Underwater noise measurements in the North Sea in and near the Princess Amalia Wind Farm in operation

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ABSTRACT

The Princess Amalia Offshore Wind Farm is one of the first two operational offshore wind farms near the Dutch shore. One of the conditions imposed by the legislator was to monitor the underwater noise during operation of the wind farm.

Ambient sound pressure levels were determined at a location at 100 m from a turbine and a location outside the farm (at 3.8 km), during 12 days. In order to check if the turbine contributes to the ambient noise levels, the sound pressure levels at both locations are compared for three wind speed ranges.

For all wind speeds, the time-average broadband sound pressure levels on both locations showed no significant differences. Some tones (<1 kHz) from the gearbox transmission of the turbine could be detected in the narrowband spectrum of the sound pressure measured at the location close to the turbine, but these do not dominate the broadband SPL. These tones were not detected at the location outside the wind farm. It is unlikely that these tones are perceived by harbour porpoises at 100 m distance from a turbine. In these measurements the operational wind farm does not significantly contribute to the ambient noise due to shipping and surface waves.

Keywords: Wind turbines, underwater noise

1. INTRODUCTION

The Princess Amalia Offshore Wind Farm (in Dutch: Prinses Amaliawindpark, or PAWP) is one of the first two operational offshore wind farms near the Dutch shore. One of the conditions imposed by the legislator was to monitor the underwater noise both during construction and operation of the wind farm. The acoustic monitoring during the construction phase has been reported by TNO in 2007 [1]. This paper covers the execution, analyses and results of the acoustic monitoring of the wind farm in operation.

Vibrations induced by rotating shafts and gear wheels of the turbine are transmitted to the tower structure and can radiate unwanted sound (noise) into the water [2]. Wind turbine related noise levels are expected to depend on the output power of the turbine, which is a function of rotational speed and torque. These parameters are controlled by governing wind speed and by settings of the controllable pitch of the blades. The turbines at PAWP are of type Vestas V80, a variable-speed, pitch-regulated turbine with a maximum output power of 2 MW. The transmission gearbox of the turbine is a multi-stage transmission with a planetary gear from the low speed input shaft (LSS) to an intermediate shaft, and another gear transmission to the high speed output shaft (HSS) driving the turbine.

2. UNDERWATER NOISE MEASUREMENTS

The aim of the monitoring is to quantify the ambient underwater noise levels at locations in and outside PAWP at different wind speed conditions. Ambient noise levels at both locations are compared in order to check if the turbines contribute to the noise levels at close and at larger distance.
2.1 Measurement method and location

During one period of 12 days the underwater noise was recorded at two locations in and near PAWP. The noise was recorded at three ranges of wind speed conditions: 4-6 m/s, 6-12 m/s and 12-24 m/s during respectively 24.3, 77.7 and 2.2 hours.

The underwater noise measurements were recorded simultaneously at two locations, see Figure 1 and Table 1:
- H1 at the edge of the wind farm, at 100 m distance from turbine WTG1, see Figure 1.
- H2 at a distance of 3780 m from WTG1 in north-eastern direction.

Both measurement locations were selected north-east of PAWP, at similar distance from the main shipping lanes and away from anchor locations south and south-west of PAWP. Figure 2 gives an overview of the location of main shipping lanes relative to the measurement locations. The wind farm is visible on this shipping traffic map due to service ships entering the area and anchoring near the turbines. The measurement systems were deployed at 100 m distance from an anchored marking buoy.

<table>
<thead>
<tr>
<th>Location</th>
<th>WGS84 N [deg]</th>
<th>WGS84 E [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>52.60549</td>
<td>4.24107</td>
</tr>
<tr>
<td>H2</td>
<td>52.63231</td>
<td>4.27295</td>
</tr>
<tr>
<td>WTG1</td>
<td>52.604579</td>
<td>4.240736</td>
</tr>
</tbody>
</table>

![Figure 1](image1.png)

**Figure 1** – Locations of wind turbine WTG1 and measurement locations H1 and H2 in red. The marking buoys are shown as blue circles.
2.2 Measurement Systems

Two different autonomous measurement systems were deployed for the monitoring. The TNO custom-built system SESAME (Shallow water Extendable Stand-alone Acoustic Monitoring Equipment) was deployed at location H1 near the turbine. In order to reduce the amount of data to be stored, observation was limited to intermittent measurement periods of 6 s per minute. Prior to deployment, the Sesame system at position H1 was started at the beginning of a minute, according to GPS time. In this way the first 6 seconds of every minute were recorded (10% duty cycle).

