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Propagation distance-of-concern for offshore wind turbine airborne sound during piling and normal operation

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Summary
Offshore wind farms are being constructed all over the world at a very high rate. The underwater noise impact, especially during construction, has attracted a lot of attention and is commonly included in environmental impact assessments. In contrast, reported research on the airborne noise impact is scarce. In this work, on-site measurements during normal operation at close distance from a wind turbine show that sound pressure levels are not excessive so that noise issues after propagation over several kilometers are unlikely. In contrast, the extremely high noise levels produced during piling need more care. An emission spectrum was estimated, based on measured sound pressure levels at close distance during a specific piling operation. Detailed numerical predictions were subsequently made to estimate sound pressure levels after propagation up to 10 km above the sea surface under various meteorological conditions. Wind and atmospheric stability influence both the refractive state of the marine atmospheric boundary layer and sea surface roughness, affecting in turn long-distance airborne sound propagation. A windless situation is predicted to be most favorable for sound propagation, leading to the highest sound pressure levels. Beyond 10 km, also piling sound pressure levels become sufficiently limited under all possible conditions.

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1. Introduction

Offshore wind farms are being constructed all over the world at a very high rate, given the beneficial combination of a large wind energy potential and space at sea. Especially the underwater noise impact has attracted a lot of attention. During normal wind farm operation, underwater noise exposure was considered to be of limited concern by Madsen et al. [1] based on their extended literature review. Marine piling (where supporting poles for the wind turbines are driven into the sea bed), in contrast, was shown to be able to lead to injury and behavioral changes in marine animals due to the extremely high sound pressure levels [1]. To mitigate such effects, e.g. pingers and air bubble curtains [2] are commonly used.

This study deals with airborne sound produced by offshore wind turbines. Measurements at close distance from a wind turbine at sea were made during normal operation and during piling (pinpiles, jacket foundation). In order to assess the propagation-distance-of-concern, sound propagation calculations were performed. The specific conditions at sea like wind refraction and the presence of a rigid scattering sea surface, influenced as well by wind, were taken into account in detail.

2. Noise during normal wind turbine operation

The measurements depicted in Fig. 1 show total A-weighted sound pressure levels measured at close distance from a 5-MW wind turbine during normal operation. The converged sound pressure level at wind speeds above 12 m/s could be explained by limiting rotational speed to prevent damage. Given these rather modest levels, airborne noise from offshore wind farms during normal operation is not expected to affect the human population given the many kilometers of propagation towards the coastline.

3. Piling noise

In Fig. 2, a selection of the recorded noise levels during the maximum impact period during piling is depicted,

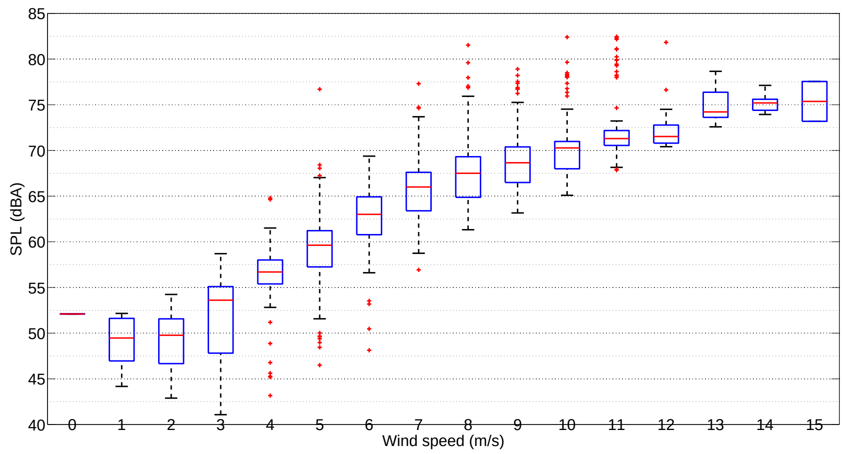

Figure 1. Distribution of SPL (measured at the wind turbine platform) as a function of wind speed class (measured at hub height) during 15 consecutive days

in between the so-called soft start period and the moment the hammer becomes submersed. The pile diameter is 1.83 m and has a length of 48 m (to support a 6-MW wind turbine). The airborne impact peaks are anticipated by an underwater generated shockwave reaching the microphone.

