Relation Between Underwater Noise and Operating Offshore Wind Turbines

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Relation Between Underwater Noise and Operating Offshore Wind Turbines

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Abstract

This chapter examines underwater noise measurements recorded within and outside operating offshore wind farms consisting of 6.3 MW and 8.3 MW turbines, respectively. Each wind farm had multiple hydrophones recording simultaneously with the nearest being located 70–100 m from a turbine, while the furthest was positioned 5 km outside the wind farm. Data were collected over 5 weeks to facilitate a statistical examination of how the magnitude of underwater noise changes with turbine activity (power production data) and natural fluctuations (e.g., tides and wind).

The results imply that there is no significant relation between the broadband underwater noise levels and turbine activity for any of the examined wind farms in the monitored distances (up to 70 m). Influence from natural fluctuations was on the other hand evident from the measured noise levels. Moreover, a comparison between recorded noise levels and simulated noise levels from an

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already-established empirical model shows that the model's extrapolated noise levels greatly exceed that of the recordings. This suggests that there are challenges associated with extrapolating aggregated results from smaller turbines to the realm of new, larger turbines. Thus, a new approach or more data are required to predict underwater noise from future operational wind turbines.

Keyword

Underwater noise · Offshore wind · Operational wind turbines · Environmental impact assessments · Marine mammals

Introduction

Earlier studies have been able to trace the vibro-mechanical oscillations from operating offshore wind turbines to changes in the ambient underwater noise levels (Betke et al. 2005; Madsen et al. 2006; Norro and Degraer 2016; Yang et al. 2018). The vibrations are excited by mechanical components such as rotating blades and the turbine's operating gear box which causes vibrations to propagate down through the turbine tower and subsequently manifest as underwater noise radiating away from the foundation. However, while it is evident that turbine activity previously has been detectable in the recorded underwater noise levels, there remains an indefinite understanding of how the underwater noise level will scale with increasingly larger turbines and offshore footprint. For instance, the number of offshore wind turbines will over the coming decades increase exponentially due to an increasing demand of renewable energy resources (COM 2020, 741). Such expansion will cause the spatial coverage of turbines in the ocean to increase accordingly.

Tougaard et al. (2020) and Stöber and Thomsen (2021) set out to address this by aggregating primarily third party's underwater noise measurements with the purpose of establishing an empirical formula that could predict noise levels for larger turbines. Tougaard et al. (2020) used a general linear model to assess the correlations between sound pressure level and measurement distance, turbine size, and wind speed. Stöber and Thomsen (2021) used linear regression to assess the correlation where the distance dependency was removed by assuming that their data sources were subject to same transmission loss of 15 $\log_{10}(r)$ where r is the radial distance from the source. Both studies relied on aggregated data from primarily smaller turbines (0.45–6.15 MW) collected under different environmental conditions and distances to the turbines. Such methodologies are challenged by the difficulty in (1) disentangling the contribution from correlating variables (e.g., wind speed and power production) and (2) estimating the accurate sound source levels as the transmission loss varies across sites.

The motivation of this chapter is to get a better understanding of how underwater noise relates to turbine activity in the vicinity of an operating wind farm. This study has recorded the underwater noise levels in and around ~250, ~330, and ~450 MW offshore wind farms consisting of 6.3 or 8.3 MW turbines, respectively (see Table 1).

Table 1 Wind farm information

Wind farm	Nominal power	Wind farm size	Turbine type	Rotor diameter	Foundation type
Gode Wind 1	6.3 MW	~330 MW	SGRE 6.3–154 (direct-drive)	154 m	Monopile
Gode Wind 2	6.3 MW	~250 MW	SGRE 6.3–154 (direct-drive)	154 m	Monopile
Borkum Riffgrund 2	8.3 MW	~450 MW	V164–8.3 (planetary gear)	164 m	Monopile and suction-bucket jackets

The relation between underwater noise and turbine activity is then examined by analyzing the co-variability of underwater noise, wind speed, and power production for multiple turbines sampled in different distances to the source. Data were collected over 5 weeks to facilitate a detailed statistical examination of how the magnitude of underwater noise changes with turbine activity (power production) and natural fluctuations (mainly tides and wind).

