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# Noise emission during construction and operation of wind power plants investigated by numerical methods

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## ABSTRACT

**The noise emission during construction and operation of wind power plants is an issue which gained of considerable importance in recent years. Therefore, not only experimental investigations but also calculations need to be performed in order to acoustically enhance the wind turbines and their installation. Due to the large size and the high complexity of the systems, however, the use of simulation methods is only possible, if the calculation models are distinguished by a particularly high numerical efficiency. In the current paper, it is shown which calculation methods are recommended and which accuracy can be expected when they are used to predict the sound emission. Two representative examples of significant practical relevance are discussed in detail: The prognosis of underwater construction noise when setting up offshore wind turbines and the acoustic emission of a complete onshore wind turbine during operation. For the investigations a variety of numerical methods is used, namely analytical formulae, the Finite Element Method (FEM), the Boundary Element Method (BEM), and the Finite Volume Method (FVM).**

**Keywords:** Noise, emission, wind, turbine, pile driving, offshore, underwater noise
**I-INCE Classification of Subject Number:** 10, 50, 76

## 1. INTRODUCTION

The growing ratio of renewable energy sources leads to an increasing number of wind turbine installations onshore as well as offshore. Hence, new operation locations have to be developed. Onshore, wind turbines are installed to a greater extent in low wind regions, which results in increasing hub heights and rotor diameters. Furthermore, operating locations relocate from remote regions to more populated areas. Recently, more and more offshore wind parks are installed far at sea, with turbine sizes even bigger than onshore. Both entail in growing dimensions of the offshore foundations. The development of more efficient wind turbines and the increasing structure sizes for onshore as well as offshore wind parks result in higher noise emissions during both construction and operation. Due to higher noise levels, an accurate prediction of sound emissions in early development phases becomes crucial with respect to environmental protection limits.

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In general, noise emissions during construction of onshore wind turbines are less critical than during operation, while the opposite holds offshore. Legislation onshore and offshore also differs, as the noise emission limits are prescribed at different receiver locations and the sound propagating medium offshore is water instead of air. Hence, also different simulation techniques have to be applied for a prognosis in order to accurately predict the noise emissions of onshore and offshore wind turbines.

In the following sections, numerical approaches suitable for the prediction of noise emissions during the construction of offshore foundations are presented first. Besides a brief overview of offshore pile driving noise, also an explanation of the noise generation and transmission mechanisms as well as a description of the modelling approaches and a comparison to offshore measurement data are given. Subsequently, a tool chain for the noise prediction of onshore wind turbines is outlined before conclusions are drawn.

## 2. OFFSHORE PILE DRIVING NOISE

### 2.1 General

#### 2.1.1 Foundation of offshore constructions

Offshore constructions are needed for different purposes, e.g., within the oil and gas industry or for offshore wind parks. The corresponding foundations are in most cases attached to the sea bed by using huge steel piles that are driven into the ground with impact hammers. Thereby, the constructions are sitting either directly on one or more piles that have a certain stick-up above the sea surface, or they are mounted on a support structure like, e.g., a jacket or a tripod that is pinned to the sea bed by submerged piles. Furthermore, also floating structures that are attached by submerged anchor piles exist, especially at deeper waters. Although alternative approaches exist, like, e.g., gravity foundations or suctions buckets, pile driving is still the major technology.

#### 2.1.2 Underwater noise

Due to the high ram energies that are needed to drive the piles to final embedment depth, a considerable amount of noise is emitted into the water column, with unmitigated source sound pressure levels clearly above 200dB. In the last decade, underwater noise emission has therefore gained more and more importance, e.g. in the European Union’s Marine Strategy Framework Directive MSFD [1]. For offshore pile driving, several countries have further introduced their individual limitations on the underwater noise emissions that have to be complied with during construction.

#### 2.1.3 Noise mitigation

To keep the prescribed limit values, often noise mitigation techniques have to be applied. Several approaches exist, where in general measures directly at the pile, like e.g. cofferdams, the IHC noise mitigation screen (NMS), the hydro sound damper (HSD), the AdBm noise abatement system (AdBm), or small bubble curtains (SBC), as well as measures in a certain distance to the pile, like big bubble curtains (BBC), are used, see e.g. [2-4].