The maximum and equivalent sound power level spectra are shown in Fig. 3. The source power level is estimated by calculating back to a point source at 15 m above the sea surface, accounting for geometrical divergence, atmospheric absorption and reflection on a rigid plane. The total maximum airborne source power level reaches 145 dBA.

4. Long-distance downwind piling noise propagation

4.1. Operating effects

Specific propagation effects over sea might result in limited attenuation, even in case of long-distance propagation:

- A flat water surface behaves as a rigid plane for sound waves reflecting on it.
- Downwind propagation leads to downward refraction of sound.
- The combination of these two phenomenons results in so-called multiple-bounce effects.

In contrast, wind-induced sea surface waves will have a noise mitigation effect [3], and the degree of roughness is proportional to the wind speed. Coupled analysis of sea state and wind conditions is therefore essential.

4.2. Refraction by wind in the marine atmospheric boundary layer

The Monin-Obukhov similarity theory [4] was used to estimate the vertical temperature and wind speed profiles that will be used in the Parabolic Equation (PE) method (using the effective sound speed approach) for long-distance propagation. A standard atmospheric temperature lapse rate of 6.5 10^{-3} K/m was used. Of importance is a good estimate of the aerodynamic roughness length, determining the strength of the gradients near the sea surface, driving refraction of sound. The approach proposed by Charnock [5] was used, linking the roughness length to the friction velocity u^*, gravitational acceleration g, and the so-called Charnock parameter z_{ch}:

$$z_0 = z_{ch}\frac{u_*^2}{g}$$

An average value of z_{ch}=0.014 m was used (between open sea and coastal region).

4.3. Wind-induced sea surface scattering

Different sea surface realizations were constructed by multiplying the amplitude of the Fourier transform of a generated white noise surface with the Pierson-Moskovitz spectral density function [6]. The absolute wave heights were linked based on the relationship between the significant wave height and the wind speed at the standard height of 10 m by using a well-established empirical relationship [7]. Short-distance full-wave calculations were performed for various wind-driven sea states (2, 3 and 4, corresponding to a light, gentle and moderate breeze, respectively) with the finite-difference time-domain (FDTD) method [8] to find an equivalent flat surface impedance at low angles of incidence [9]. A similar

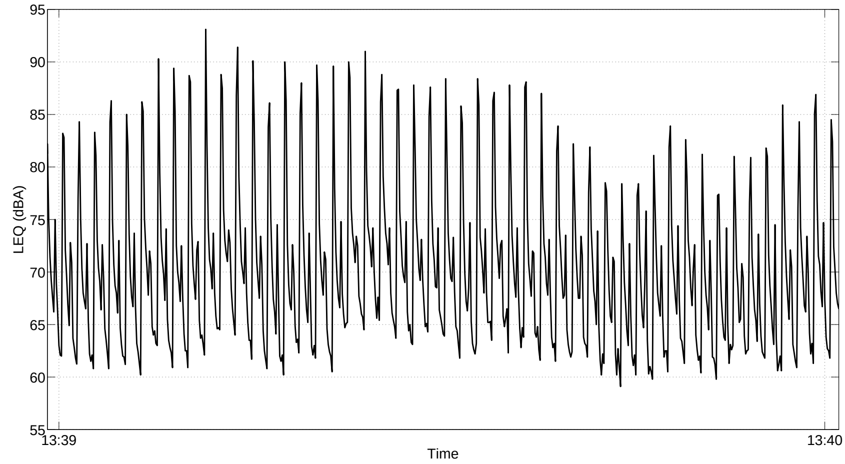

Figure 2. Detail of 1 minute of recorded equivalent sound pressure levels using an integration period of 100 ms, at about 280 m from the piling platform during maximum piling airborne sound emission

