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INGEMANSSON

Utgrunden off-shore wind farm

- Measurements of underwater noise

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Summary

Airicole, GE Wind Energy and SEAS/Energi E2 have initiated this project in order to achieve a better understanding on how offshore based wind farms effect the underwater noise. The main reason is to gain knowledge on how marine wildlife could be effected by this kind of installation.

The measurements were performed at Utgrunden wind farm that is situated at the reef Utgrunden on the Swedish southeast coast. The farm consists of seven 1,5 MW turbines. Three hydrophones registered the underwater sound and four accelerometers the tower vibrations. The measurement campaign was conducted during a period from November 2002 to February 2003.

The objectives with this project is to answer the following issues and its results are:

1. What is the character of sound from a single power station?

   – The turbines radiate sound mainly at a few dominating frequencies from 30 Hz up to 800 Hz. At frequencies below 3 Hz no contribution from the turbines can be detected due to the high background level from the waves and the low tower vibration level.

2. What are the sound generating mechanisms in the turbine?

   – Gearbox mesh frequency vibrations that are transmitted via the tower structure and radiated out to the water mainly generate the sound. Airborne blade sound is effectively dampened in the transition from air to water.

3. How does the sound attenuate with increasing distance at different frequencies?

   – The average attenuation per doubled distance for frequencies between 31 Hz and 722 Hz is approximately 4 dB in the measured positions. No clear frequency dependence could be found.

4. How does the sound pressure level vary with increasing wind speed?

   – With increasing wind speed, the sound pressure level increases and the dominating frequencies move upward due increasing turbine rotational speed.

5. How does sound from different power stations interfere with each other and influence the over all sound image?

   - No clear tendencies of interference could be observed in this study. This could be due to small variations in turbine speed and that the hydrophone positions needs to be less dominated by a single turbine.

6. How is a passing ship influencing the sound level in the farm?

   - Passages of ship dominates the sound in the park for frequency higher than approx. 63 Hz. There is a strong dependence of type of ship, distance etc.

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1. Background

Airicole, GE Wind Energy and SEAS/Energi E2 have initiated this project in order to achieve a better understanding on how offshore based wind farms effect the underwater noise. The main reason is to gain knowledge on how marine wildlife can be effected by this kind of installation. Since there are a large number of farms under planning around the coasts of especially Europe there is great need to obtain knowledge in these matters.

Previous studies on offshore-based wind turbines have only been made on single and smaller turbines. This study is the first to our knowledge that is performed on a complete wind farm with large turbines (1,5 MW) during a longer period in time.

The objectives with this project has been to answer the following issues:

1. What is the character of sound from a single power station?
2. What are the sound generating mechanisms in the turbine?
3. How does the sound attenuate with increasing distance at different frequencies?
4. How does the sound pressure level vary with increasing wind speed?
5. How does sound from different power stations interfere with each other and influence the over all sound image?
6. How is a passing ship influencing the sound level in the farm?

Representatives from organizations involved where:

Airicole	Hans Ohlsson
GE Wind Energy	Martin Kuhn, Andreas Petersen, Bert-Ove Svensson
SEAS/Energi E2	Pernille Holm Skyt
Swedish Navy	Björn Berndtsson

Björn Berntsson from the Swedish Navy arranged radar surveillance of the ship traffic during the measurement campaign and assisted to a large extent with his knowledge and experience in the project.

2. Underwater acoustics

2.1. Decibels under water and in the air are not the same

The unit decibel for sound pressure is used in many contexts and are defined by the relation:

$X\ dB = 20 \log (Y/Y_{ref})$

where,

Y = Sound pressure in Pascal

Y_{ref} = Sound pressure reference value

Sound pressure levels in air should always refer to a pressure of 20 µPa according to ISO standards.

Water is a fluid with properties that are very different from air, and so is the physics of underwater sound waves. For both physical and historical reasons a different reference has been chosen. The standardised reference pressure is 1 µPa.

As an example, the pressure 1 Pascal in air is defined as 94 dB but in water is the same pressure defined as 120 dB due to the difference in reference used. In order to convert from water decibels to air decibels just subtract 26 dB from the water dB value.

The different references imply that sound pressure levels in air and in water cannot and should not be compared directly. This is also due to the fact that the coupling of sound waves to human or animal organs is different in air and in water.

2.2. Sound propagation

The propagation of underwater sound is different from that of sound in the air in some important aspects.

If we consider a wind turbine, the sound generated in the air will spread in all directions. The only limit is the ground or the water surface. Thus, at large distances the sound will be distributed over a hemisphere, one half of a ball, up in the sky and to all sides. The area of the hemisphere increases as the square of the distance to the centre ($A = \pi * r^2$). A doubling of the distance means that that the area is quadrupled and thus the intensity of the sound will be reduced by a factor of four.

The sound generated underwater will be trapped between the bottom and the water surface. Thus, in shallow waters, the sound will propagate over a cylinder and the area of the cylinder will be directly proportional to the distance ($A = h*\pi * r$). A doubling of the distance means that the area of the cylinder is doubled and the sound intensity will be halved.

The decibel scale is logarithmic, which means that the sound from a wind turbine will decrease by 6 dB per doubling of the distance in the air and by 3 dB per doubling of the distance underwater. Thus underwater sound from a wind turbine may propagate much longer distance than the sound in the air.

This is the basic model for sound propagation. Special meteorological and hydrological conditions may also affect the propagation significantly such as dampening in the sea bottom, thermal layers in the water, varying depth etc.

2.3. Perception of sounds

A young normal hearing person can hear sounds in the air in the frequency range of 20 to 20 000 Hz and is most sensitive to sounds between 2000 to 4000 Hz. We may also be affected by sounds under 20 Hz even though we can't hear them.

Marine animals perceive sounds very differently from humans and there is a large variation between different species. A cod is sensible to frequencies between 50 and 5000 Hz while seals and dolphins can perceive frequencies far above 20 000 Hz.

A often rule of thumb for relating the sound pressure between air and underwater measurements for animals e.g. seal is to subtract 62 dB from the underwater sound level. As an example, a tone measured underwater to 95 dB re. 1μPa is above water in air perceived as

95-62 = 33 dB re. 20 μPa.

This assumption behind this that the same sound energy should be transmitted to the ear both underwater and in air.

2.4. Underwater sound radiation from wind turbines

The underwater sound from wind turbines is mainly generated by vibrations in the tower. The towers have a large contact area with the water, which transmits the sound effectively. The tower will also transmit vibrations to the sea floor but this effect is judged to be of minor importance. Airborne sounds from blade tips are effectively reflected in the water surface and do not affect the underwater sound level.

The tower vibrations are mainly generated from the gearbox mesh frequencies and the generator. Thus, underwater sounds from a wind turbine can be identified as tones mainly below 1000 Hz.

3. Measurement object

3.1. Utgrunden wind farm

Utgrunden wind farm consists of seven 1,5 MW turbines situated on the reef Utgrunden that is situated between the Swedish southeast coast and the Öland island. The distance from the Swedish coast to Utgrunden is 12,5 km. The seven wind turbines are placed at a depth ranging from 4 to 10 meters. The measurements have been taken from the middle turbine number 4 in the farm.