Measurement Campaigns

Noise levels were recorded from three offshore wind farms in the Summer of 2020 (Gode Wind 1 and 2) and Spring/Summer of 2021 (Borkum Riffgrund 2) for five continuous weeks. The Gode Wind turbines have power production capacities of 6.3 MW, while the Borkum Riffgrund 2 turbines have a capacity of 8.3 MW. Each wind farm had four to five hydrophones recording simultaneously with the nearest being located 70–100 m from a turbine, while the furthest was positioned 5 km outside the wind farm. The 5-km position is used as a reference of the ambient noise signal when analyzing the impact from turbine activity on changes in underwater noise levels. The assumption is that there is no influence of turbine noise at 5 km due to the geometrical propagation loss having diminished the signal. All sites have similar water depth of approx. 30 m.

Hydrophone Setup

Two types of hydrophones were deployed: (1) a completely continuous recording device and (2) a hydrophone that recorded for 10 min every 2 h (see Table 2). The reason for utilizing two different types of hydrophones is that these measurement campaigns were part of the underwater noise measurement requirement for offshore wind farm commissions stated in the German StUK4 (BSH 2013). Thus, in addition to the BSH-requested hydrophones, four additional continuously recording high-resolution hydrophones were deployed to record the underwater noise levels. These devices were positioned as close as safely possible to the pre-selected turbines per wind farm to ensure one could record the actual turbine signal. Furthermore, the

Table 2 Hydrophone specs: the hydrophones deployed near suction-bucket jackets are marked in the "Position" column

Wind farm	Measurement name	Recording device type	Hydrophone type	Recording resolution	Position
GOW01	MP5	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	70 m to WTG
GOW01	MP7	Wildlife Acoustics SM2M	Bruel & Kjäer 8106	Uncompressed MP3 format	75 m to turbine
GOW01	MP5a	Wildlife Acoustics SM2M	HTI-low noise	16-bit WAV format	150 m from turbine
GOW01	MP7a	Wildlife Acoustics SM2M	HTI-low noise	16-bit WAV format	70 m from turbine
GOW02	MP6	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	Inside OWF (1 km to the nearest WTG)
GOW02	MP8	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	Inside OWF (1 km to the nearest WTG)
GOW02	MP9	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	Outside OWF (1 km to the nearest WTG)
GOW02	MP4	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	Inside OWF (1 km to the nearest WTG)
BKR02	MP8	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	Inside OWF (1 km to the nearest WTG)
BKR02	MP4	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	100 m to WTG (suction-bucket jacket)
BKR02	MP4b	Wildlife Acoustics SM2M	HTI-low noise	16-bit WAV format	63 m to WTG (suction-bucket jacket)
BKR02	MP5	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	100 m to WTG
BKR02	MP5b	Wildlife Acoustics SM2M	HTI-low noise	16-bit WAV format	94 m to WTG
BKR02	MP10	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	5 km outside OWF
BKR02	MP11	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	1 km outside OWF
BKR02	MP12	itap	Bruel & Kjäer 8106	Uncompressed MP3 format	1 km outside OWF

All other positions are monopile foundations measurement position close to the turbines were selected in such a way that any disturbing background noise from vessel lanes, other turbines in the vicinity, etc. were minimized.

Each hydrophone had a fixed position at 1.5 m above seabed throughout the campaign and followed the measurement protocols outlined in ISO 18406:2017 and BSH (2011). All hydrophones were calibrated by itap GmbH using a pressure chamber process.

The Gode Wind MP5a data were excluded from the analysis as the data were found to be compromised. This was determined by the deployment of two hydrophones close to each other (MP5 in this case).

Data Pre-processing

Figures 1 and 2 show that the recorded broadband SPLs oscillate steadily with time (10 min averages of 5 sec SPL measurements). The variation is ranging from 115 to 130 dB, and this steady oscillation is therefore a dominant feature in the noise recordings. The periodicity is first examined through power spectral analysis of the calibrated noise recordings (5 s averages) as seen in Fig. 3. From this, it is evident that all four positions are influenced by the semi-diurnal tidal modes M_2, S_2, and N_2 (~2 cycles/day), while three of the measurement positions are further dominated by the M_4 shallow water overtide of the principal lunar (~3.85 cycles/day) (Bartels 1967). The MP7a (GOW02) data don't have the M_4 mode even though its water depth of ~33 m is like that of MP5a (GOW01) with ~32 m. This difference might be a consequence of some site-specific attribute as the MP7a position is located ~12 km northeast of MP5a.