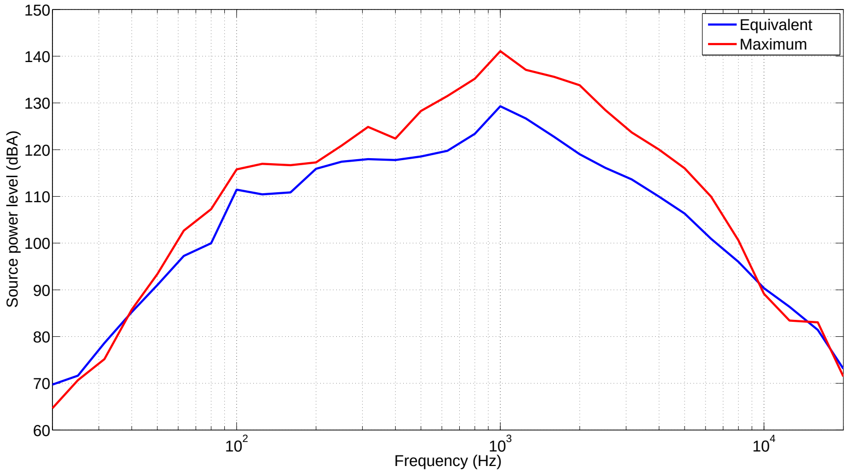

Figure 3. The estimated equivalent and maximum source power level spectrum during piling; the maximum level is defined as the level exceeding 1% of the time

approach was used in Ref. [10]. Best fits to the following function [9] were made (with Z the complex impedance, and f the sound frequency) :

$$Z = \frac{a_r}{f^{m_r}} + b_r + \left(\frac{a_j}{f^{m_j}} + b_j \right) j$$

With increasing wind speed, lower impedances were obtained, both for the real and imaginary part [9]. The use of effective impedances allowed easily including rough sea surface scattering in the PE method.

4.4. Numerical results

If was found that the noise decreasing action of sea surface scattering is more important than the noise increasing effect of downwind refraction for the range of wind speeds considered (up to u_{10m}= 7m/s at sea state 4, no turbulent atmospheric scattering). This means that piling in some wind is beneficial to avoid noticing sounds onshore. Sound propagation in absence of wind represents the worst situation (see Fig. 4), leading to the highest sound pressure levels. For this specific piling operation, the predicted peak level is still 50 dBA at 4.5 km. In case of wind (sea state 3), the level at this distance drops with 14 dBA. The equivalent levels are 5 to 10 dBA lower than the level exceeding 1% of the time during piling. A stable atmosphere at the same reference wind speed at a fixed height gives somewhat higher sound pressure levels than an unstable or neutral atmosphere [9]. Beyond 10 km, sound pressure levels become sufficiently low under all possible conditions.

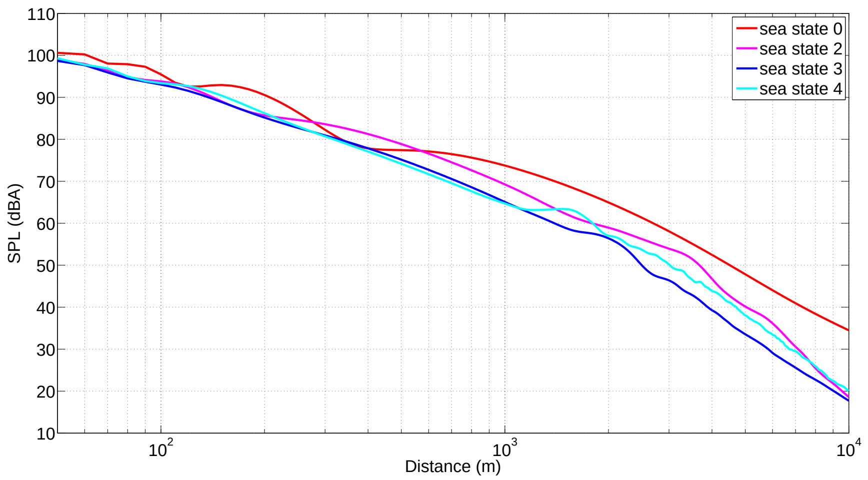

Figure 4. Predicted total (maximum) sound pressure levels with distance resulting from the monitored piling operation at different sea states, in case of a neutral atmosphere

5. CONCLUSIONS

Normal operation of offshore wind turbines do not pose airborne noise issues given the rather modest levels produced and the fact that distances to shorelines usually exceed several kilometers. The very high airborne sound power levels during piling (up to 145 dBA) are of greater concern.

Detailed calculations, coupling wind-driven refraction and sea surface state, indicate that the propagation-distance-of-concern can be large. The predicted maximum level for the specific piling operation under study still reaches 50 dBA at 4.5 km. It is beneficial to perform piling when there is some wind, since rough sea surface scattering is more important than downward refraction effects. However, at a distance of 10 km, no problems are expected under all possible atmospheric conditions.

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