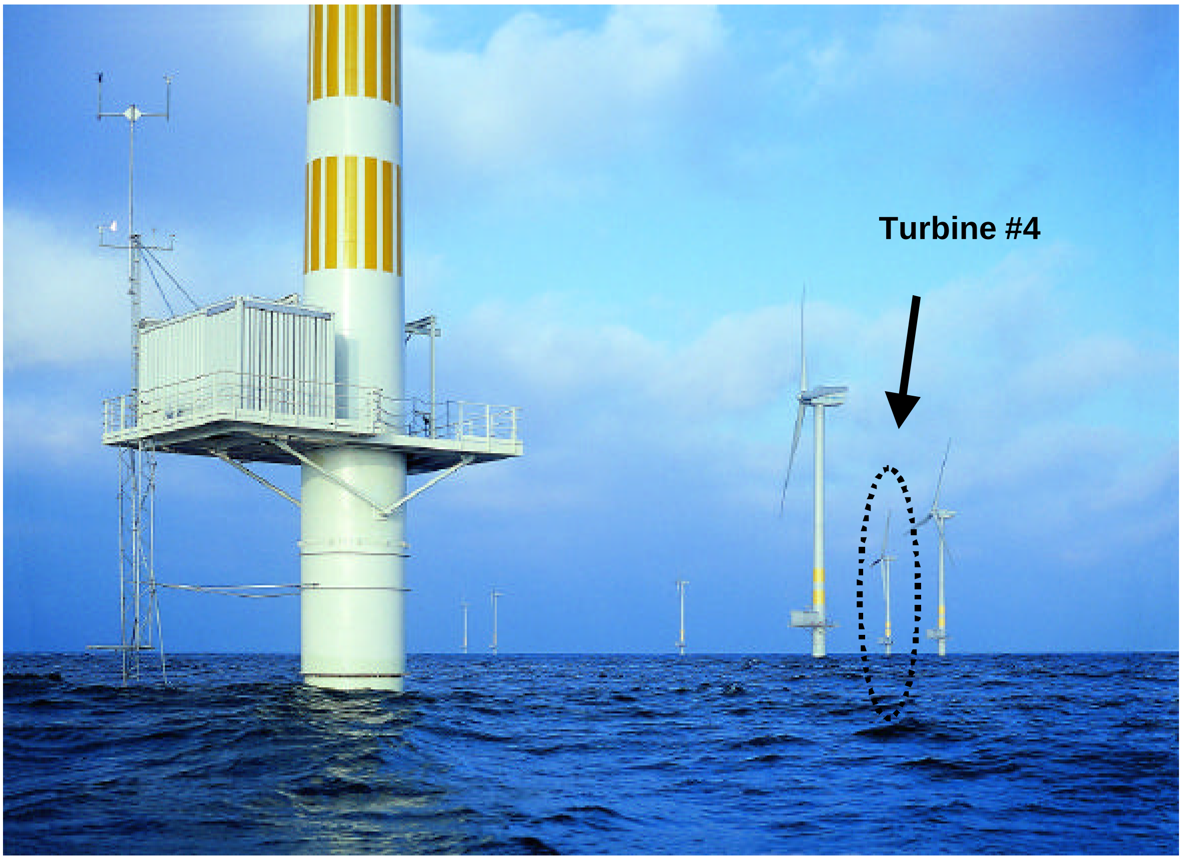

Figure 1 Utgrunden wind farm, looking north

Figure 2 Utgrunden wind farm in the Baltic Sea

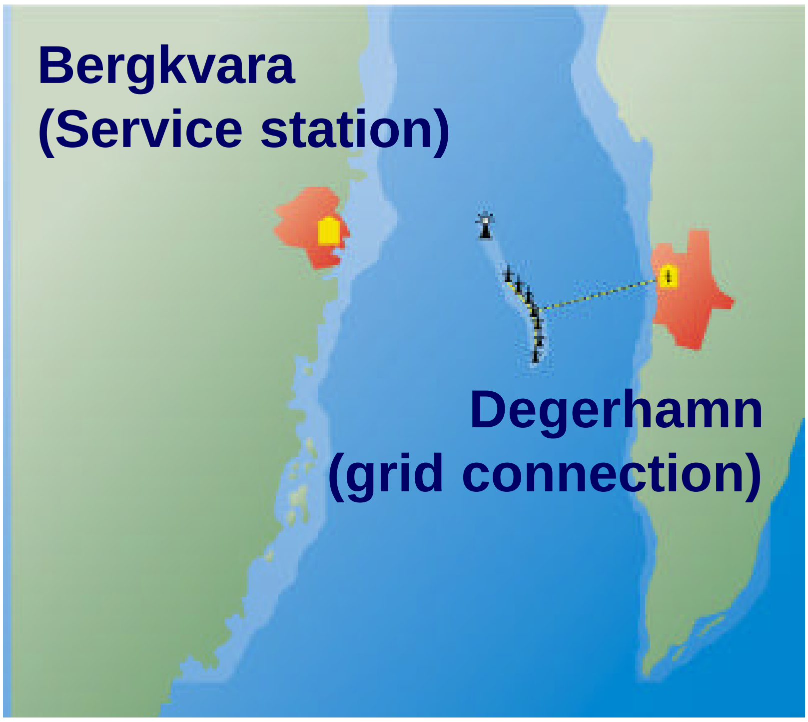

Figure 3 Utgrunden in Kalmarsund

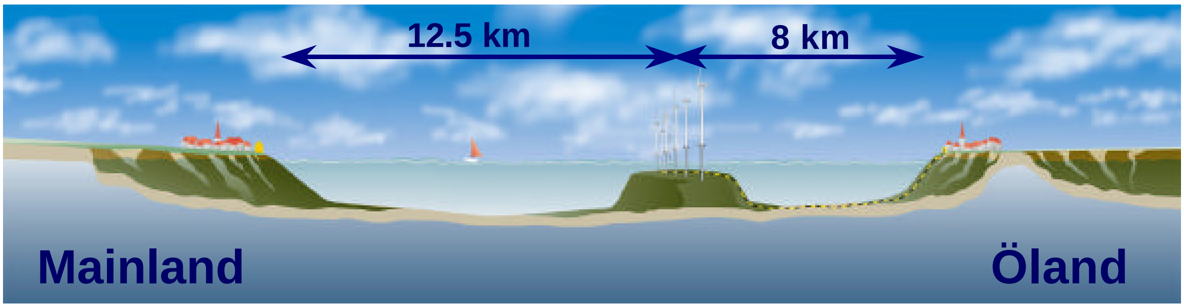

Figure 4 Utgrunden wind farm

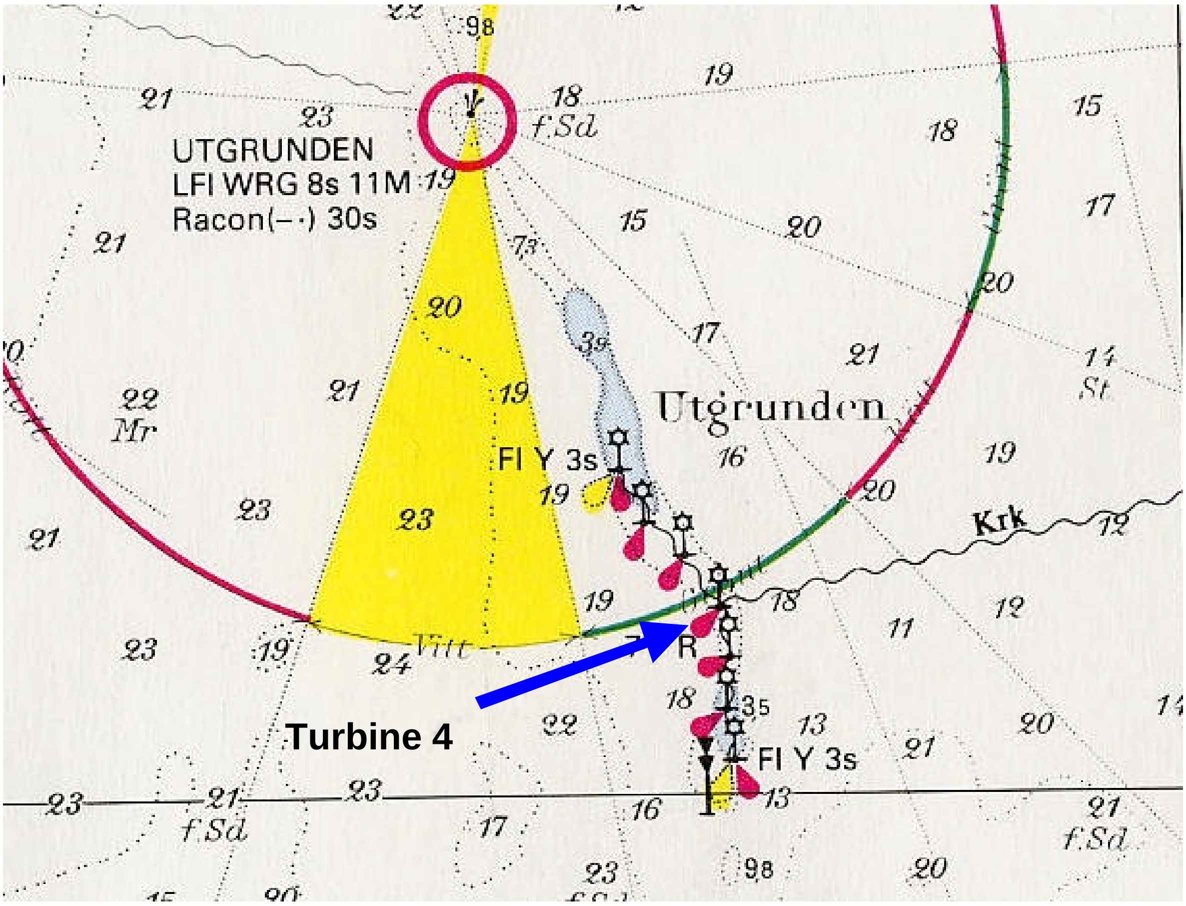

Figure 5 Utgrunden wind farm with depth curves in meters

3.2. Description of turbine

The turbines are of model **GE Wind Energy 1,5s offshore** with the following specifications:

- Rated power, 1,425 MW
- Number of blades, three
- Rotor diameter, 70,5 m
- Hub height above ground, 65 m
- Cut-in wind speed, 3 m/s
- Cut-out wind speed, 25 m/s
- Turbine speed, 11 to 20 rpm
- Variable speed design with asynchronous generator
- Foundation, driven monopile
- Gearbox type, Eickhoff CPNHZ-195
- Gear ratio turbine:generator, 1:90,3
- Generator, Loher JFRA560LB-04A, asynchronous

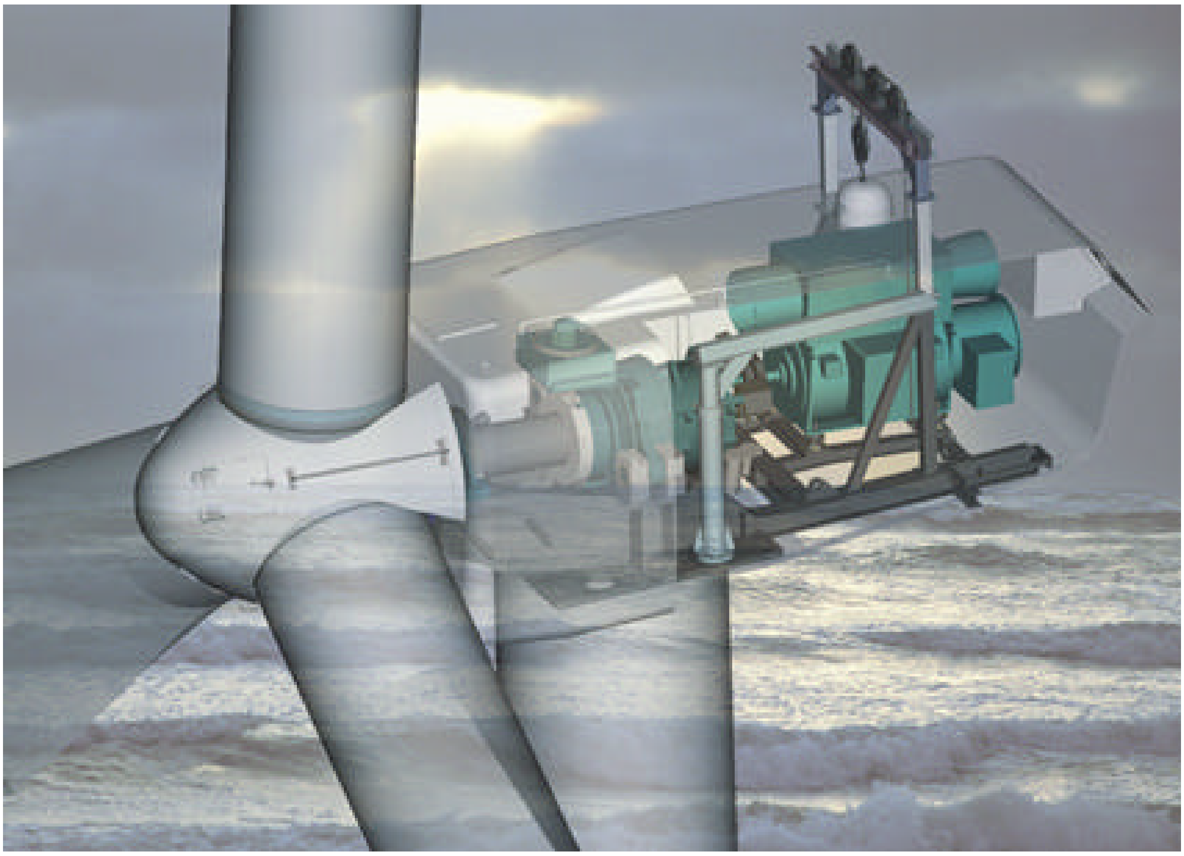

Figure 6 Turbine interior, service crane mounted

4. Measurement conditions

The measurement campaign was conducted from November 2002 to February 2003. The initial intention was to measure sound and vibration from the farm at three wind speeds low, medium and high at approx. 4, 8 and 12 m/s. During the measurement period the ship traffic were surveyed by radar ensuring that no ship sound would interfere with the measurements. Beside this "intensive" measurements also long time registration of the signals were measured.

At each wind condition the wind farm should be operated in accordance to Table 1.

