cdot \log \frac{u_2}{u_1}$$

Where L_{px} is the relative noise level from the wind turbine at a wind speed of u_x

u_x is the wind speed in situation x

The ambient noise follows the wind speed as described in the following relation:

$$L_{p2} - L_{p1} = 22 \cdot \log \frac{u_2}{u_1}$$

Where $L_{p2} - L_{p1}$ is the change in the ambient noise

L_{px} is the relative ambient noise level at the wind speed u_x

u_x is the wind speed in situation x

The very significant noise contribution from the ship traffic is taken out by smoothing the ambient noise curve.

Because of the different situations, as the condition of the sea bed, the condition of the current and the ship traffic, the ambient noise is not quite the same off of Gotland as it is off of Vindeby with the same wind speed. In Figure 10, however, an average value is shown to normalise the curve to the same conditions.

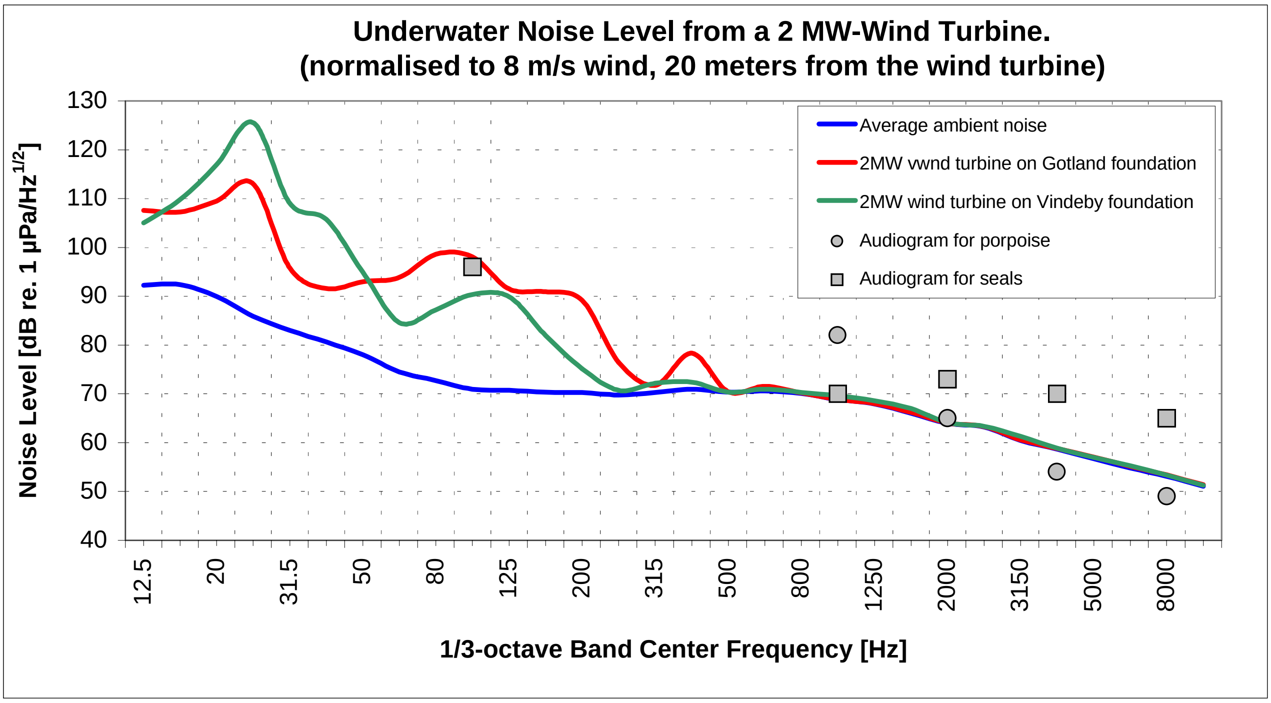

Figure 10

Normalised underwater noise level at a distance of 20 meters from an offshore wind turbine. Wind speed of 8 m/s. The sound pressures are given in Power Spectral Density (PSD) – units for a 2MW offshore wind turbine on a concrete foundation (green curve) and on a steel pipe foundation (red curve). The ambient noise is also given (blue curve). The grey circles indicate the measured hearing threshold for porpoise and the grey squares the hearing threshold for seals, ref.: Marine Mammals and Noise 1995.

As seen in Figure 10, that specific concrete foundation is more noisy below 50 Hz, whilst that specific steel pipe foundation is more noisy in the frequency range from 50 Hz to 500 Hz.

This difference in the noise situation of the two foundation types is probably dependent of the dimensions and construction of each specific foundation. Thus, another type concrete foundation may have other characteristics considering noise propagation.

The audiograms are put in the figure to relate the noise level in a distance of 20 meters to the hearing of porpoises and seals. The audiograms are only shown in the frequency range above 1000 Hz. This is not because the mammals have no hearing ability at frequencies below 1000 Hz, but because we had no access to data of their hearing ability below 1000 Hz. A more detailed treatment of the circumstances around the noise influence on the animal life under water is not taken into consideration in this report.

6 Discussion

The noise from an offshore wind turbine can be transmitted to the water in two ways. Either the noise comes through the air as airborne noise and is transmitted to the water, or the noise is coming from structure-borne noise through the tower and the foundation of the wind turbine and from there radiated underwater. The measurements of the underwater noise will be the total sum of these two contributions.

During the measurements, measurement of the noise above the sea was performed. Based on these measurements, the contribution to the underwater noise under water caused by structure-borne noise and airborne noise was determined. The measurements showed that the airborne noise has a negligible contribution to the underwater noise level. So, the noise measured underwater from the wind turbines, is transmitted through the tower and the foundation of the wind turbine.