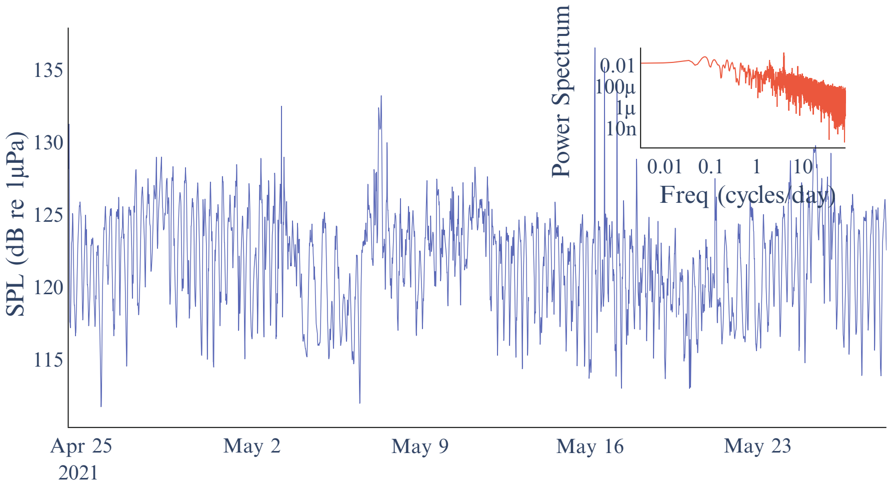

Fig. 1 Time series of 10-min averaged broadband SPL (BKR02, MP4b, 63 m from a WTG). Top right subplot shows the corresponding power spectral density

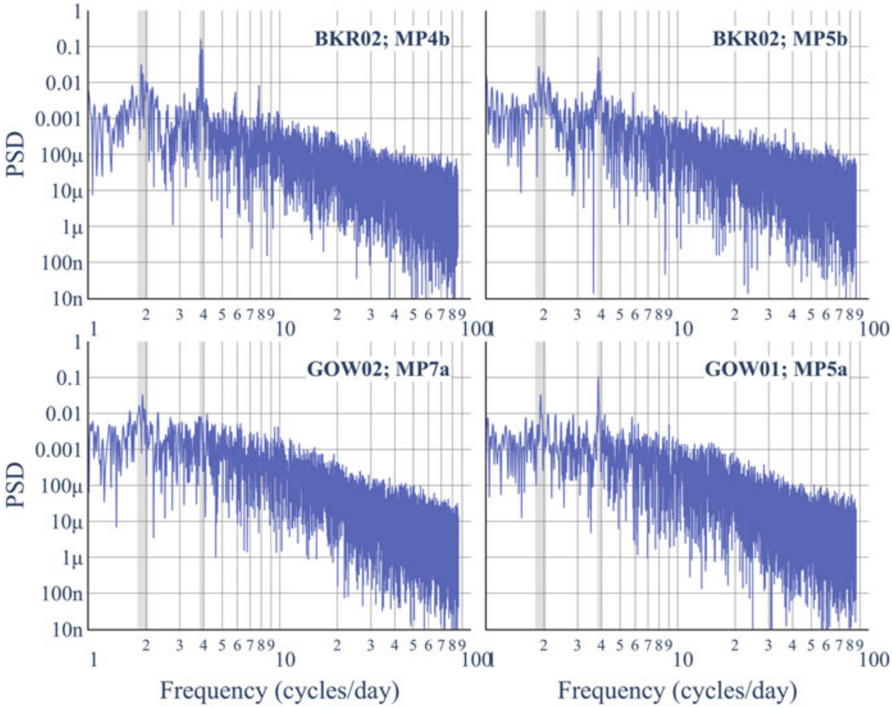

Fig. 2 Power spectral densities (PSD) of broadband SPL computed through Lomb-Scargle Periodograms. The gray bars denote different observed tidal oscillations (e.g., M2 and M4)

The power spectral analysis indicates that the changes in SPL predominantly are attributed to tidal variations. Thus, daily averaged SPLs are calculated to remove any bias from the subsequent analyses with wind and power production data. As SPL is a logarithmic metric, the daily averages are calculated through logarithmic means. This is done by (1) taking the anti-log of the SPL series, (2) calculating the mean, and (3) re-applying the decadic logarithmic factor again.