Measurement #	Turbine #	Operation mode	Measurement time (min)
1	All	Running	30
2	4	Stopped	5
3	4 – 5	Stopped	5
4	3 – 5	Stopped	5
5	3 – 6	Stopped	5
6	2 – 6	Stopped	5
7	2 – 7	Stopped	5
8	All	Stopped	30
9	4	Running	5
10	4 – 5	Running	5
11	3 – 5	Running	5
12	3 – 6	Running	5
13	2 – 6	Running	5
14	2 – 7	Running	5
15	All	Running	30

Table 1 Wind farm operation modes

- **The high wind speed measurement**s were taken in November 11:th 2002 between 11:10 and 14:23. The wind was then 12 to 14 m/s from East and the generator speed 1780 rpm. The complete measurement program was successfully conducted.
- **The medium wind speed measurements** were taken in January 2:nd 2003 between 9:15 and 11:48. The wind was then 7 to 9 m/s from Northeast and the generator speed 1760 rpm. At this period turbine 5 was at stand still due to gear problem and turbine 7 was also shut down due to unknown operation problems. Beside this the measurement program were successfully conducted.
- **The low wind speed measurements** could not be conducted in accordance with the measurement program due to freeze-up of the see in Kalmarsund in January. During the break-up of the ice some weeks later in a storm the hydrophone cables were torn off. This forced us to cancelled further measurements. We were unfortunate since this was the first freeze-up of Kalmarsund since the mid 80:s. In order to still get information about low wind speed conditions measurements were taken from the long time measurements recorded in December 2:nd between 2:00 and 2:30. The wind was 4 m/s from Southeast and generator speed 1080 rpm.

During the whole measurement campaign the water temperature were close to constant over the water depth according to measurements performed by the Swedish Navy. The layer effects could thereby be considered to be negligible during the measurement period.

5. Measurement procedure

The sensors used in the project are three hydrophones for registering the underwater sound and four accelerometers placed in the turbine tower for detecting the tower vibrations.

5.1. Hydrophone positions

Figure 7 and Figure 8 describes the position of the hydrophones in relation to the turbines.

The sea bottom consists mainly of fine sand with some small rocks.

Distances and depth of the hydrophones are described in Table 2. The distances have an uncertainty of +/- 10 m.

Hydrophone	Distance to turbine 4	Water depth
Hyd 1	463 m	18,0 m
Hyd 2	160 m	15,2 m
Hyd 3	83 m	12,9 m

Table 2 Distance to turbine 4 and water depth for the hydrophones

The hydrophones were mounted on an aluminium rod standing on a concrete foundation. This arrangement places the sensing element of the hydrophone 1 meter above the sea floor. Around the sensing element a nylon stocking were placed in order to prevent flowing water from introducing dynamic pressure fluctuations acting directly on the sensing surface. Small holes were also opened in the top of the stocking for letting the trapped air out (Figure 9).

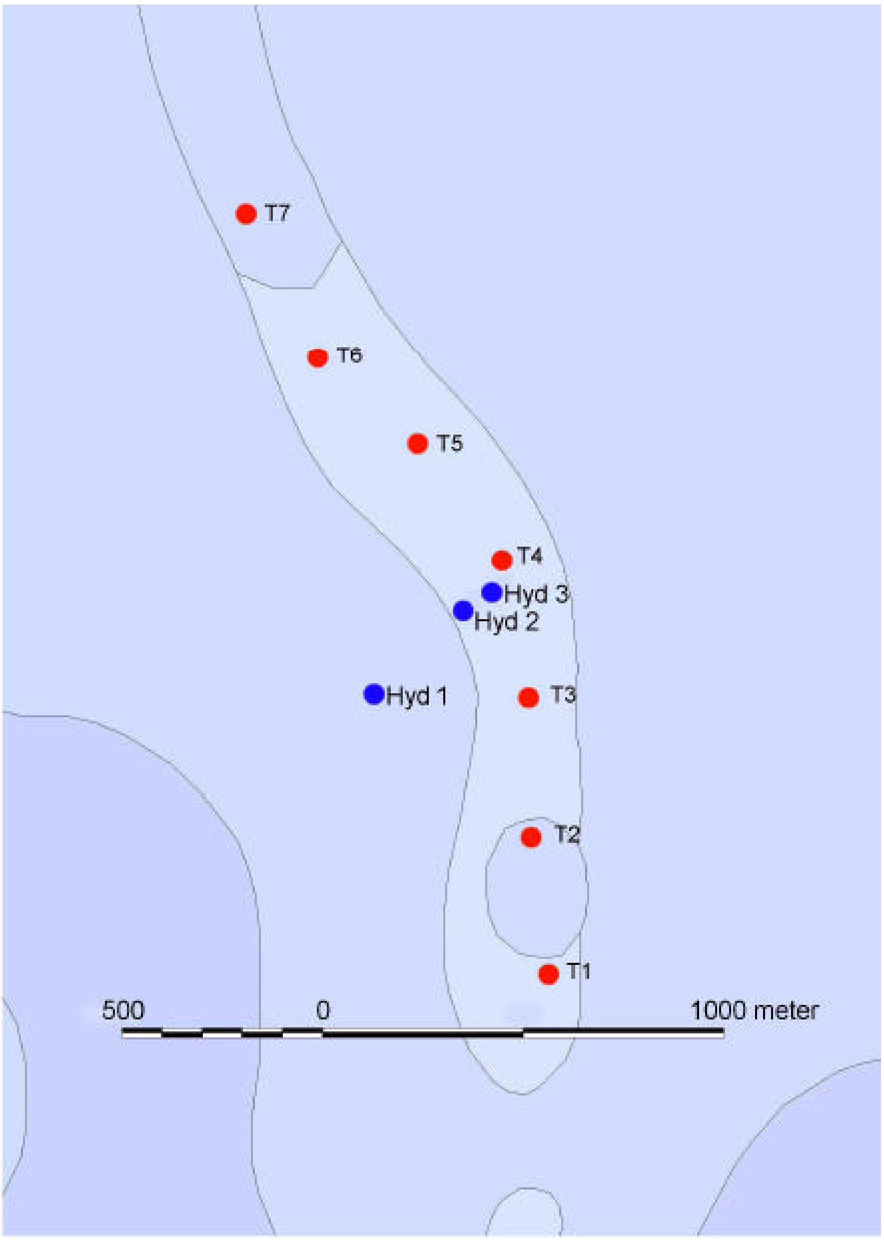

Figure 7 Utgrunden wind farm and hydrophone positions

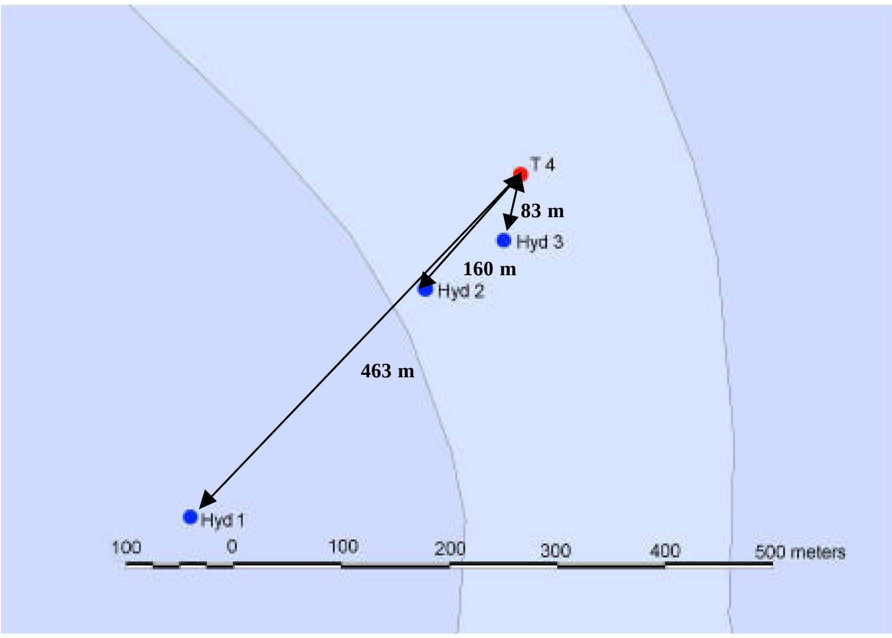

Figure 8 Turbine 4 and hydrophone positions

Figure 9 Hydrophone B&K 8101 on concrete foundation

5.2. Accelerometer positions

The two locations of the accelerometers are described in Figure 10. In each location are two accelerometers located measuring both in the radial and tangential direction. These locations are exactly the same as Klaus Betke et al from ITAP (Institut fuer Technische und Angewandte Physik GmbH an der Universitaet Oldenburg) used in their project during their measurements in October 2002.

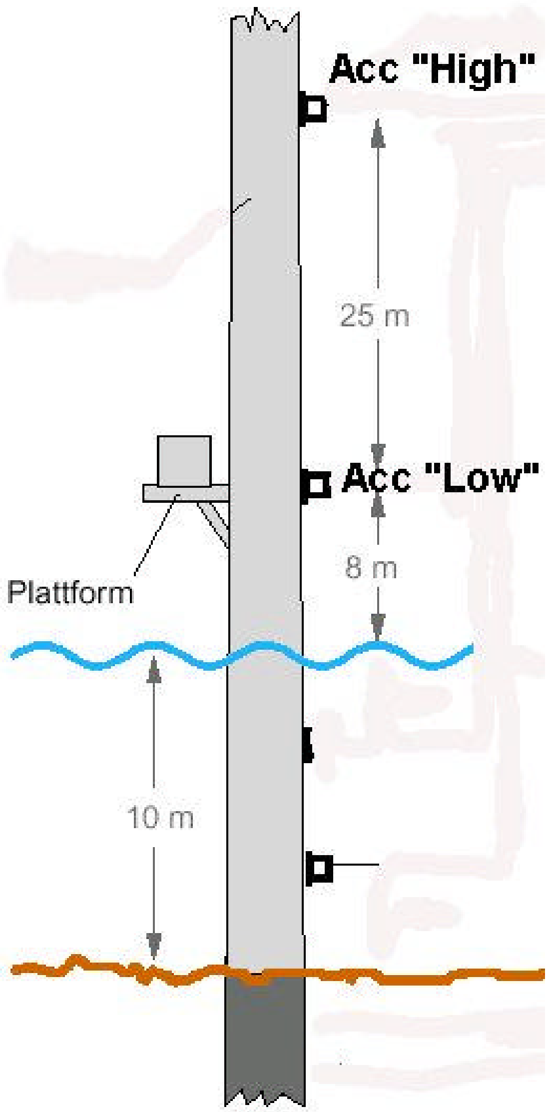

Figure 10 Accelerometer positions in turbine tower

5.3. Measurement equipment

5.3.1. Hydrophones

The sound was measured from 1 Hz to 2000 Hz. The reason not to measure below 1 Hz is due to dynamic measurement problems with the very high sound pressure level generated by waves at very low frequencies will overhear sound at higher frequencies at lower amplitudes. The turbines also generate low sound levels at frequencies below 1 Hz.