For the second measurement point TNO commissioned the German company Institut für Technische und Angewandte Physik GmbH (ITAP). The ITAP systems have a maximal duty cycle of 10 minutes recording time every 30 minutes. In order to increase the duty cycle, two identical measurement systems were installed, with two separate hydrophones. Prior to deployment, the first ITAP recorder was started at the beginning of a minute. The second recorder was started 15 minutes after the first, resulting in an effective duty cycle of 67% (10 minutes recording every 15 minutes).

Table 2 lists technical details of the applied systems.
Table 2 – Signal conditioning and data acquisition settings applied by the SESAME and ITAP systems during the noise measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SESAME</th>
<th>ITAP/ Marantz PMD 620</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample frequency</td>
<td>200 kHz</td>
<td>44.1 kHz</td>
</tr>
<tr>
<td>Low-pass filter -3 dB cut-off frequency</td>
<td>80 kHz</td>
<td>-</td>
</tr>
<tr>
<td>High-pass filter -3 dB cut-off frequency</td>
<td>42 Hz</td>
<td>5 - 10 Hz</td>
</tr>
<tr>
<td>Gain</td>
<td>Auto range</td>
<td>0 dB</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>16 bit</td>
<td>16 bit</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>10 % (6 s per minute)</td>
<td>66 % (10 minutes per 15 minutes)</td>
</tr>
<tr>
<td>Hydrophones</td>
<td>2x B&amp;K 8101</td>
<td>2x B&amp;K 8106</td>
</tr>
<tr>
<td></td>
<td>(-184 dB re 1V/µPa)</td>
<td>(-172 dB re 1V/µPa)</td>
</tr>
</tbody>
</table>

2.3 **Measurement set-up**

Figure 3 shows a schematic overview of the measurement set-up, with the locations of the measurement systems and hydrophones relative to wind turbine WTG1.

2.4 **Environmental conditions**

The underwater noise levels that are measured near a wind farm in the North Sea are not only caused by the wind turbines, but also by shipping noise, wind noise and precipitation noise. Therefore these environmental conditions were also monitored together with the operational conditions of the turbine, like rotational speed of the input shaft and the output power, during the measurement period.

3. **DATA ANALYSIS**

3.1 **Data selection**

The underwater noise has been assessed for three wind speed ranges: 4-6 m/s, 6-12 m/s and 12-24 m/s. PAWP provided the measured wind speed of WTG1 as a function of time for the entire measurement period. From this data, the required acoustic data was selected according to the following criteria:

- Wind speed is within one of the three defined speed ranges;
- WTG 1 is operational; production output power > 0 kW;
- All measurement systems on both locations were operational and recording acoustic data;

3.2 **Determination of sound pressure levels**

The sound pressure level (SPL) is a measure of the mean square sound pressure defined by:

\[
SPL(T) = 10 \log_{10} \left[ \frac{1}{T} \int_{0}^{T} \frac{p^2(t)}{p_{ref}^2} dt \right]
\]

where \( T \) is the duration of considered time interval in [s] and \( p \) is the acoustic pressure in units of µPa (\( p_{ref} = 1 \) µPa is the reference pressure). The SPL is expressed here in units of dB re 1 µPa².

There are two ANSI and ISO approved approaches to determine the exact centre frequencies for 1/3-octave bands [4]. Both approaches use a centre-band frequency of 1000 Hz as a basis. In the first approach (the so-called base-ten approach) the ratios of centre-band frequencies for adjacent bands equal \( 10^{1/10} \). In the other approach (the so-called base-two approach) the ratios of centre-band frequencies equal \( 2^{1/3} \). The lower and upper edge-band frequencies are obtained by multiplying the centre-band frequencies by \( 2^{-1/6} \) and \( 2^{1/6} \), respectively. The differences between the centre-band
frequencies of both approaches are maximally in the order of 1% in the considered frequency range between 20 Hz and 80 kHz. In the present analysis the base-two approach is used to determine the 1/3-octave bands. According to the standards, the frequency bands are indicated by nominal rather than exact centre-band frequencies.

From the data recorded by the measurement systems, sound pressure levels (SPLs) in 1/3-octave bands were determined. The following steps were taken to convert the stored 16-bit data into SPLs for 1/3-octave bands:

- The 16-bit data were converted to time series of voltages by using the information on the set voltage range of the ADC and the sample frequency. The resulting time series for each measurement corresponds to a time interval of 6 seconds;
- The 1/3-octave band SPL spectra were determined in the time domain by using digital filters following ANSI S1.11-2004 [3];
- The frequency components of the voltages were converted to frequency components of the acoustic pressures registered by the hydrophones. This was done by accounting for the hydrophone sensitivity and the frequency dependent filter and gain factors;
- The SPL’s of both hydrophones for each location were energy averaged.