Additionally, in the subsequent analysis, a 30-min moving median filter is applied to the data to remove any noise impacts caused by nearby passing vessels. This is applied prior to calculating the daily averages. The data shows that service vessels visiting the turbines occasionally caused elevated noise when passing the deployed hydrophones. This was visible in the raw broadband SPL data as a sudden and short-duration noise increase of 5–10 dB SPL. Such a change cannot result from turbine-induced noise as it was observed during low winds and since it was characterized by a sudden increase and decrease in noise. Moreover, it takes ~10 min for the turbine to either steadily ramp up or down from full capacity. The sudden noise increase could therefore not be a turbine signal.

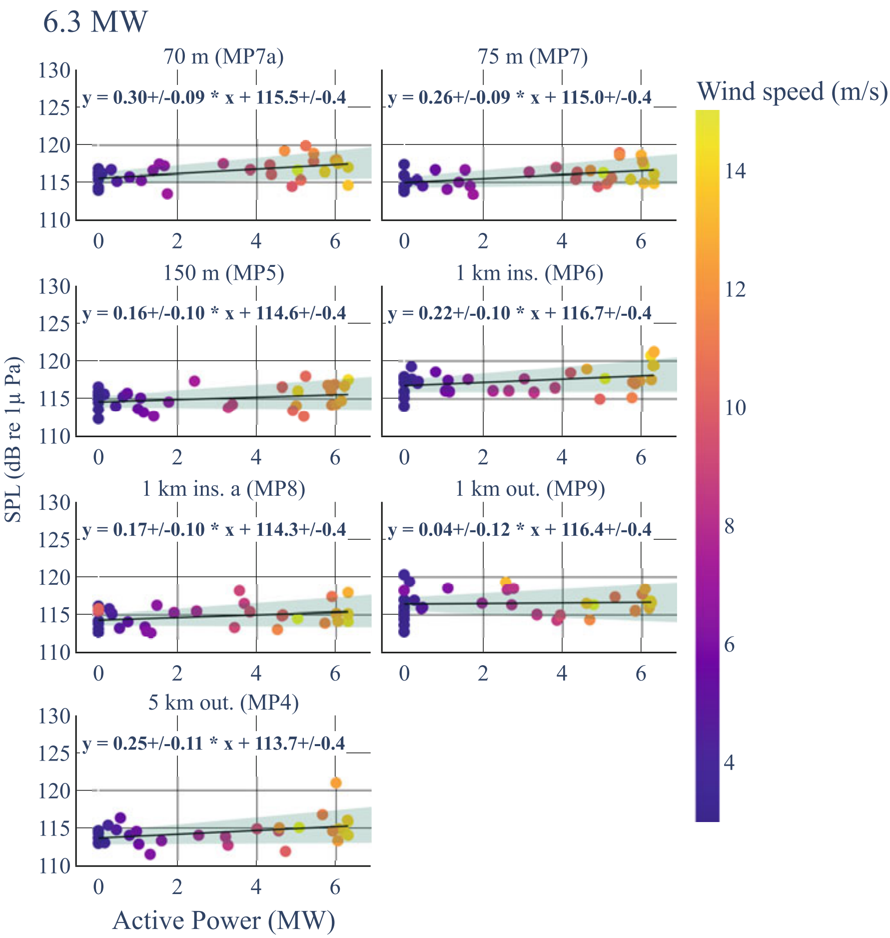

Fig. 3 GOW01 and GOW02: Daily averaged SPL with respect to power production at the nearest turbine and wind speed (color). Regression coefficients denote the best estimate ± the corresponding standard deviation. Shaded area is 95% confidence intervals based on a two-sided Student *t*-test. Turbines are off at 0 MW, and there is no significant difference in slopes across measurement positions