Frequencies above 2000 Hz is considered not to be of any importance due to that fish can not hear above this frequency.

Hydrophone 1 and 2, type B&K 8101, are powered by B&K 2804 power supplies and the signals are amplified in B&K 2635 charge amplifiers. Due to the fact that the built in amplifier in B&K 8101 is an impedance amplifier the signal needs to be further amplified before the AD converter. This is done by fitting serial capacitors at 100 nF at the input of a B&K 2635 charge amplifier. This converts the voltage signal from the hydrophone to a charge signal and amplifies at the same time the signal 40 dB.

Hydrophone 3, type Burns Electronics CR-3DC, is powered by a Ingemansson S6 power supply with 12 V. Since the hydrophone already has a built in 40 dB amplifier no further amplification is needed before the AD converter.

Hydrophone	Type	Ingemansson ID # Serial #
Hyd 1	Bruel&Kjaer, 8101	933646
Hyd 2	Bruel&Kjaer, 8101	1442560
Hyd 3	Burns Electronics, CR-3DC	HF-001

Table 3 Hydrophones used

5.3.2. Accelerometers

Acceleration was measured from 1 Hz up to 2000 Hz, which is the same as the hydrophone signals.

The accelerometers were powered directly from the measurement system.

Accelerometer	Type	Ingemansson ID #
High radial	Endevco 61-500	VP85
High tangential	Endevco 61-500	VP82
Low radial	PCB 356B18, tri axial	VP 213
Low tangential	PCB 356B18, tri axial	VP213

Table 4 Accelerometers used

5.3.3. Data collection

Data collection is made in a Leuwen Measurement System (LMS) Road-Runner, which is a 16 channel, 16 bit measurement computer. The Road-Runner was during the whole measurement period connected to the wind turbine network. This enabled the possibility to remotely control data acquisition and verifying results.

An external hard disk at 60 G byte were connected to the Road-Runner allowing long time registration of time signals.

The measurements were divided in two types. The first type is during intensive measurement when individual turbines were controlled. The signals were then sampled at 10 kHz at all channels.

The second type is for long time registration for registering ship traffic and for later evaluation of data. In order to save disc space the hydrophones were sampled at 5 kHz and the accelerometers at the Low position at 2500 Hz.

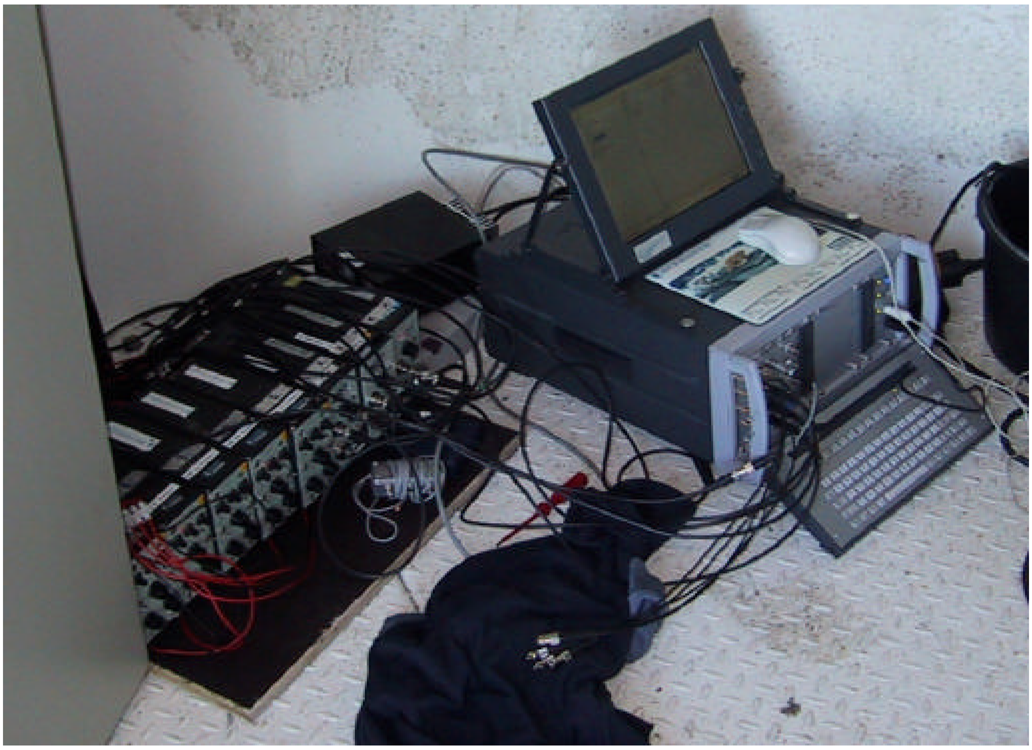

Figure 11 Measurement equipment installed in turbine tower

5.3.4. Frequency analysis

The narrow band spectrums in the report are calculated by FFT with a resolution of 1 Hz and Flattop window. Spectrums are averaged over time available and are at least 3 minutes.

5.4. Verification of quality

Ingemansson Technology is certified to ISO 9001and the project has been subjected to Ingemansson quality assurance routines. E.g. measurement equipment are calibrated with traceability to national laboratories, sensors are calibrated before and after measurement.

6. Results

6.1. Character of sound from wind turbines

In order to analyse the sound from a turbine, measurements were taken from Hydrophone 3, 83 m from Turbine 4 while operating at 14 m/s and compared with stand still measurements. Data were collected from the "High wind speed" measurements described in chapter 4 with only turbine 4 in operation. Hydrophone 3 was chosen since it picks up the highest signal amplitude from the turbine.

The measurements showed that the turbine mainly radiates sound at few frequencies that can be found in Figure 12.

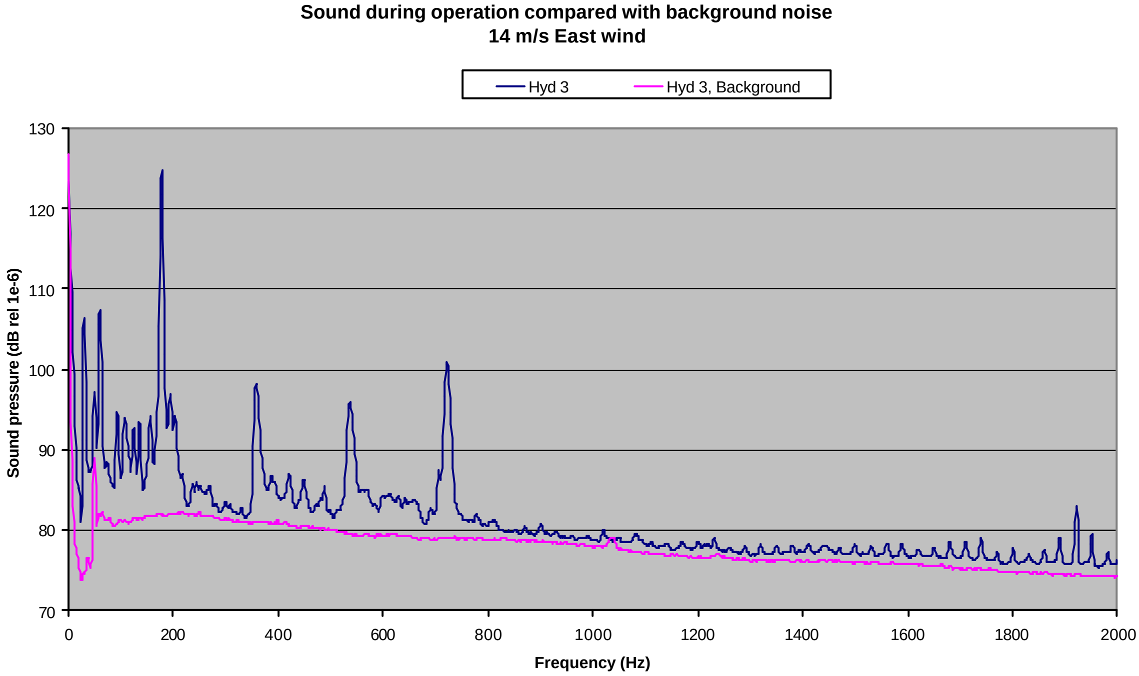

Figure 12 Sound power at 14m/s East from Hydrophone 3

Figure 13 and Figure 14 is the same as in the previous figure but from 1 to 200 Hz and 1 to 20 Hz. The peak at 50 Hz is related to power frequency noise. The detectable sound pressure contribution from the turbine starts from 3 Hz.

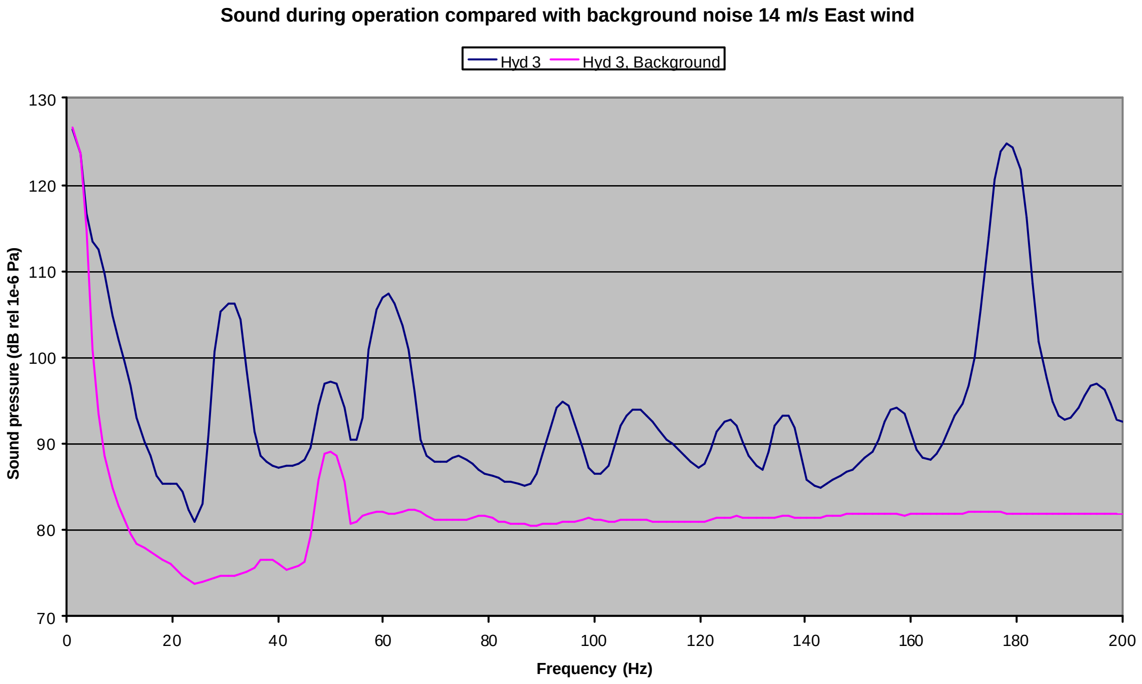

Figure 13 Sound power at 14m/s East from Hydrophone 3, low frequency close up.

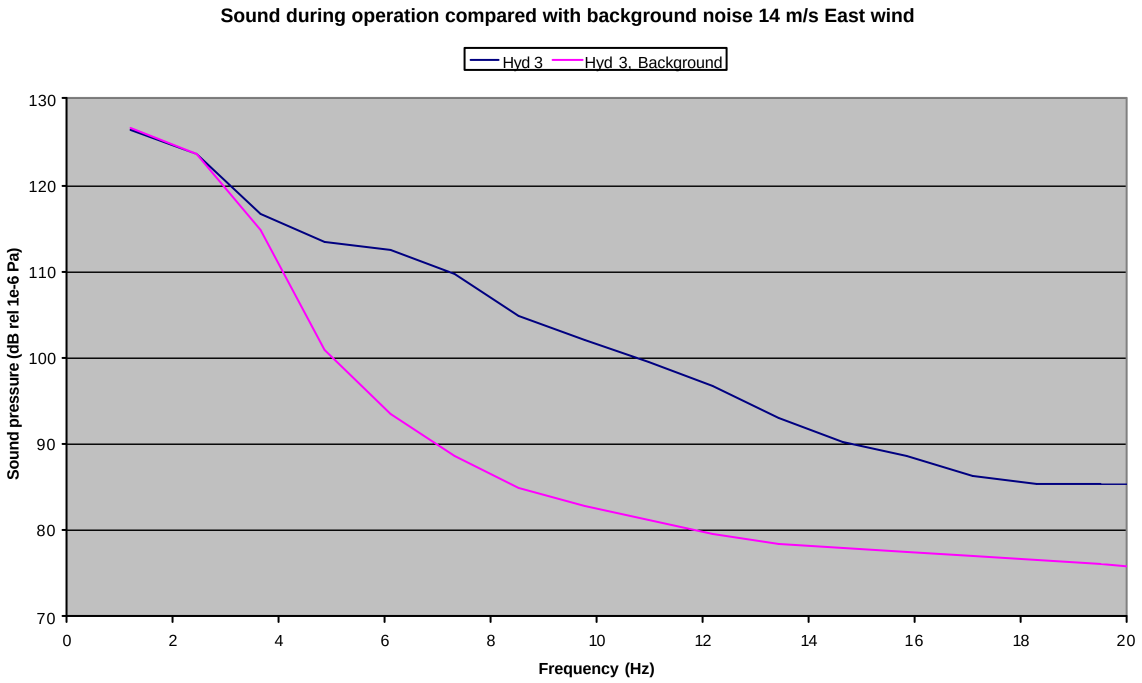

Figure 14 Sound power at 14m/s East from Hydrophone 3, very low frequency close up.

6.2. Sound propagation

One question is how the sound level will decrease with increasing distance from the turbine. As mentioned in chapter 2.2 the attenuation with no dampening effects and constant water depth is 3 dB per doubling of distance but in reality there is dampening in the sea bottom and the water depth is increasing which spreads the sound over a larger area.

In order to estimate the real attenuation sound peaks from the three hydrophones are measured and then by knowing the distances from the turbine to the hydrophone an attenuation ratio can be calculated. Figure 15 shows the peaks from the hydrophones at the "High wind speed" measurement described in chapter 4 with only turbine 4 in operation.

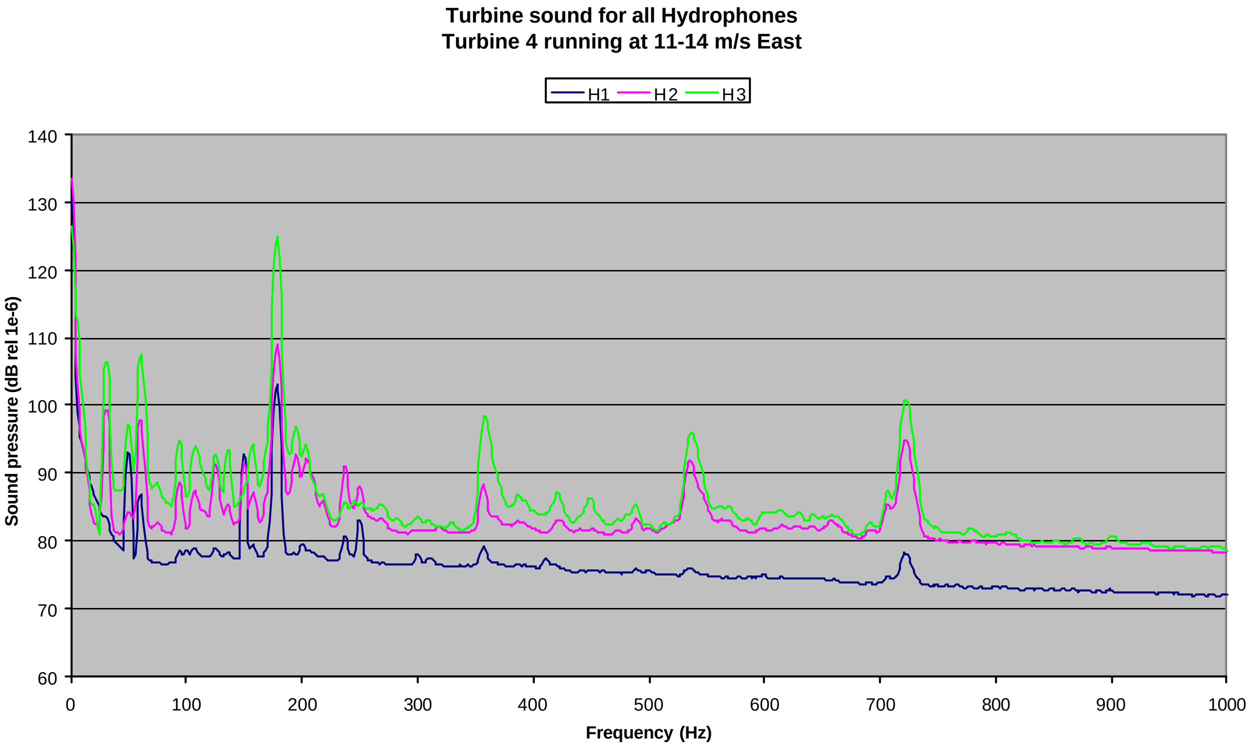

Figure 15 Turbine 4 sound at 11-14 m/s east at the different hydrophone positions.

The amplitudes at the frequencies were measured and the calculated attenuation ratios are presented in Table 5. These results which show approximately 4 dB attenuation per distance doubling comply well with the theoretical attenuation ratio of 3 dB per doubling of distance where the assumption of cylindrical propagation, no surface or bottom dampening and constant depth were made.

By knowing the attenuation per distance sound levels can be estimated at greater distances and can be used to predict sound levels in future wind farms.

Freq (Hz)	Attenuation per doubled distance (dB)		
	H3-H2	H3-H1	H2-H1
30,5	3,5	4,1	5,4
61,0	4,8	3,7	3,8
178,2	7,9	3,9	2,1
357,7	5,1	3,4	3,1
537,1	2,2	3,6	5,4
722,7	3,0	4,1	5,8
Avg	**4,4**	**3,8**	**4,3**

Table 5 Attenuation per doubled distance at different frequencies and distances

6.3. Tower vibration and underwater noise relation

In order to investigate the source of the noise four accelerometers measuring tower vibrations were mounted as described in chapter 5.2. The tower vibrations are then compared with the sound from Hydrophone 3. Measurements were taken from the "High wind speed" conditions described in chapter 4 with only turbine # 4 in operation. What can be found in Figure 16 is that almost all peaks in the sound level from Hydrophone 3 can also be found in one or several of the accelerometer signals from the turbine tower. The pattern is the same for the Hydrophone 1and 2.

This shows that the sound peaks found in the water originate from tower vibrations. The tower vibrations are mainly generated from the gearbox.

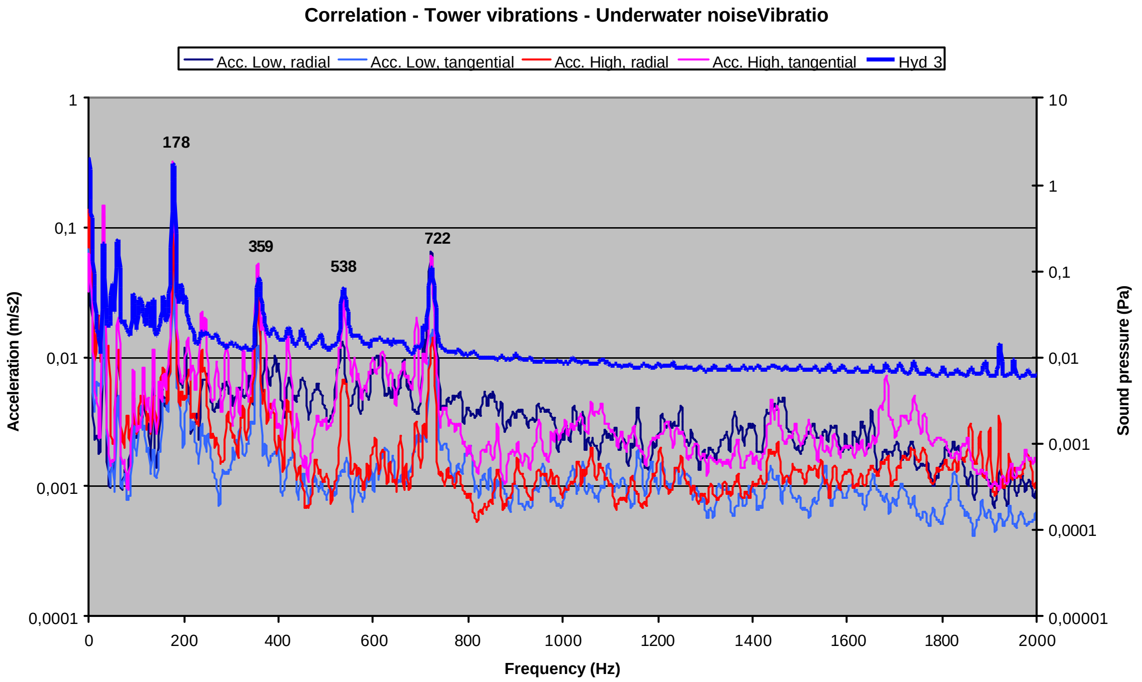

Figure 16 Vibration-sound correlation on Turbine 4. Measurement taken at "High wind speed" conditions 14 m/s East.

If we concentrate in the lower frequency region the picture becomes even clearer which is shown in Figure 17.