For both measurement systems, the SPL values are determined for the time interval of the first 6 seconds of a minute.

### 3.3 Determination of exceedance levels

From the measured SPL values, exceedance levels were determined according to ISO 1996-1: \( L_2, L_{10} \) and \( L_{95} \) in \( \mu Pa^2 \), see also [4]. Each exceedance level indicates the percentage (5\%, 50\%, and 95\%) of measurements for which the SPL has a higher value than the exceedance level.

### 3.4 Measures of shipping conditions

In order to investigate to what extent shipping traffic has affected the measured background noise, information on all shipping, including service ships of PAWP, within a 17 km range to H1 and H2 was provided by PAWP using an AIS (Automatic Identification System) receiver in combination with radar data. Shipping density measures [5] were determined from the available information on the positions and speeds of ships. The distances of all ships within this range, to the measurement locations were determined every minute. By using these distances, the following shipping density metrics were determined for each minute of the recording period:

- The distance to the nearest ship \( (ND) \)

\( ND \) can be used to identify service ships entering the wind farm and passing the measurement station H1 at close range.

- Weighted sums \( N_s \) over a selection of ships:

\[
N_s = \sum_i r_i^{-n}, \quad \text{with} \quad n = 2
\]  

(3)

where \( i \) labels the selected ships, and \( r_i \) is the distance of each ship relative to the location of the measurement. These metrics take into account the number of ships in the vicinity of the measurement location as well as the distances of these ships relative to the measurement location. In the analysis of earlier background noise measurements [5], it was found that the \( N_2 \) measure, with \( r_i^{-2} \)-weighting, is correlated with the measured shipping noise and gives a very rough estimation of the potential contribution of ships to the measured background noise, based on the following assumptions:

- all ships have the same source level
- propagation loss is due to spherical spreading only.

\( N_2 \) is used as an indicator of the relevant shipping density in the vicinity of the hydrophones. Only moving ships with a speed higher than 1 m/s were included.

### 3.5 Wind Noise

In order to investigate to what extent wind has affected the measured background noise, the correlation between the wind speed and the measured noise levels was determined. For this purpose wind speed information, measured on top of the turbine at 60m height, was provided by PAWP. The provided wind speed data represents the 10 minute averages of the wind speed in units of m/s. The correlation of measured SPL and governing wind speed is investigated. The wind speed measurement
points are plotted against the underwater sound pressure levels, averaged over the same time window. In case wind generated noise is dominating the SPL, both parameters will show correlation.

4. RESULTS

4.1 Overview sound pressure levels

Figure 4 shows the overall broadband SPL (one 6 s average per minute) as a function of time for the entire monitoring period of 12 days. The broadband SPL is determined in the frequency range between 20 Hz and 63 kHz for location H1 and 20 Hz and 16 kHz for location H2. Figure 4 (right) also shows histograms of the broadband SPL, for all wind conditions, showing a similar distribution. The dynamic range of the total sound pressure levels is large, about 40 dB at both locations. The maxima are caused by pass-by of near-by shipping traffic, resulting in local maxima at the closest point of approach (CPA) of individual ships to the location of the measurement systems, see also section 4.4.

![Image of broadband sound pressure levels as a function of time, one 6 s average per minute, at both measurement locations (left upper H1; lower H2) and on the right: Histograms of the broadband sound pressure levels (in 1 dB steps) at locations H1 and H2.]

4.2 Sound levels per wind speed range

Next, the SPLs and exceedance levels are determined per wind speed range. PAWP provided the wind speed of WTG1 as a function of time for the entire period. The wind speed is measured on top of the turbine at a height of 60 m above the waterline. From this data, the time frame for which acoustic data could be used was determined according to the criteria of section 2.5.

Figure 5.4 shows the wind speed, rotational speed of the generator input shaft and output power of WTG1, during the monitoring period. This data was provided by PAWP, at 10 minute intervals. The colour coding shows which of the data points was used per wind speed condition, based on the selection criteria. In total the usable data set consisted of 24.3 hours for wind speed range 1 (4-6 m/s), 77.7 hours for range 2 (6-12 m/s). For the highest wind speed range (12-24 m/s) only 2.2 hours of data could be recorded during the selected monitoring period. In this period the turbine produced its maximum output during about 15 minutes.