Underwater Noise Versus Turbine Activity

The relation between underwater noise and turbine activity is examined by using power production data as a proxy of turbine activity. This metric is directly proportional to the blades' revolution per minute (RPM) and therefore an indicator of the vibrational motion and general activity within the nacelle. In the analysis, 10-min time series of mean active power is converted to daily averages to facilitate a comparison with the daily averaged SPLs. For each hydrophone, the SPL data is compared with the nearest turbine's power production data. This is because there can be minor differences in the power production data between turbines due to site-specific conditions (e.g., wakes), maintenance, or curtailment requirements. Besides the daily averaged power production data, the daily averaged wind speed measurements recorded at the nacelle are also utilized in the analysis (10 min means converted to daily averages). This level of detailed information enables an examination of how the underwater noise levels change with both turbine activity and naturally caused phenomena (e.g., wind variations).

Theoretically, there exists a log dependency between the displacement velocity (turbine activity) in the structure and underwater SPL. This can be concluded as there exists a log dependence between acoustic pressure in water and SPL. From assuming a linear mechanical system, the displacement velocity in the structure (vibrations) is directly proportional to the RPM (turbine activity). In water, the propagation is in the far field through plane waves where sound pressure is directly proportional to particle velocity. The law of continuity applies for the normal pressure and displacement as the boundary conditions at the pile-water interface. Thus, the particle velocity in water is directly proportional to the displacement velocity in the structure, which implies that the displacement velocity in the structure is directly proportional to acoustic pressure in water. As there is a log dependency between acoustic pressure and SPL, then there also exists a log dependency between the displacement velocity (turbine activity) in the structure and underwater SPL.

The relations between SPL, active power, and wind speed are first examined in Fig. 3 (6.3 MW) and Fig. 4 (8.3 MW). For all measurement positions, it is observed that there is no logarithmic relation between turbine activity and SPL which would be expected. For Gode Wind 1 and 2, some positions exhibit a minor linear SPL increase with power production and wind speed, whereas no relation is evident for Borkum Riffgrund 2. The relations and their significance are first quantified by estimating the linear least-square regression coefficients, their standard deviations, and the corresponding 95% confidence intervals (CI; estimated through a double-sided Student *t*-test).

By comparing the regression coefficients at different positions relative to the turbine and wind farm, it is evident that there is no significant difference in slope (dB/MW) with distance. This is further illustrated in Fig. 5 where the significance of difference in estimated slopes is tested using the 5-km control measurements. This comparison shows that the slopes are not statistically different. Thus, the minor change in elevated broadband SPL values for Gode Wind 1 and 2 must be a wind contribution rather than an influence from turbine activity as a similar relation exists at distances of 5 km away from the wind farm.

The dual influence from the co-varying turbine activity and wind speed on the underwater noise levels is a testimony to the challenges in disentangling the contribution of two statistically dependent variables. Such an effort is therefore only possible if one has multiple hydrophones recording simultaneously in different distances to the turbine.

For Borkum Riffgrund 2 (8.3 MW), there is no impact on daily averaged SPL from neither power production nor wind speed as shown in Fig. 4. This contrasts

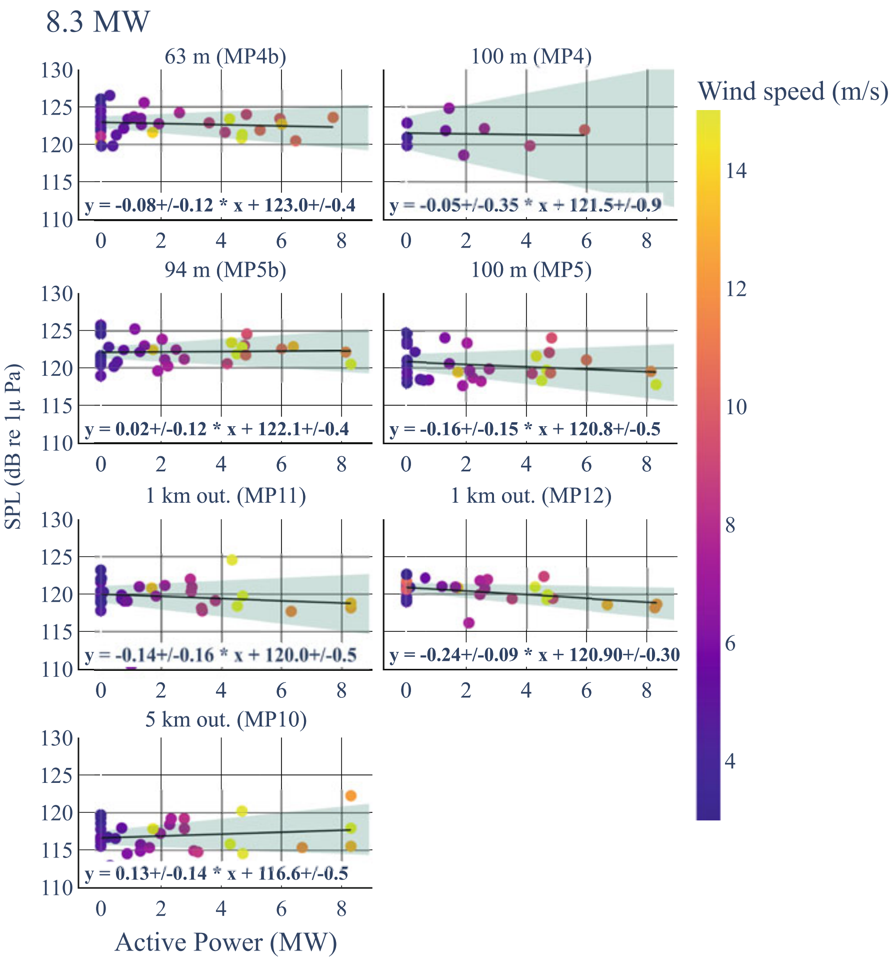

Fig. 4 BKR02: Daily averaged SPL with respect to power production at the nearest turbine and wind speed (color). Regression coefficients denote the best estimate ± the corresponding standard deviation. Shaded area is 95% confidence intervals based on a two-sided Student *t*-test. Turbines are off at 0 MW, and there is no significant difference in slopes across measurement positions

with the smaller 6.3 MW turbines at Gode Wind where a minor wind dependence might exist (slope is significantly different from 0). The Borkum data were sampled in the Summer of 2021 which generally was a period characterized by low winds. This is also noticeable in the data as a slight non-uniform distribution of SPL data points for different MW. Regardless, it is observed that the variation in SPL during turbine standstill greatly exceeds any potential for turbine-inflicted SPL increases at its maximum power production capacity (8.3 MW). Thus, the great variation in SPL at turbine standstill must indicate that there is some other process that causes the signal to change in low wind conditions (either natural or anthropogenic). Other

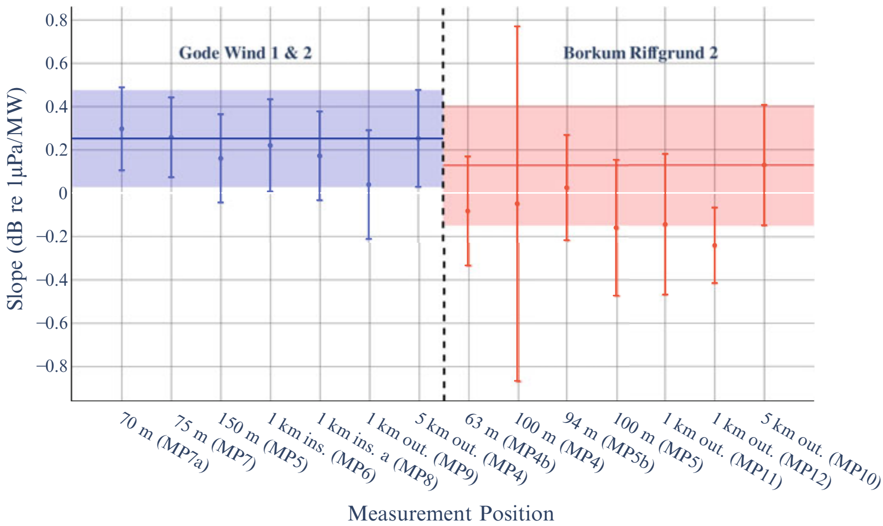

Fig. 5 Slope (dB/MW) at different positions relative to the turbine and wind farm. Error bars are the 95% CI, while the horizontally oriented bars represent the reference measurements 5 km outside the wind farm with its 95% CI. Left part of the figure is Gode Wind 1 and 2, and the right part of the figure is for Borkum Riffgrund 2

anthropogenic sources could be vessel traffic not identified and removed in the pre-processing (either recreational or transportation), whereas natural influences could be changes in water currents and heavy precipitation which don't average out in daily means.