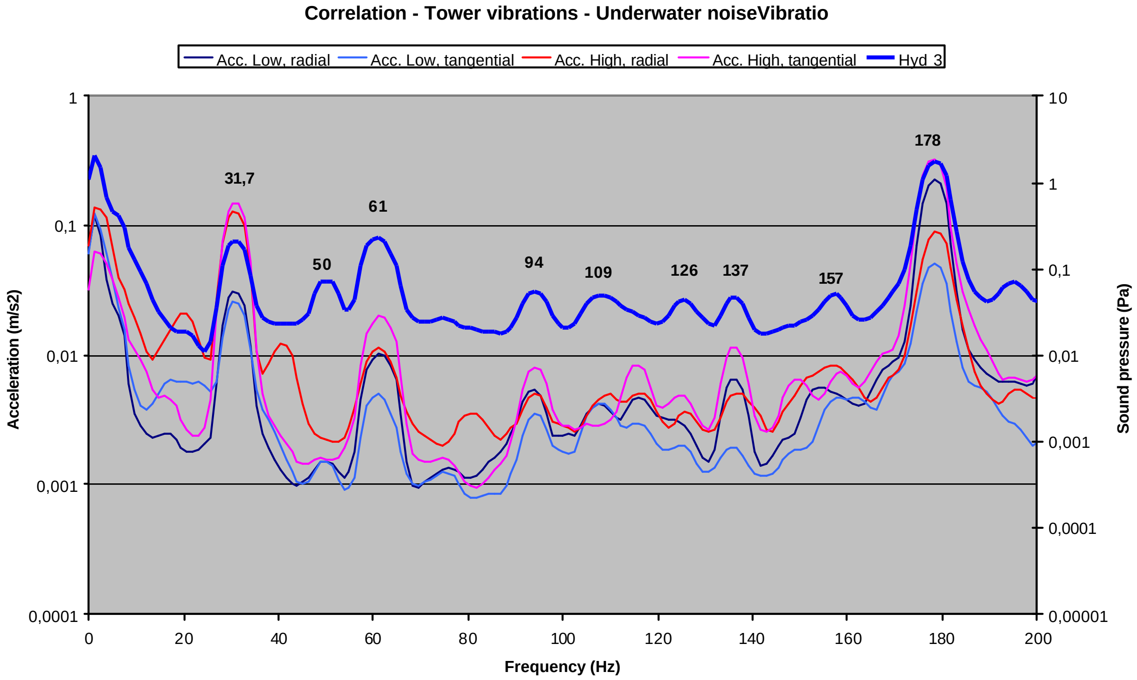

Figure 17 Vibration-sound correlation on Turbine 4, low frequency close up

The measurements were recorded at 14 m/s, East wind with only turbine 4 in operation. Dominating frequencies and their originating sources, where easily located are:

Number	Frequency, Hz	Source
1	31,7	Gearbox stage 1, Planetary stage, fundamental tone
2	61,0	Gearbox stage 1, Planetary stage, 1:st harmonic tone
3	94,0	Gearbox stage 1, Planetary stage, 2:nd harmonic tone
4	109	-
5	126	Gearbox stage 1, Planetary stage, 3:rd harmonic tone
6	137	-
7	157	Gearbox stage 1, Planetary stage, 4:rt harmonic tone
8	178	Gearbox stage 2, fundamental tone
9	359	Gearbox stage 2, 1:st harmonic tone
10	538	Gearbox stage 2, 2:nd harmonic tone
11	722	Gearbox stage 3, fundamental tone

Table 6 Dominating frequencies and their sources

6.4. Wind speed influence on sound

In order to estimate the influence of wind speed on the sound level. The sound level with the farm in operation has been measured at three wind speeds at approximately, 4 m/s, 8 m/s, and 14 m/s. The measurement are taken from the High, Medium and Low wind speed conditions described in chapter 4.

Since there are no measurements of only turbine 4 in operation at low wind speed due to conditions earlier explained in chapter 4, the measurements used are taken from all turbines in operation for the different wind speeds.

The results are found in Figure 18 and shows how the sound increases with increasing wind speed for hydrophone 3. Also the background levels from the medium and high wind speeds are presented in the same figure.

The implication of all turbines being in operation at the same time is that interference from the neighbouring turbines can effect the results. But since the evaluation is made on the closest hydrophone # 3 this effect is negligible.

One observation is that the dominating frequencies vary with the wind speed due to varying rotational speed of the turbine. This can be seen by looking at e.g. the 3:rd octave band at 31,5 Hz. At the High and Medium wind speed there is a clear peak that moves to the 20 Hz 3:rd octave band at the Low wind speed.

The results are presented in 3:rd octave plots which is the commonly used method of presenting sound levels at different frequencies and displays the received sound energy in a specific frequency interval. Since there is a need for distinguishing frequencies more at the lower frequencies than at the higher, the frequency interval increases logarithmically with increasing frequency as found in the X-axis in the figure below.

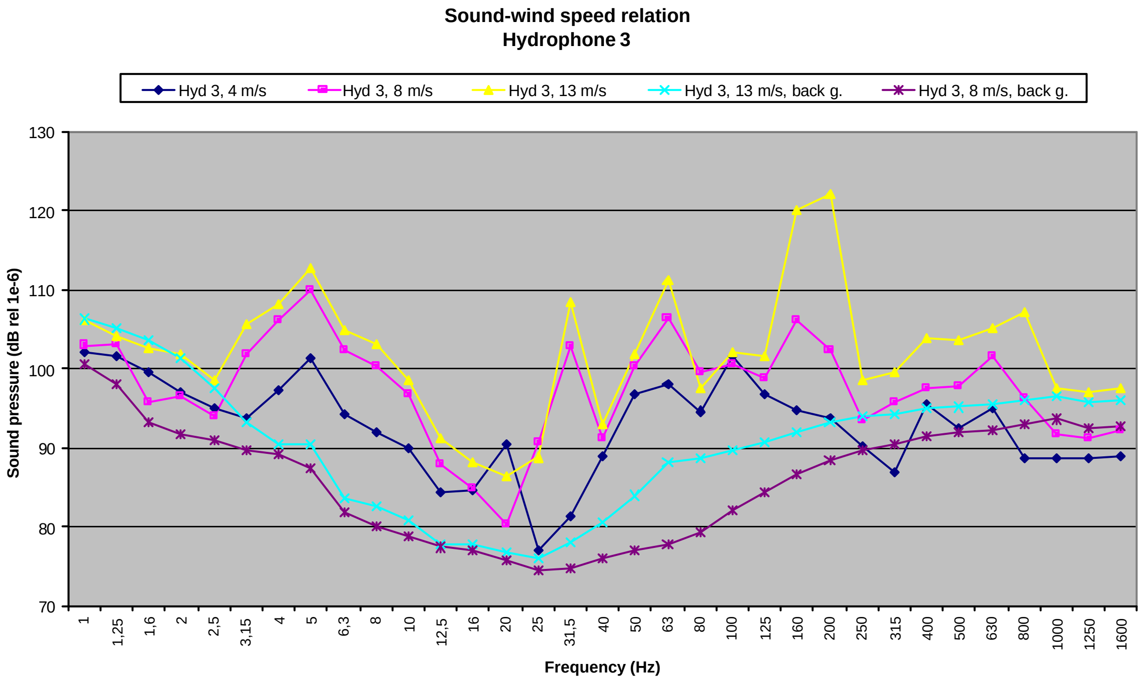

Figure 18 Sound-wind speed relation and background sound levels, Hydrophone 3, 3:rd octave plot

6.5. Sequential farm shut down

Figure 19 to Figure 21 displays the sound in the farm at the tree hydrophone positions during a sequential shut down of the farm. Measurements are taken from the High wind speed condition described in chapter 4. It can be seen that the sound levels in general are decreasing as the turbines are shut down. The effects are best seen in Figure 19 with the sound from hydrophone 3 where the sound level drops dramatically when turbine 4 is shut down due to the close distance. Shutting off the other turbines then gradually lowers the sound level.

The results need to be interpreted with the fact in mind that there is potentially strong interference from neighbouring turbines.

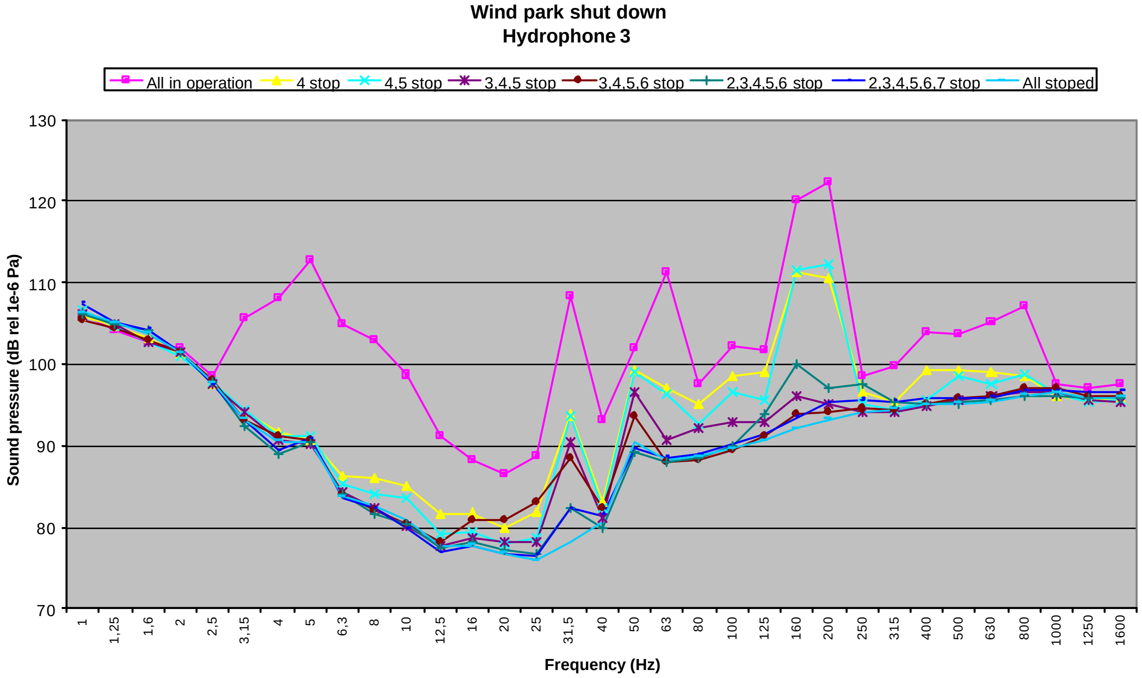

Figure 19 Sequential farm shut down, Hydrophone 3.