The rotational speed of the turbine is limited to 18.1 rpm at a governing wind speed of about 10 m/s, which is in the second wind speed range (6-12 m/s). However, the output power reaches its limit (rated power of 2 MW) at a wind speed of about 13 m/s, in the highest wind speed range. Above its rated power, the wind turbine controller pitches the blades to maintain constant generator torque and rotational speed, so that the power remains constant [6].
Figure 5 – Measured wind speed, turbine input shaft rotational speed and produced power for WTG1 during the monitoring period (source PAWP). Colour-coded data points indicate the usable data, based on wind speed, turbine operational conditions and availability of acoustic data.

Table 3 – Total broadband values for three exceedance levels ($L_5$, $L_{50}$ and $L_{95}$) and for the mean square sound pressure level (SPL, in dB re 1 µPa$^2$) per wind speed range and for all wind speeds (all ranges) at the two measurement locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>range1 4-6 m/s</th>
<th>range2 6-12 m/s</th>
<th>range3 12-24 m/s</th>
<th>All ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_5$</td>
<td>H1 123</td>
<td>124</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>H2 124</td>
<td>125</td>
<td>126</td>
<td>124</td>
</tr>
<tr>
<td>$L_{50}$</td>
<td>H1 113</td>
<td>113</td>
<td>116</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>H2 112</td>
<td>113</td>
<td>115</td>
<td>113</td>
</tr>
<tr>
<td>$L_{95}$</td>
<td>H1 107</td>
<td>107</td>
<td>110</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>H2 105</td>
<td>105</td>
<td>107</td>
<td>105</td>
</tr>
<tr>
<td>SPL</td>
<td>H1 118</td>
<td>118</td>
<td>118</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>H2 119</td>
<td>120</td>
<td>121</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 3 lists the total values of the exceedance levels.

Table 3 shows that the measured broadband sound pressure levels are very similar at both locations. The SPL averaged over the measurement period at H$_2$ is 2 dB higher than at H$_1$. The median $L_{50}$ is equal at both locations. This suggests that the ambient noise measured close to a wind turbine at H$_1$ is not dominated by turbine noise and that the ambient noise level at both locations is dominated by shipping and wind noise.

Figure 6 shows the 1/3-octave band spectra for the various exceedance levels per wind speed range and measurement location. This allows for a comparison between the levels as measured near to and further away (3.8 km) from the turbine. For both locations, the spectra of $L_{95}$ are about equal for wind speed ranges 1 and 2. For wind speed range 1 the rotational speed of the low speed shaft (LSS), and consequently the output power, are low. In the next section it will be shown that no turbine generated
tonal noise could be detected at location H1 for this range. The peak at 50 Hz which can be found in the $L_5$ and $L_{95}$ spectra for wind speed range 3 at both locations is caused by two ships cruising by within the 2.2 hour time window of the recordings in the highest wind class and is not produced by the wind turbine. This illustrates that the amount of data in the highest wind class is too small to draw firm conclusions. Nevertheless, the increase of $L_{95}$ in the 25 Hz band on location H1 in the highest wind speed range is probably caused by the turbine (shaft noise), as illustrated in the next section.

Figure 6 – Spectra of $L_5$ (lower) an $L_{95}$ (upper) in 1/3-octave bands for three wind speed ranges for the locations close to (left) and further away (right) from the turbine.

### 4.3 Narrow-band analysis

Previous studies have shown that the underwater noise radiated from operational wind turbines is dominated by tones at frequencies associated with the rotation of the gears in the nacelle, see e.g. [2]. In order to be able to identify such tonals, a Fast Fourier Transform was applied to the time series. In the Fourier-transform a time weighting was performed by using a Hanning window, with a 50% overlap. The block size equals the sample frequency, resulting in a 1 Hz frequency resolution.

Table 4 shows the tones of the gears at various rotational speeds of the low speed shaft (LSS). The rotational speed of the high speed shaft (HSS) is calculated from the gear transmission ratio. The gearbox of the turbine is of type EH804A Offshore (ZF/Hansen), and has a transmission ratio of 1:92.3. Also, the gear meshing frequency of the gear wheels on the HSS is listed, which have 26 teeth. Tonal noise at this frequency is expected for the gear transmission noise. The transmission gearbox of the turbine, which is a multi-stage transmission with a planetary gear from the low speed shaft to an intermediate shaft, and another gear transmission to the high speed shaft, will generate multiple tones.
Figure 7 – Rotational speed of the WTG1 LSS (upper) and narrow-band sound pressure levels (Δf=1Hz), measured on location H1 over the entire measurement period (upper figures) and over a selected period with high rotational shaft speed (lower figures) The sound pressure levels are indicated by colours (red low levels, yellow high levels). When the time dependency of the rotational speed of the LSS in the upper figure (indicated by the dotted box) is compared to the time dependency of the sound pressure level inside the dotted box in the lower figure, indicated by HSS, the same trend can be observed.
Table 4 – Examples of frequencies of the turbine related to the rotational speed of the low speed shaft