Moreover, when comparing the average broadband SPL across sites, the values are up to 5 dB greater at Borkum Riffgrund 2 than at Gode Wind despite no turbine-activity dependence. This indicates that there are general differences in ambient noise levels across sites. It can generally be noted that the ambient noise levels are higher across the German Bight than many previously monitored sites (e.g., those presented in Tougaard et al. (2020)). Thus, part of the missing relation between SPL and power production is likely a direct consequence of this area's high ambient noise levels. With that said, there are observed neither single nor cumulating effects from interfering wind turbines on the ambient noise levels.

Even though the analysis shows no link between turbine activity and SPL, it is still clear that the average noise levels throughout the measurement period are lower further away from the turbines. For instance, BKR02 MP9, MP10, and MP11 have lower noise levels than those inside the wind farm. The three measurement positions are located, respectively, 1 and 5 km east of the wind farm. Thus, the reduced noise levels might be a consequence of the hydrophones being located further away from the nearby vessel traffic route (German Bight, Western Approach).

Moreover, both monopile and suction-bucket jacket foundations are examined in the chapter. Most of the foundations are monopiles, but there are recordings for suction-bucket jackets at BKR02 MP4, MP4a. However, the results show that there are no noticeable differences on the broadband SPL between the two foundation types. This is evident as there are no differences observed neither in the power spectral densities (Fig. 2) nor on the dependence from turbine activity (Fig. 4).

Comparison Between Data and Model

This section compares the underwater noise measurements with the model predictions of Tougaard et al. (2020). Their model is currently the most comprehensive published study and therefore the best publicly available knowledge and starting point when wanting to predict the underwater noise from future operating wind farms. As noted by Tougaard et al. (2020), this empirical equation has not been tested against independent measurements to validate its predictive power (e.g., cross-validation tests). Thus, the motivation for this chapter is to test the model to benchmark its predictive capabilities as their model primarily was based on data from smaller turbines.

This study only uses Gode Wind in the comparison as the broadband SPL signal had a minor dependence on the wind speed (albeit no dependence on turbine activity). Borkum Riffgrund 2 is deemed unsuitable for this analysis as it is a pure ambient noise signal. The recorded noise levels can therefore not be a representative for an 8.3 MW turbine.

In the model, the Tougaard et al. (2020) equation is used:

$$\begin{aligned} \mathrm{SPL}_{\mathrm{predictor}} = 109\ \mathrm{dB} - 23.7 \cdot \log_{10} \frac{\mathrm{distance}}{100\ \mathrm{m}} + 18.5 \cdot \log_{10} \frac{\mathrm{wind\ speed}}{10\,\frac{\mathrm{m}}{\mathrm{s}}} \\ + 13.6 \cdot \log_{10} \frac{\mathrm{WTG\ size}}{1\ \mathrm{MW}} \end{aligned} \tag{1}$$

For this case, the maximum scenario is analyzed where wind speed is set to 13 m/s, produced power set to 6.3 MW, and the distance as a variable parameter respective to the source. Firstly, all turbines within Gode Wind 1 and 2 (~580 MW) are positioned on a uniform grid based on their coordinates. Secondly, the noise contribution from all 97 sources is calculated based on Eq. 1 for each grid cell. Here the different sources are added together as:

$$\mathrm{SPL}_{\mathrm{sum}} = 10 \cdot \log_{10} \sum_{i}^{N} 10^{\frac{\mathrm{SPL}_{\mathrm{predictor}_i}}{10}} \tag{2}$$

The model prediction is plotted in Fig. 6, and the comparison with the corresponding noise recordings is presented in Table 3. For the measured SPL, only the noise data for the same wind speeds and active powers are used to ensure compatibility with the model estimates. For this, the linear regression coefficients presented in Fig. 3 are used as a representative of the SPL distribution (data-based SPL).

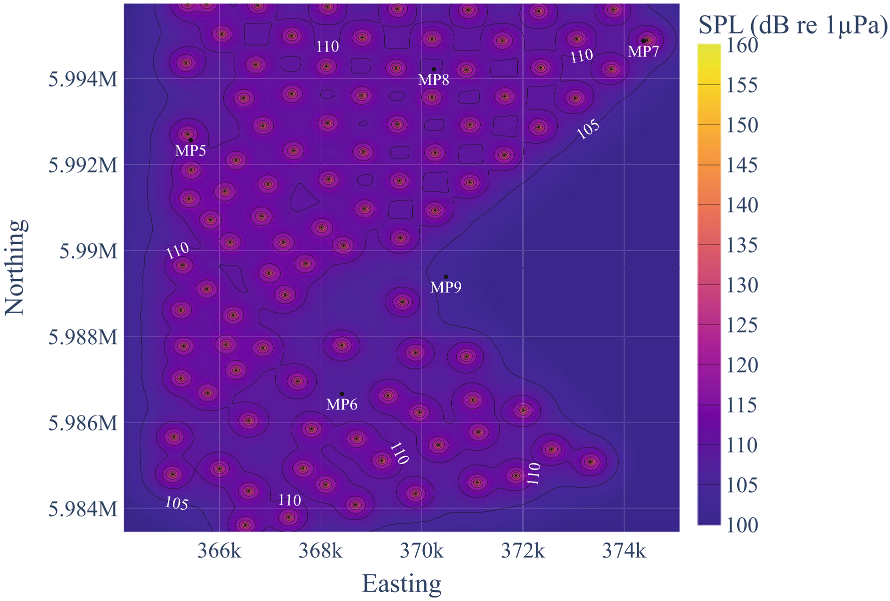

Fig. 6 Modeled SPL for a ~580 MW OWF based on Tougaard et al. (2020) (assuming 6.3 MW turbines and wind speed of 13 m/s). The *x-y* axis contains Easting and Northing values (*m*) with respect to origin

Table 3 Comparison between model-based and data-based estimates (mean ± 1 standard deviation)

	Distance	Model-based SPL	Data-based SPL	Model overestimation
MP7a	70 m	125.4 dB	117.3 ± 0.9 dB	~8 dB
MP7	75 m	124.7 dB	116.5 ± 0.9 dB	~8 dB
MP5	150 m	117.9 dB	115.6 ± 1.0 dB	~2 dB

The data-based estimates are calculated from the linear regression coefficients between power and SPL. Only the nearest positions are presented as the model estimates decreases with distance

From Table 3 it is evident that the Tougaard et al. (2020) model overestimates the noise by ~8 dB at the nearest positions of ~70 m. The data-based and model-based results converge as the distance from the turbines increases. This is a result of the model yielding decreasing noise levels with distance due to its transmission loss, whereas the data-based estimates almost remain constant within the recorded distances. Hence, no comparisons were made with the recordings further away as there was no turbine effect on the broadband SPL.

These results can therefore provide a contribution to benchmarking of underwater noise predictions for future studies to avoid under- or overestimations of noise levels. While the results don't show what SPL to expect from these turbine types and sizes, they do provide an upper limit to what the noise levels can be in a certain distance.

Conclusion

This chapter found no changes to the ambient broadband SPL from neither 6.3 nor 8.3 MW operating wind turbines. While this partly was attributed to the high ambient noise levels of the German Bight, it remained evident that natural effects (e.g., wind speed and tidal changes) were the dominating forces behind changes to the ambient noise levels. Nearby crossing vessels caused short-term elevated noise levels, which were filtered out in the analysis. Furthermore, the results showed that the recorded noise levels were up to 8 dB lower in distances up to ~70 m to the turbines than those predicted through the Tougaard et al. (2020) model. This suggests that there are challenges associated with extrapolating aggregated results from smaller turbines to the realm of new, larger, and technologically different turbines. Such findings have implications to efforts set to predict the noise impact of future offshore wind farms, as broadband SPL does not scale with increasingly larger turbines.

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