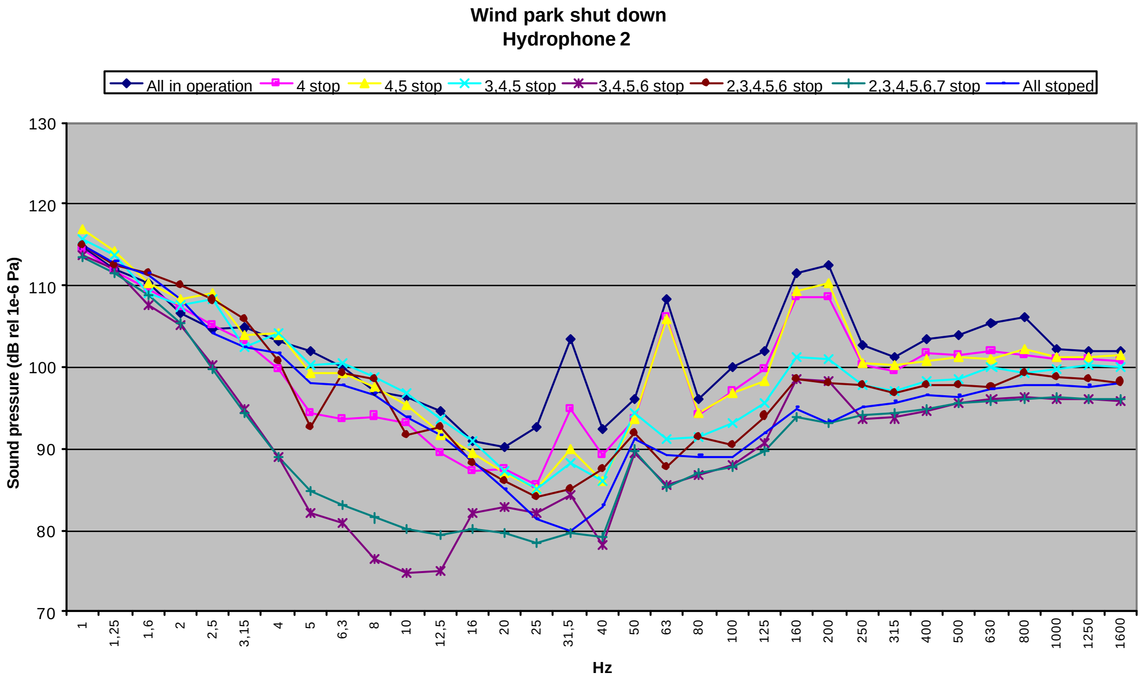

Figure 20 Sequential farm shut down, Hydrophone 2.

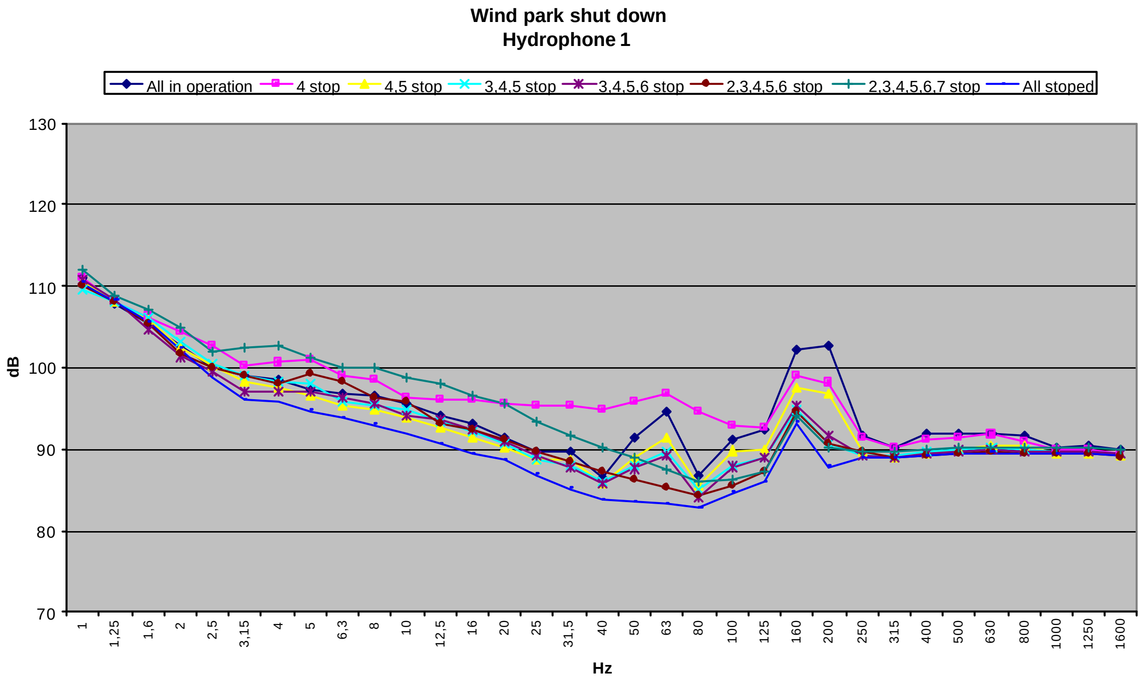

Figure 21 Sequential farm shut down, Hydrophone 1.

6.6. Ship passage sound compared with turbine sound

In Figure 22 to Figure 24, two ship passages are shown at the three hydrophone positions. Plotted time is 15.000 seconds or 4,16 hours. On the X-axis we have frequency and the Y-axis is time starting from bottom. The colour represents the sound pressure amplitude in dB relative 1µPa.

The wind farm was in operation and the wind speed 8 m/s from east. The ships passed west of the turbine farm at a distance of 2,700 m +/- 500 m.

The first passage, the lower, were a freighter "Alteland" from Germany, 2996 ton at 15 knot speed, heading south. The second passage, the upper, is undefined but heading north at 11 knot.

Figure 25 shows the sound from Alteland passage compared with a period one hour earlier with no ships in the area. It can bee seen that the contribution from the ship is in the frequency from 63 Hz and higher.

The sound from the turbines can be seen as vertical lines at different frequencies.

What also can be observed is that we only find small tendencies of varying interference between the wind turbines, at least not during the studied period. This is probably due very small variation in turbine speed and the fact that there are several turbines in the park that averages out the sound.