Beside the mentioned passive noise mitigation techniques, which decrease the noise levels that are already in the water, also active approaches exist, which aim at reducing the source levels, for example by modifying the characteristic signal of the hammer impulse at the pile head, see e.g. [5].

#### 2.1.4 Prognosis of underwater noise emission

As offshore measurements are a complex and costly task, reliable models to quantify the noise emission and to optimize the construction process are required. Such models are further needed to enable a prediction of the noise emission prior to any construction activities which is often mandatory, e.g. for environmental impact studies or regulatory approval procedures, and dimension potential noise mitigation measures.

As a result, several modelling approaches for offshore pile driving noise have been developed. They are in a process of constant enhancement and regularly compared to measurements, e.g., in the frame of the COMPILE initiative [6].

## 2.2 Noise generation and transmission

### 2.2.1 Noise generation

Due to the hammer impact on the pile head, a longitudinal compression wave is initiated that is travelling downward towards the pile toe, where it is reflected and travels up again, and so on. The longitudinal compression causes a radial expansion of the pile, which initiates a pressure front in both the water column and the soil [7]. Due to losses especially in the embedded part of the pile, the signal is decaying with time, resulting in the typical shape of a pile driving noise signal (Figure 1).

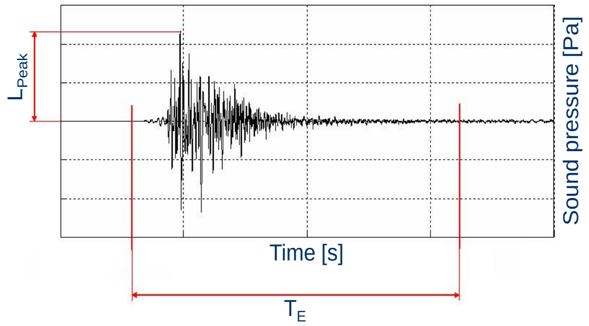

*Figure 1: Typical underwater sound pressure signal due to offshore pile driving.*

### 2.2.2 Noise transmission

The impact energy of the hammer results partly in pile penetration into the soil, vibration of the pile, vibration of the soil, and elastic/non-elastic deformations. The noise transmission into the water column occurs on the one hand via the direct path from the pile into the water, but partly also from the pile via the soil into the water (Figure 2). Especially when noise mitigation systems are applied, the soil becomes a very important transmission path and enables a “tunneling” of the noise mitigation system by pressure waves propagating through the soil back into the water.

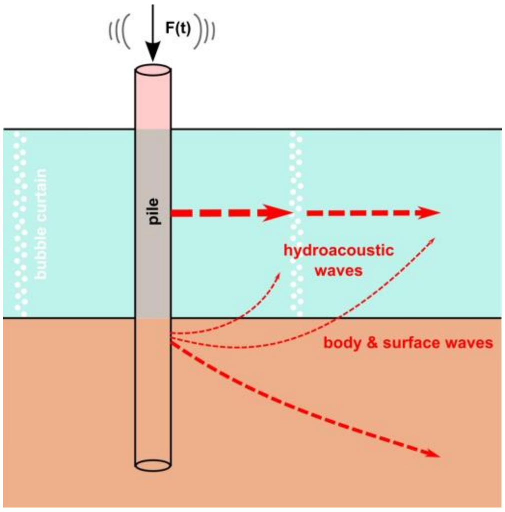

*Figure 2: Noise generation and transmission.*

2.2.3 Characteristic quantities

For pile driving noise, often two characteristic quantities are used to evaluate the underwater sound pressure signals: The sound exposure level (SEL), which is a measure for the energy equivalent sound level of a continuous sound signal of length 1s, and the peak sound pressure level (SPL). According to [8], these are defined by

$$SEL = 10 \cdot \log\left( \frac{1}{T_E} \int_{T_1}^{T_2} \frac{p(t)^2}{p_0^2} dt \right) \tag{1}$$

and

$$SPL = 20 \cdot \log\left( \frac{\left| p_{peak} \right|}{p_0} \right), \tag{2}$$

where $p_{peak}$ is the maximum positive or negative sound pressure, $p_0$ is the reference pressure of 1µPa, $T_E$ represents the reference period of 1s, and $T_1$ and $T_2$ mark the starting as well as the end time of the averaging. The time-dependent pressure development within the averaging period is referred to as $p(t)$.

## 2.3 Modelling approach

2.3.1 Available methods for offshore pile driving noise

Although underwater acoustics has been a research topic since several decades and different models are available, the prediction of pile driving noise is still a complicated task. The main reasons are the huge size of the domain with distances of interest up to several kilometers, the special line-source-like characteristic of the pile, where a part of the source is embedded in the soil, and the complex interaction between impact hammer, pile, and soil.

During the last years, several approaches for the prediction of offshore pile driving noise have been developed and continuously refined, see among others [7][9-20]. Currently, mainly five different groups can be distinguished. Thereby, all of the five different approaches and methods have their individual advantages and drawbacks:

*Close range discretization methods* are normally based on a FE model in the time domain and allow for an extremely fine representation of many details, e.g. regarding pile geometry, soil layering, pile-soil-interaction, hammer impact, consideration of noise mitigation systems, etc. Due to the time domain modelling, sound pressure signals equivalent to hydrophone measurements are produced and can be animated in the complete computational domain, which allows for a high physical insight. However, their major drawbacks are the high computational cost, which typically requires a 2D rotational symmetric representation of the problem and limits the extent of the propagation path.

*Long range propagation codes*, on the other hand, are dedicated for predicting the sound propagation up to several kilometers distance to the pile. They are using efficient approaches based on, e.g., parabolic equations, wavenumber integration, or normal modes to propagate a starting field or single point sources over long distances. Although some 3D implementations exist to consider a complex bathymetry at the site, many codes are still restricted to a 2D rotational symmetric representation of the domain. The major drawbacks are the need to define the pile as a set of single point sources or to prescribe a corresponding starting field to be propagated in both water column and soil, which decreases the amount of details that can be considered in the model when compared to close range discretization models.

Approaches that couple a *close range model with a long range propagation code* combine the best of both worlds of the two tactics. However, major disadvantages arise from the necessity to set up two different computational models and to implement a coupling between close and long range model that is both accurate and efficient.

*(Semi-)Analytical approaches* partly try to make up some of these drawbacks by using a simple point source characterization for the pile instead of a complete close range model, which, however, directly goes along with even more loss of detail.

A completely different approach to the aforementioned numerical methods are *empirical models,* which are typically based on a huge data set of measurements. By using scaling laws and interpolation algorithms, already basic information regarding pile dimensions, hammer type, general soil characteristics, etc. are sufficient to obtain a good estimation of the noise levels to be expected, which makes empirical models especially interesting in early stages of the planning process, when detailed data to set up a comprehensive numerical model of the site is not available. Nevertheless, empirical models are not suitable to give a sound statement regarding, e.g., different pile designs or alternative hammer options.

### 2.3.2 Possibilities to consider new technologies

While empirical models are restricted to problems that are covered by the existing measurement data set and do not allow a prediction when changing major pre-conditions, like e.g. new hammer technologies or alternative/optimized noise mitigation concepts that are not represented in the data base so far, numerical models offer many possibilities to include new technologies.

Due to the representation of many details, especially close range FE models offer a lot of freedom in this respect. On the one hand, they typically use an excitation force at the pile head that represents the hammer impact and has been computed by a separate pre-calculation model. This offers the possibility to easily consider new hammer technologies, like e.g. vibro hammers or BLUE piling hammers, by replacing the excitation of the impact hammer by another signal. Alternative pile designs or new mitigation system, on the other hand, can be included directly in the model.

The integration of new technologies allows for a thorough investigation without costly offshore testing. Particularly the high physical insight regarding noise generation and propagation when using numerical models helps for a target-oriented optimization of new concepts and components.

## 2.4 Comparison to offshore measurements

The prediction of the underwater noise emission prior to the construction activities is a difficult task. Especially when applying comprehensive numerical models, the derivation of the necessary input parameters can be challenging.

Typically, detailed information regarding the pile design, the intended hammer type, and corresponding driving energy profiles are available in a form that is sufficient for the model setup. However, site-specific information like the soil layering from seismic surveys is often only provided with respect to the geotechnical properties that are needed for pile stability analysis and drivability studies. Important input parameters for numerical models, like e.g. sound velocities in the different soil layers or damping properties, are normally not available. The careful derivation of the relevant parameters based on the existing data is left open to the modeler and controls the quality of the prognosis.

To allow for a comparison of different prediction models for pile driving noise, the Hamburg University of Technology (TUHH) and the Netherlands Organization for Applied Scientific Research (TNO) founded the COMPILE initiative in 2014. After a first workshop with a rather empirical test case (see [19]), a more realistic benchmark scenario has been defined for the COMPILE II workshop, which took place at TUHH in 2017. E.ON Climate & Renewables helped to define the benchmark scenario by providing the necessary details regarding pile, soil, and impact hammer as well as corresponding measurement data from a recent wind farm project. Thereby, all the 12 participating research teams from all over the world had to hand in their computed noise levels before the workshop started, while the measured noise levels have been unknown to all participants (including TNO and TUHH). For further information on the COMPILE II benchmark case, please see [6], [21-22].

The sound exposure levels (SEL) that have been predicted by the different participants as well as the measured data at 250m, 750m, and 1500m distance to the pile are shown in Figure 3. Typical measurement uncertainty is accounted for with ±3dB. The results of TUHH and of Novicos, which is a spin-off-company from TUHH, are indicated. Novicos used a close range FE model, while TUHH applied a combination of a close range FE model and a long range propagation code. The type of approaches of the other participants are given in the legend.

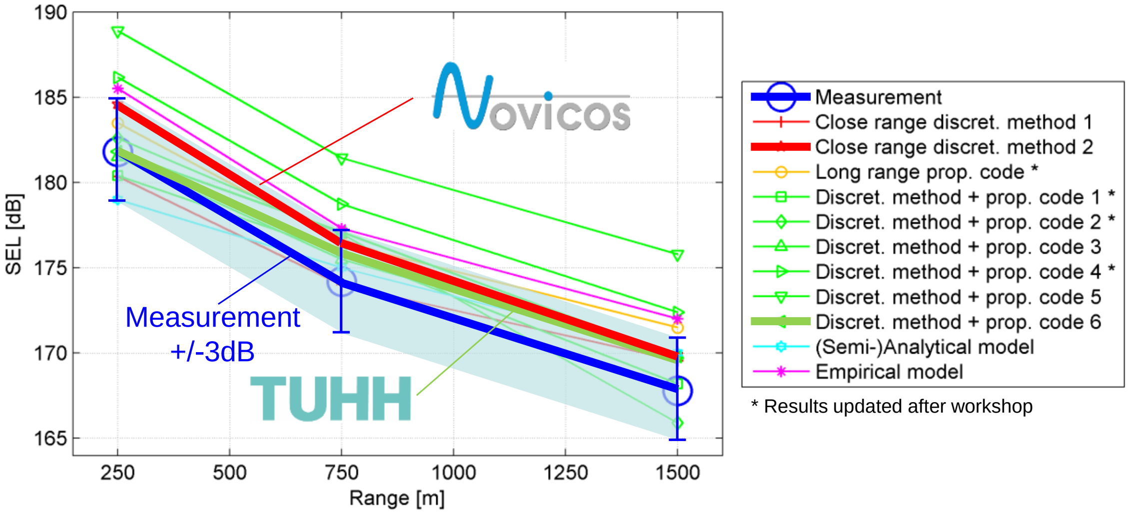

*Figure 3: Sound exposure level (SEL): Comparison of predicted noise levels and measurement data (measurement uncertainty ±3dB). Result sets that have been updated after the workshop took place are indicated with an asterisk (*).*

A detailed discussion of the results is not the intention of this contribution, still some general conclusions can be drawn from the data. Overall, it can be observed that the spread of the predicted noise levels is rather moderate. Many of the approaches based on a numerical model deliver a prediction that is well within the confidence level of the measurements. Also the empirical model shows results which are close to the confidence range, although the predicted levels are very conservative. Two models, however, compute noise levels that are clearly above the measured values. As one would expect, the uncertainty of the predictions increases with distance to the pile, as small deviations in the propagation parameters like, e.g., damping settings multiply with propagation.

It can be noted that many approaches rather overestimate the SEL. One reason may be the ideal representation of the reflection conditions for the propagating sound pressure wave in the water column (flat sea surface) in most models and the sensitive consideration of damping. The numerical models typically assume ideal propagation conditions, while embedded air bubbles and an uneven surface due to waves may increase both scattering and damping in reality. Nevertheless, such a conservative approach is meaningful, as calm sea states can occur during construction.

Beside the absolute delta between predicted and measured levels at a certain distance, the decay of the signal with range is an important indicator to assess, if the propagation path is correctly reproduced. It can be observed that some of the models reflect the decay characteristics of the site very well. These models will be able to produce reliable results even for larger distances above 1500m. Other approaches, however, seem to reflect the propagation conditions less accurate, which will cause an increasing over- or underestimation of the noise levels with distance to the pile, respectively.

Similar conclusion can be drawn regarding the peak sound pressure level (SPL). Although it is much more difficult to accurately predict absolute peak values like the SPL than energy-averaged quantities like the SEL, still many of the models produced results that are within the confidence range of the measurements (for further details, see [6]).

## 3. ONSHORE WIND TURBINE SOUND EMISSIONS

The sound emissions of wind turbines mainly result from sound waves emitted by the tower, the blades, and the nacelle housing. In comparison with offshore wind parks, the noise imission locations are substantially closer for onshore wind turbines. According to the IEC regulations, the locations to assess the noise imissions are located in the far field at a distance of about 150m. Hence, the acoustic properties of wind turbines are of great importance for onshore installations. In order to prevent expensive down times and rectifications due to the non-compliance of acoustic limits, the prediction of the sound emission at early development stages is crucial. Due to the distant evaluation points and the occurrence of structural resonances with large amplitudes, the acoustic properties of wind turbines are mostly characterized by low frequency tonalities. Hereafter, a simulation tool chain to assess tonalities of gearbox wind turbines is outlined.

### 3.1 Structure model

In order to assess dynamic drive train loads, which lead to vibrations of the wind turbine, different FEM-simulation techniques have to be utilized. An established simulation sequence is to determine structural loads during operation by means of a multi body simulation (MBS) in the time domain, followed by a frequency response analysis with an excitation which is deduced from the MBS-model. As the focus of the MBS-model is on the rotating drive train and its components, the frequency response model comprises a detailed description of sound emitting surfaces.

An interface between the time and frequency domain models is defined by a set of coupling nodes, which represent connections between subsystems and enable the utilization of FRF-based substructuring techniques. The interface definition leads to a subdivision into the subsystems: (1) tower + bedplate, (2) nacelle housing, () gearbox, (4) generator, and (5) hub + blades. Figure 4 illustrates the resulting subsystems condensed to theirs interface nodes.

In a first step, the mode shapes of each subsystem are computed up to a frequency of 600Hz. Based on modal superposition an arbitrary fine frequency resolution can be chosen for the subsequent FRF computations in order to accurately account for resonances. By defining connection properties between interface nodes of different subsystems, the local FRFs can be combined to a global set of FRFs which represents the dynamic behavior of the turbine. From the global FRF set mode shapes can be extracted using the PolyMAX method [23]. Since the FRFs of the subsystems have to be computed only once and the coupling procedure is not expensive, the FRF-based substructuring is an efficient method to analyze, optimize, and define connection properties of the gearbox bushings, the main bearing, the nacelle bushings, and the generator bushings.

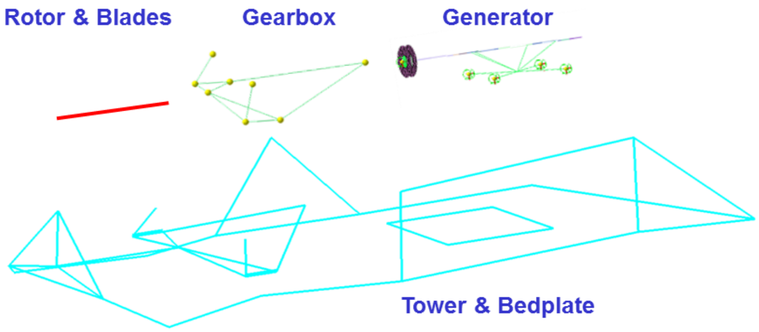

*Figure 4: Condensed subsystems of frequency domain model.*

Once the reduced structure model is in good agreement with measurement data, forces at the interface nodes are determined from the MBS-model as a function of wind loads. The subsequent FFT of these time dependent forces is used as excitation for the sound emitting subsystems in the frequency domain. Normal velocities induced by these forces are prescribed as Neumann boundary conditions for the acoustic simulation and are computed based on the same mode sets used to determine the FRFs. For gearbox wind turbines, the dynamic behavior of the drive train is strongly influenced by load spectra, which arise in the gearbox when transforming slow rotations of the rotor to high speed rotations for the generator. The following acoustic simulations are based on two generic load spectra (Figure 5): While by the blue forces a moment about the vertical axis of the wind turbine is induced, the red forces create a moment about the longitudinal gearbox axis.

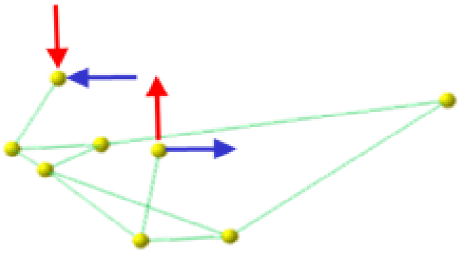

*Figure 5: Gearbox excitation vertical (red) and horizontal (blue).*

### 3.2 Acoustic model

Due to the distance of the evaluation points, the acoustic simulation is performed by means of the BEM [24-25]. In contrast to the acoustic FEM only the surface $\Gamma = \partial\Omega$ of the solution domain $\Omega \in \mathbb{R}^3$ needs to be discretized. Once the Cauchy-data $[p(\boldsymbol{x}), \partial p(\boldsymbol{x})/\partial \boldsymbol{n}(\boldsymbol{x})]$, namely the acoustic pressure and the sound velocity, are known on the surface $x \in \Gamma$, the solution can be reconstructed in the entire solution domain $\boldsymbol{y} \in \Omega$ by the boundary integral equation

$$p(\boldsymbol{y}) = i\rho\omega \int_{\partial\Omega} G_H(\boldsymbol{x},\boldsymbol{y}) v_n(\boldsymbol{x}) \partial\Omega(\boldsymbol{x}) - \int_{\partial\Omega} \frac{\partial G_H(\boldsymbol{x},\boldsymbol{y})}{\partial \boldsymbol{n}(\boldsymbol{x})} p(\boldsymbol{x}) \partial\Omega(\boldsymbol{x}). \tag{3}$$

In the above equation $\rho$ denotes the density of the fluid, $\omega$ the angular frequency, $\boldsymbol{n}$ the surface normal vector and

$$G_H(\boldsymbol{x},\boldsymbol{y}) = \frac{1}{4\pi|\boldsymbol{x}-\boldsymbol{y}|} e^{-ik|x-y|} - \frac{1}{4\pi|\boldsymbol{x}'-\boldsymbol{y}|} e^{-ik|x'-y|} \tag{4}$$

the 3D-half-space fundamental solution, which accounts for sound hard ground reflections. Additionally, $k = {}^{\omega}/_{c}$ represents the wave number and $c$ the speed of sound. A drawback of the BEM is the quadratic memory requirements O($n^2$) for storing the fully populated system matrices. Due to the large dimensions of the wind turbine and a frequency range of interest up to 300Hz, the surface discretization leads to systems of equations with more than 500.000 degrees of freedom (d.o.f.) $n$, and thus to memory requirements of at least 3.6TB, which exceeds the available memory of current workstations. The memory consumption as well as the computational effort are reduced to $O(n \log n)$ by means of the hierarchical matrix (H-Matrix) compression [26-27].

Figure 6 illustrates the sound pressure levels (SPL) at the IEC-measurement locations for two characteristic loads acting on the gearbox, as shown in Figure 5. Here, the IEC SPLs are determined as the maximum sound pressure on a circumference section with an apex angle of $\pm 15^{\circ}$ behind $(0^{\circ})$ the wind turbine.

However, the small differences between the SPLs for applied moments about the vertical axis of the wind turbine (blue) and the longitudinal axis of the gearbox (red) should not be utilized as a generalized quantity for the acoustic behavior of a wind turbine, as can be seen in the directivity plots, see Figure 7 (left).

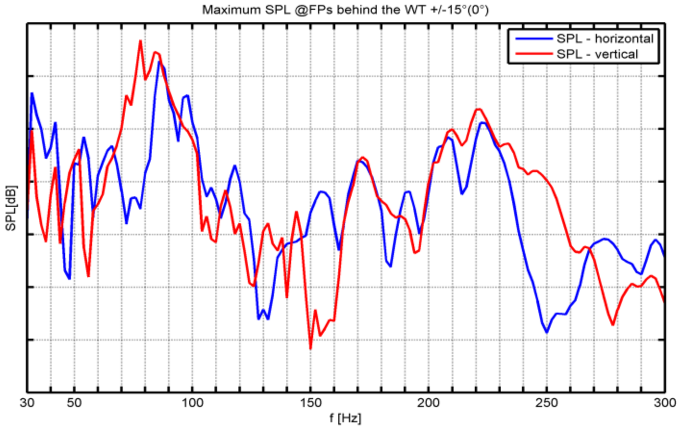

*Figure 6: SPL for load cases at IEC-measurement locations.*

In contrast to the IEC SPLs, the directivity plot contains field points on the entire circumference $(\Delta\alpha = 1^{\circ})$ and specifies the emissions in all directions. Additionally, by partitioning the evaluation of equation (3) with respect to the surfaces of the tower, the nacelle housing and the blades contributions of sound emitting components can be identified. As illustrated in Figure 7 (right), only 2 of the 3 surface areas contribute to the SPLs in the far field. For a more detailed analysis of the sound propagation to the IEC locations the sound path can be sampled with additional field points. Figure 8 shows the SPL distributions at 78Hz close to the ground as well as for a vertical plane, which covers the directions in front of (180°) and behind (0°) the wind turbine. The corresponding field point meshes comprise more than 3 million sampling points, which are evaluated at reduced computational costs by utilizing the H-Matrix compression. As a result of the detailed sound path comparison, it turns out that the different load spectra acting at the gearbox lead to entirely different noise emissions. This is not obvious when considering the IEC SPLs only. Furthermore, even if the directivity plot could hardly be measured, the contributions and the sound path resolution are practical infeasible.

The proposed method can be extended to more than one wind turbine. By exploiting structures of the system matrices [28] for wind park configurations, exterior BEM problems exceeding $10^8$ d.o.f. are solvable. The unstructured wind park configuration shown in Figure 9 leads to systems of equations with 2.5 million unknowns.

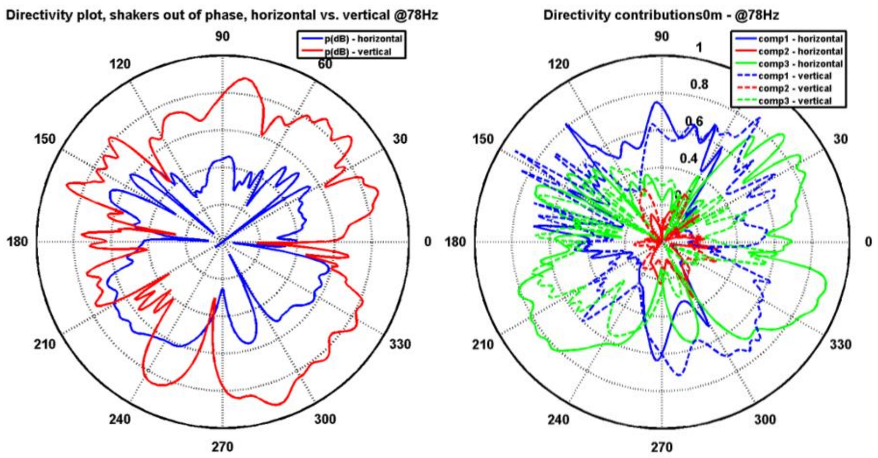

*Figure 7: Directivity plot with an angular resolution of $\Delta\alpha = 1^{\circ}$ (left) and emitting surface contributions to the directivity plot (right).*

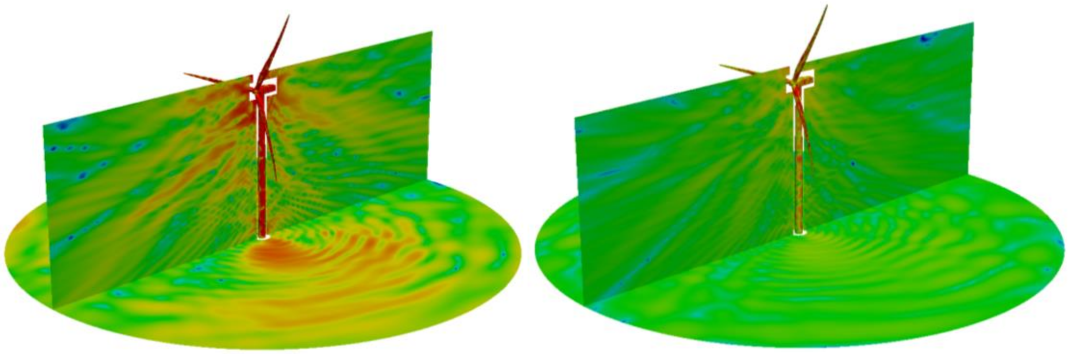

*Figure 8: Sampling of the sound path at 78Hz with 3 million field points for vertical (top) and horizontal (bottom) gearbox excitation.*

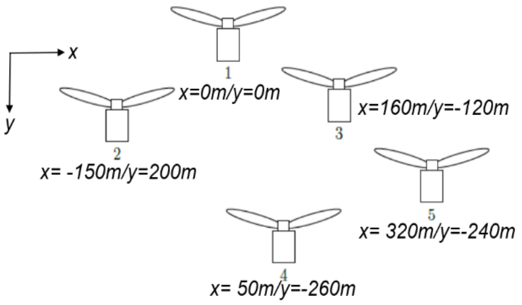

*Figure 9: Unstructured wind park configuration with 5 wind turbines.*

Taking advantage of the fact that only specific blocks need to be compressed by H-Matrices, the memory requirements for fully populated system matrices of 97TB can be reduced to 39GB. Compressing the necessary matrix blocks and solving the resulting system of equations can be done in parallel and takes only about 8 minutes (32 CPUs). The reconstruction of the pressure distribution above the ground for 12 million field points takes about the same amount of time, see Figure 10.

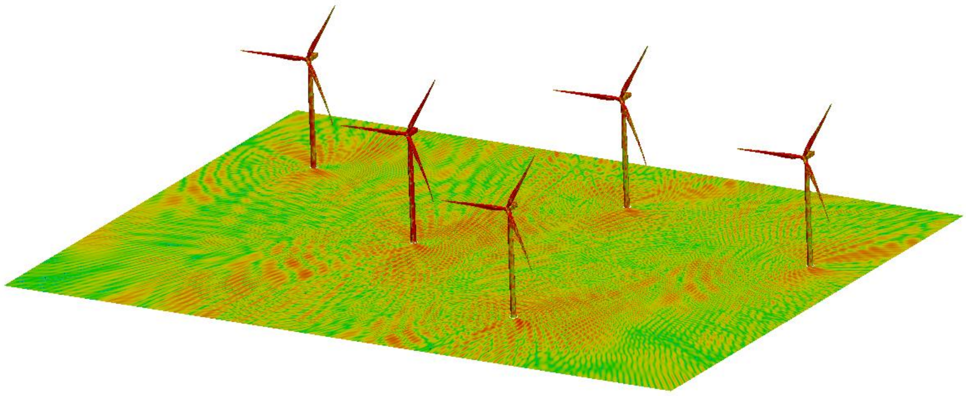

*Figure 10: Sound pressure distribution sampled with 12 million field points.*

## 4. CONCLUSIONS

The outlined modelling approaches both for the prediction of offshore construction and onshore operation noise of wind turbines provide a detailed understanding of the noise generating mechanisms during construction and operation. Especially, the high degree of physical insight due to the possibility of evaluating the complete sound field, which cannot be deduced by measurements, helps immensely to optimize the systems and reduce the noise emissions. Furthermore, new technologies can be included and improved without costly prototype measurements. Nevertheless, due to the huge size of the simulation models, very efficient numerical methods are necessary to further reduce the computational costs for the acoustic simulations.

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