The given winds speed are all read on the wind turbine and expresses therefore an average value, which is a rough description of the fluctuating wind situation.

Scaling used for Prediction of Noise Levels

The scaling of the noise levels is based on the measurements of 3 specific wind turbines. It must be expected that the specific spectres are dependent on the different properties of the wind turbines. That is, for other wind turbines, another distribution of maximums and minimums must be expected than the ones reported here. However, generally, it can be expected that the predicted spectres are representative.

From the vibration measurements it is evident that the measurements have not been performed at exactly the same wind speed. This has not been taken into consideration in the scaling. This effect alone is expected give an uncertainty to the prediction of about a two dB.

The prediction is based on individual measurements under different weather conditions. As a consequence a certain uncertainty must be expected. It is estimated that the total uncertainty is about 6-10 dB.

Measurement of Underwater Noise with a Hydrophone

The underwater ambient noise level was determined by the bubbles and waves, which are dependent on wind speed. At frequencies below 50 Hz, incoming waves on the wind turbine, current etc. explains that the noise level can vary up to 20 dB. Empirically the noise spectres vary about 5-6 dB when averaged over a measurement period of 5 minutes as a consequence of the varying wind speed.

The measurement uncertainty of the measurement in this report is estimated to be about 6 dB.

Difference between a Concrete Foundation and a Steel"Monopile" Foundation

From the measurements it is not clear, that the noise from an offshore wind turbine on a concrete foundation is less noise than an offshore wind turbine situated on a steel tube "monopile" foundation. Additional measurements of the two types of wind turbines under the same weather conditions would give this estimate a better standard of reference. In this report however, a normalisation of the measurement results of the two foundation types to the same wind speed and background noise level has been performed. From this comparison it shows that that specific concrete foundation is noisier at frequencies below 50 Hz, whilst the specific steel tube "monopile" foundation is noisier in the frequency range from 50 Hz to 500 Hz.

This difference in the noise levels and spectre of the two foundation types is evident for these investigated foundations, but the noise level and spectre will probably depend of the dimensions and construction of a specific foundation. Another type of concrete foundation will probably have other characteristics considering propagation of noise.

Background Noise

The background noise or the underwater ambient noise was measured in connection to the measurement of the noise from the wind turbine. That is, measured at a distance of about 20 meters from the foundation of the wind turbine with the wind turbine stopped.

In order to determine if there is a difference in ambient noise levels close to a foundation of a wind turbine (wind turbine stopped) compared to ambient levels at a great distance from a foundation, additional ambient noise measurements were performed. This measurement location was South of the island Omø (DK), where a future offshore wind turbine park is planned.

From the results of the measurements it appears that the ambient noise level varies a great deal. The measurements shows variations of approaximately 10 dB.

These measurements were performed in co-operation between Oluf Damsgaard Henriksen, Syddansk Universitet. A more specific statement will be prepared and reported by Danmarks Miljøundersøgelser (DMU) by Oluf Damsgaard Henriksen.

Based on this investigation of the ambient noise, it was concluded, that no noise contribution from the foundation of the wind turbine could be seen when the wind turbine is stopped. So the ambient noise level presented in this report, represents the conditions without offshore wind turbines and a situation with stopped offshore wind turbines.

Noise from Ship Traffic

Ship traffic also generates underwater noise, which can be seen in the presented measurement results. In the Storebælt Channel there are around 12400 ship passages in each direction per year. The noise from the major part of these passages will contribute to the background noise in the planned offshore wind turbine park south of Omø. In other words, it can be expected that the ambient noise is influenced by ship traffic. Thus, the noise from the ship traffic has an effect on the ambient noise but no effect on the measurement results concerning measured noise from the running offshore wind turbines.

7 Conclusion

On behalf of SEAS, Ødegaard & Danneskiold-Samsøe has performed an investigation of the underwater noise radiated from offshore wind turbines.

The results of the investigation are an estimate of the noise that can be expected from the offshore wind turbines underwater. This result is subsequently going to form a base of the evaluation of how the animal life in the sea is effected.

The investigation is based on measurements of the underwater noise from offshore wind turbines with two different types of foundation. The first type is a concrete foundation, which is placed on the seabed (Vindeby, Denmark). The other one is called a “monopile”. In this case, a steel pipe has been driven into the seabed (Gotland, Sweden).

The noise that can be expected by the set-up of new offshore wind turbine of the 2MW class has been estimated and presented in Chapter 4. In Chapter 5, the noise from the two types of wind turbines is presented in a normalised form to give a clearer comparison. The underwater noise from the offshore wind turbines is given in a distance of about 20 meters from the mill. The noise decreases with growing distance.

Primarily you can draw the following conclusions concerning the wind turbine noise propagated underwater:

- Underwater noise from the offshore wind turbines is not higher than the ambient noise in the frequency range above approaximately 1 kHz.

- Underwater noise emitted from the offshore wind turbines is higher than the ambient noise in the frequency range below approaximately 1 kHz.

- Underwater noise levels from offshore wind turbines are different between the two specific foundation types investigated. The specific concrete foundation is more noisy than the specific steel pipe foundation below 50 Hz and less noise in the frequency range of 50 Hz to 500 Hz

- Underwater noise emitted from offshore wind turbines in the 2MW class will, compared to the older offshore wind turbines in the 500 kW class, be noisier at frequencies below 100 Hz and less noisy at frequencies above 100 Hz.