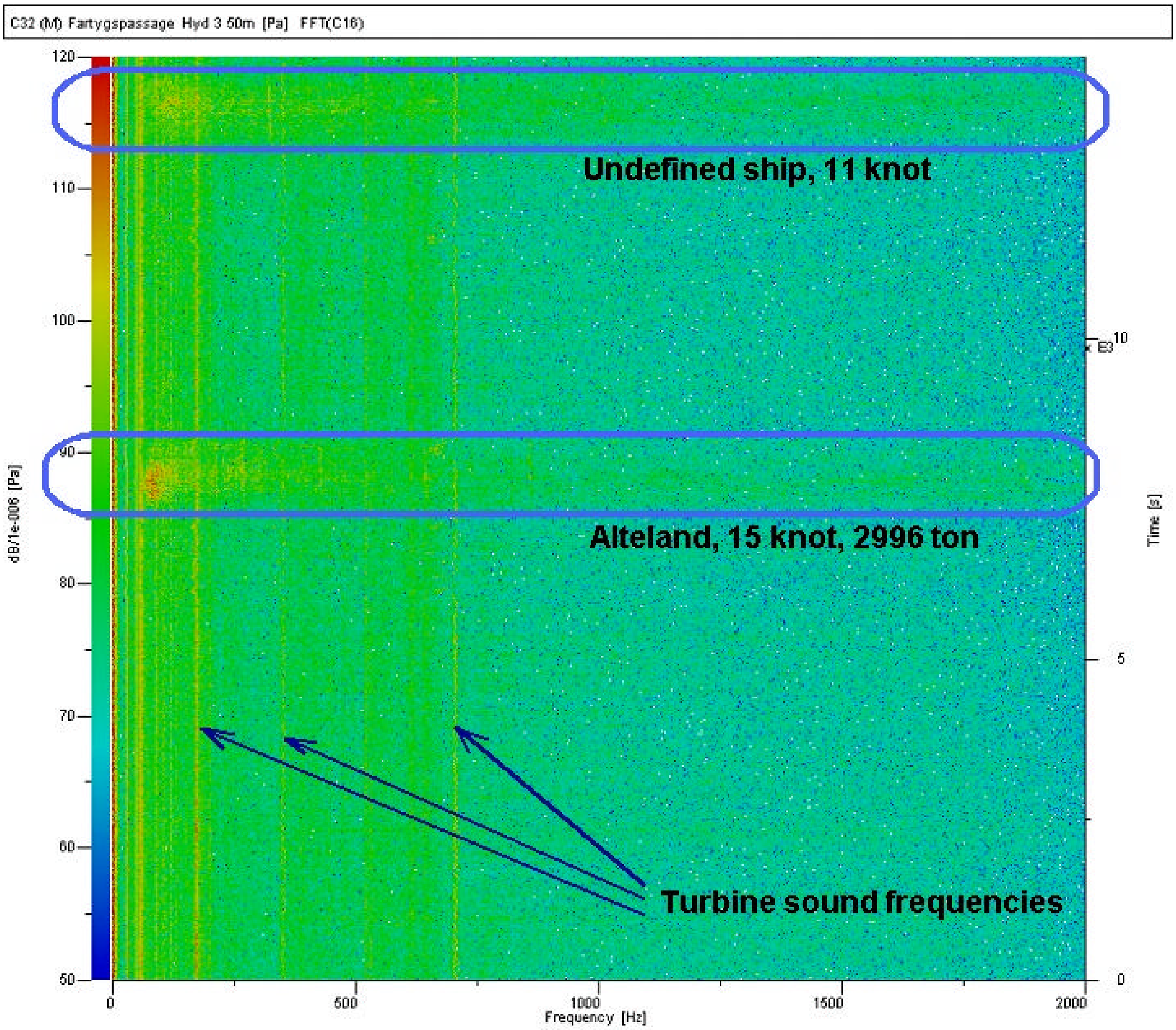

Figure 22 Ship passages, Hydrophone 3

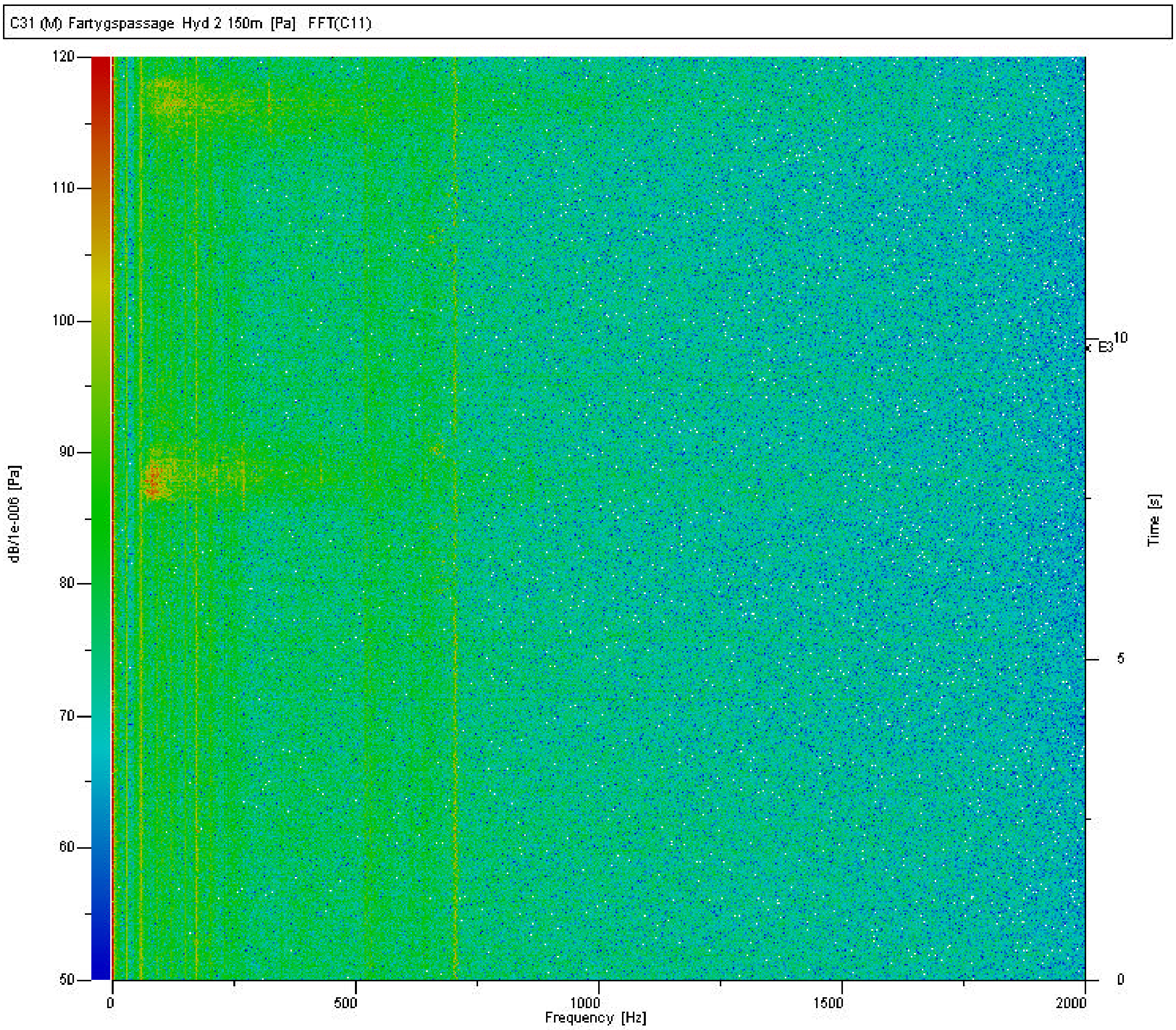

Figure 23 Ship passages, Hydrophone 2

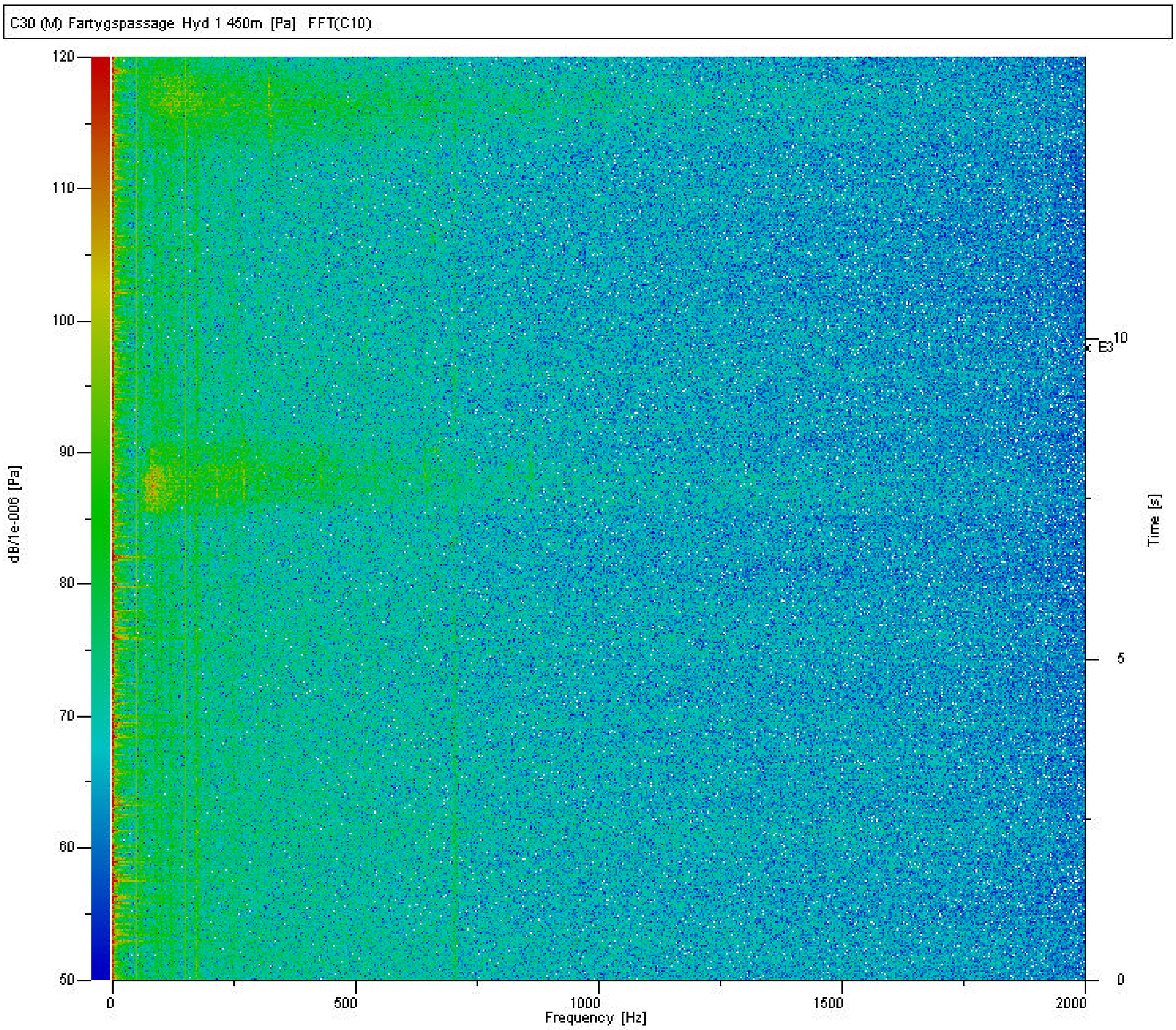

Figure 24 Ship passages, Hydrophone 1

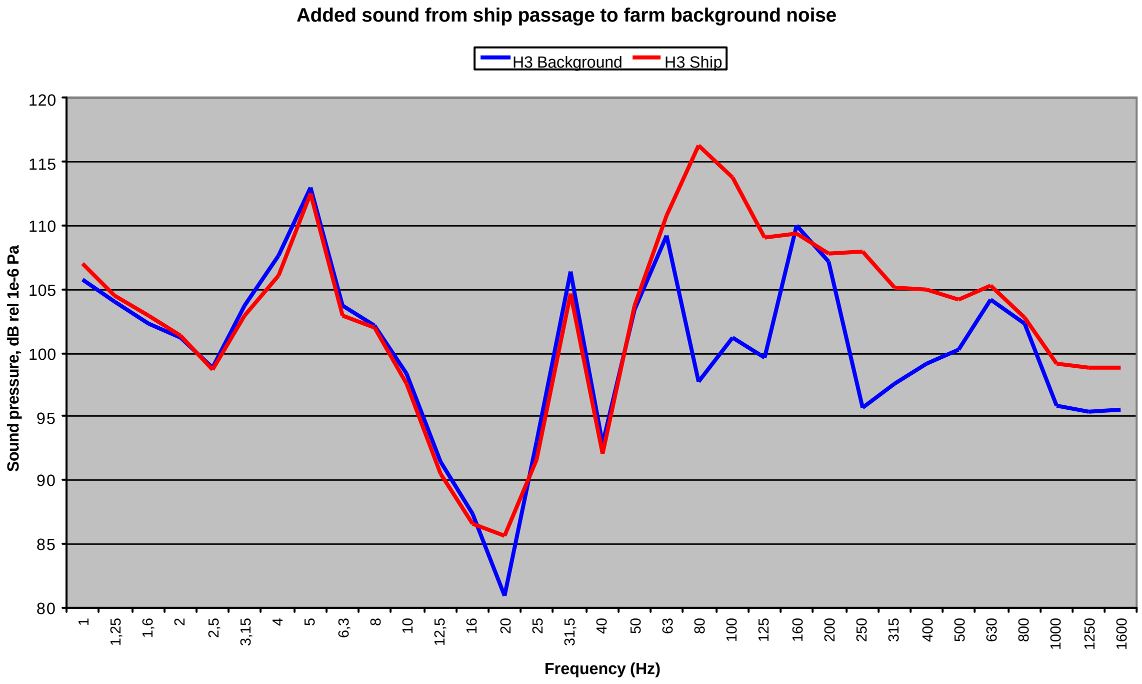

Figure 25 Added sound from ship passage to farm background noise for hydrophone 3

7. Discussion

This study was the first of it's kind to our knowledge of measuring underwater sound from an offshore farm during a longer period of time under varying wind conditions and have put light on some underwater sound radiating issues that are presented in this report.

During the period we have worked with this project other issues have come up that we would like to share with others that will continue investigating this interesting field.

Suggested future activities

Particle acceleration measurements/calculation

Since fish in the very low frequencies mainly is sensitive for water particle acceleration rather than sound pressure it would be interesting to investigate the character of acceleration. This could be estimated in calculations and with measurements.

Interference measurements

In wind farms the sound will always interfere with each other from the different turbines. In order to study this phenomenon more closely measurements could be performed with the turbines running at controlled speeds with a well-defined variation. This would generate interference patterns that could be used for verifying calculations.

Noise reduction measures

If there is a wish to reduce emitted underwater sound there is a considerable potential of reduction on the turbines.

Since the absolute main part is generated by the gearbox-generator measures should in first hand be directed toward minimizing gear mesh vibrations reaching the tower structure by designing effective vibration isolation. Since the emitted frequencies are relatively high even stiff isolators could reduce the vibrations considerably.

Secondly measures should be made isolating the wet surface of the tower from direct contact with the water. With the existing design tower vibrations are effectively coupled to the surrounding water. Inserting a layer of air between tower and water would reduce emitted noise significant. This could be implemented by building a shell around the towers wet surface or adding a layer of foamed polymer.