<table>
<thead>
<tr>
<th>LSS rpm</th>
<th>HSS Hz</th>
<th>HSS rpm</th>
<th>HSS Gear Meshing Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.1</td>
<td>0.30</td>
<td>1671</td>
<td>28</td>
</tr>
<tr>
<td>15.4</td>
<td>0.26</td>
<td>1421</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
<td>185</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 7 shows a narrowband spectrogram of the underwater noise levels over the entire monitoring period at H1, for a frequency range between 20 Hz and 1 kHz. Also, the turbine rotational speed is shown in the upper figure. For rotational speeds higher than 13 rpm, the time dependency of the rotational speed of the LSS in the upper figure (indicated by the dotted box) can also be recognized in the underwater noise spectra in the lower figure, in the 20 to 50 Hz frequency range. The sound at higher frequencies is dominated by ambient shipping noise. For lower speeds, no speed related components can be found in the underwater noise. For the higher speeds between days 6-10, the varying tone in the underwater noise, see lower plot of figure 7, can be identified as the HSS rotational frequency, which is the transmission ratio of the gear transmission times the rotational speed of the LSS.

4.4 Ship traffic

Following the procedure of section 3.4, shipping density factors as a function of time were determined. Figure 8 shows the total SPL and the Shipping density factors for both locations for each minute of the first three days of the monitoring period. A high $N_2$ implies either a ship pass-by at close range, or the presence of many ships in the environment of the measurement location. Local maxima in SPL seem to generally coincide with maxima in the $N_2$ factor, indicating that shipping noise is probably dominating the SPL for these time frames.

Figure 8 – Total SPL and Shipping density factor $N_2$ for locations H1 and H2 for each minute of the first three days of the monitoring period.

4.5 Correlation of SPL with wind speed

The wind generated breaking of waves is expected to lead to a positive correlation of the ambient noise with the wind speed. However, if the background noise is dominated by other sources, such as ship radiated noise, the broadband SPL will not show clear correlation with wind speed. This effect can be seen in figure 9. For low wind speeds the SPL for the 10 kHz band shows no clear correlation with wind speed, but for wind speeds above 5 m/s some correlation can be found.
4.6 Marine mammals

In order to assess if turbine induced noise could be perceived by marine mammals, their audiograms need to be considered. These audiograms represent the tonal SPL threshold at which a sound can be detected with a 50% probability, in a situation without masking background noise. Figure 10 shows the audiograms of harbour seals [7] and harbour porpoises [8,9] plotted together with measured $L_{95}$ exceedance levels. It is likely that the measured underwater noise up to 700 Hz, including wind turbine related noise at a close range, can be perceived by the harbour seal, but not by a harbour porpoise. This figure does not provide direct information regarding physiological or behavioural effects of the measured sound on the animals.

Figure 10 – Tonal audiograms of harbour seals (*Phoca Vitulina*) and harbour porpoises (*Phocoena Phocoena*) plotted together with $L_{95}$ at location H1.
5. CONCLUSIONS

At two locations, at close range of an operational wind turbine (H1 at 100 m) and at large distance (H2 at 3.8 km) the underwater noise was recorded for nearly 12 days. The SPLs were averaged over periods of time within certain wind speed ranges (4-6 m/s, 6-12 m/s and 12-24 m/s). For the first range, 24.4 hours of data was available, for the second 77.7 hours. For the third range 2.2 hours of data was available. The wind turbine operated at its maximum output power for 15 minutes of this period.

The average broadband sound pressure levels on both locations show no significant differences. Only at the location close to the operational turbine, a narrow band analysis revealed some tonals which are caused by the high speed shaft of the turbine. It can be concluded that even at the location close to the PAWP wind turbine, these tonals do not dominate the broadband SPL.

It can be concluded that, at the location of the Princess Amalia Wind Farm in the North Sea, the noise generated by the operational wind farm does not significantly increase the local ambient noise due to shipping and wind.

On both locations, the average sound pressure levels are comparable within 2 dB (118 dB re 1 µPa² at H1 and 120 dB re 1 µPa² at H2). This is to be expected if shipping noise dominates the average broadband SPL and both measurement locations have about similar distances from shipping lanes.

ACKNOWLEDGEMENTS

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REFERENCES
3. ANSI S1.11-2004 Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters  